By Jonathan R. Ackerman

A thesis submitted to the University of Leicester in fulfilme requirements for the degree of Doctor of Philosophy

Department of Engineering

Supervisor: Prof. J.P. Gostelow Co-supervisor: Dr A. Rona Industrial Supervisor: Dr W.E. Carscallen (NRC)

August 2004





UMI Number: U191990

All rights reserved

INFORMATION TO ALL USERS

The quality of this reproduction is dependent upon the quality of the copy submitted.

In the unlikely event that the author did not send a complete manuscript and there are missing pages, these will be noted. Also, if material had to be removed, a note will indicate the deletion.



UMI U191990 Published by ProQuest LLC 2013. Copyright in the Dissertation held by the Author. Microform Edition © ProQuest LLC. All rights reserved. This work is protected against unauthorized copying under Title 17, United States Code.



ProQuest LLC 789 East Eisenhower Parkway P.O. Box 1346 Ann Arbor, MI 48106-1346 My parents, Raymond and Judy. Thank you for everything. _

Abstract

Eckert and Weise first measured time-averaged energy separation behind a circular cylinder in 1943. Although a significant amount of work has been carried out on the subject since Eckert and Weise's discovery no time-resolved measurements have been made of the phenomenon at high subsonic Mach numbers. The aim of this project was to make these measurements, along with those of surface pressure. Energy separation and base pressure are investigated at high subsonic Mach numbers, behind a circular cylinder in crossflow, for the first time.

The measurement of energy separation has involved developing a novel operating procedure for a high frequency response thin film total temperature probe, allowing it to be heated in stagnant conditions while keeping the wind tunnel running. In addition the analysis of the results has involved the development of a fully automated phase lock averaging routine.

The principal original contribution of this work is to demonstrate clearly that unsteady energy separation occurs as a result of vortex shedding at high subsonic Mach numbers. The time-resolved measurements show how the areas of increased and decreased total temperature and total pressure are related. The results also give a good qualitative description of the shape of the vortex street, showing the presence of interconnecting ribs and the areas of maximum entropy increase and thus drag creation.

The surface pressure results have permitted the study of how Strouhal number, drag, base drag and vortex shedding mechanisms change with Mach number. Of particular note they show that the vortex mechanism present in the *permanent shock wave* regime does not replace that present in the *intermediate shock wave* regime but rather develops from it.

Acknowledgements

I would like to thank my supervisor, Prof. Paul Gostelow, for his continual support and help throughout the last few years, my co-supervisor, Dr Aldo Rona, and my industrial supervisor, Dr Bill Carscallen of the National Research Council of Canada, for making the tests in U-66 possible and for his support and help throughout the project. I would also like to thank Mr Joe Templin for his sustained support for the project.

In addition, I would also to thank:

From the UK

Dr Simon Hogg for the vast amount of help he gave me with the total temperature probe, Mr Paul Williams for his help in developing and testing the boundary layer probe, Mr Julian Jones for making the steel cylinder models, Mr Alan Wale for making the prototype of the boundary layer traverse and the rest of the workshop staff for their help and support. Mr Andy Willby for his help in with the stepper motor for the boundary layer probe, Mr Andrew McMullan, Mr Paul Bennett, Dr Ed Brooksbank, Dr John Twiddle and all the other postgrads and postdocs who have helped and encouraged me, Mr Tom Robotham, Mr Jason Palmer and Mr Andrew Norman for IT support, and everyone else at the University of Leicester who has lent their support.

From Canada

Mr Paul Hunt for his help with everything, from data acquisition to lifts to U-66, and his continual support throughout the project, Mr Steve Totolo for his work with the high speed data acquisition system and for numerous lifts to and from U-66. Mr Cabot Broughton, Mr Fred Ellis, Mr Steve Pynn and the rest of the members of the operations, instrumentation and data processing teams from U-66 who worked exceedingly hard to make this project happen. Dr Steve Zan for the use of the aluminium cylinder, Mr Darcy Boudreau and his design team at M-4, Mr Kevin Waterman and the technicians of M-4, Mr Nathan Barry for the use of his Matlab FFT tool, Mrs Yvonne Hope for admin support and everyone else in M-10, M-4, M-2 and U-66 who helped, and supported me during my time there.

I'd also like to thank my parents, Raymond and Judy Ackerman for putting up with me, encouraging me and, when necessary, nagging me to get this thing finished. Also Denis and Dan who both put a roof over my head when I needed it and everyone else: siblings, friends, mates, drinking partners, and acquaintances that have helped and supported me, you know who you are. And last, but far from least, Sarah, thank you.

Contents

List of Tables		vii
List of Figures		
Nomencla	ature	xii
1. Introdu	uction	1
1.1.	Energy Separation	2
1.2.	Base Pressure	2
1.3.	Moving Away From Turbomachinery	3
1.4.	Aims and Objectives	5
2. Vortice	es Behind Cylinders and Turbomachine Blades	10
2.1.	Vortex Shedding and Vortex Streets	10
2.2.	Energy Separation in the Wake of Circular Cylinders	14
2.3.	Energy Separation Theories	16
2.4.	Vortex Shedding in the Wake of Turbomachinery Blades	18
2.5.	Energy Separation in the Wake of Turbomachines	22
2.6.	Compressible Flow	26
2.7.	Total Temperature Instrumentation	27
2.8.	Summary	30
3. Faciliti	es, Equipment and Procedure	34
3.1.	Facilities	34
3.	1.1. 1.5m Transonic Blowdown Wind Tunnel	34

	3.1.	.2.	The Large Scale Transonic Planar Cascade	40
3.2	2.	Cir	rcular Cylinders	44
	3.2.	.1.	IAR 1 ¹ ⁄ ₂ " Aluminium Circular Cylinder	44
	3.2	.2.	37.26mm Steel Cylinder	45
	3.2	.3.	Boundary Layer Probe Cylinder	47
3.3	3.	Ins	strumentation 1. Trisonic Blowdown Wind Tunnel Tests	55
	3.3	.1.	Total Temperature Probe	55
		3.3	.1.1. How the Probe Works	55
		3.3	1.2. Calibration of the Total Temperature Probe	57
		3.3	1.3. Using the Total Temperature Probe in the TBWT	58
	3.3	.2.	Total Pressure Measurement	59
	3.3	.3.	Surface Pressure Measurement	60
	3.3	.4.	Phase Reference Transducers	61
	3.3	.5.	Pressure Transducer Calibration	61
	3.3	.6.	Boundary Layer Probe Transducers	61
	3.3	.7.	Running Conditions and Probe Position	62
	3.3	.8.	Wake Traverse Probe Holder	62
3.4	4.	Ins	strumentation 2. Large Scale Transonic Planar Cascade	67
3.5	5.	Da	nta Acquisition	71
	3.5	.1.	2000 Series	71
	3.5	.2.	2002 Series	72
	3.5	.3.	Nozzle Pressure Distribution	73

3.6. Experimental Procedure	75
3.6.1. 2000 Series	75
3.6.2. 2002 Series	77
3.6.3. Large Scale Transonic Planar Cascade Testing	79
4. Data Processing	82
4.1. Raw Pressure Signals	82
4.2. Raw Total Temperature Signals	83
4.2.1. Low Speed Data	83
4.2.2. High Speed Data	85
4.2.3. Calculation of Total Temperature	86
4.3. Boundary Layer Data	90
4.4. Interpreting Oil Flow Visualisation	93
4.5. Dealing with Jitter	95
4.5.1. Jitter in the 2000 Series Data	95
4.5.2. Jitter in the 2002 Series Data	96
4.6. Phase Lock Averaging	100
4.6.1. Why it was Needed	101
4.6.2. What is Ensemble Averaging?	102
4.6.3. Phase Lock Averaging	103
4.6.4. How Phase Lock Averaging was Applied	103
4.6.5. Selection of Record Lengths and Number of Records	108

5. Handling Anomalous Data	117
5.1. 2000 Series Wake Total Pressure Anomalies	117
5.2. Time-Averaged Total Temperature Gradient	123
5.3. Time-Resolved 2002 Series Results	126
6. Results and Discussion	136
6.1. Cylinder Surface Pressure	136
6.1.1. Across the Mach Number Range	136
6.1.2. Mach 0.4	145
6.1.3. Mach 0.5	146
6.1.4. Mach 0.6	148
6.1.5. Mach 0.7	149
6.1.6. Mach 0.8	150
6.1.7. Mach 0.9	151
6.1.8. Mach 0.95	151
6.1.9. Summary	152
6.2. Wake Results	179
6.2.1. Wake Total Pressure Results	179
6.2.2. Wake Total Temperature Results	183
6.2.3. Losses and Entropy Production	185
6.2.4. Summary	186
6.3. Comparison of Wake Data With CFD	200
6.3.1. Total Pressure	200

6.3.2. Total Pressure	201
6.3.3. Entropy Creation	201
6.3.4. Location of Flow Features	202
6.3.5. Summary	203
6.4. Large Scale Transonic Planar Cascade Results	212
6.4.1. Comparison of Wake Results	212
6.4.2. Comparison of Isentropic Mach Number Distributions	213
6.5. Boundary Layer Results	221
6.5.1. Mach 0.5 to 0.7	221
6.5.2. Mach 0.4	221
6.6. Oil Flow Visualisation	224
7. Conclusions	226
7.1. Suggestions for Further Work	230
Appendix A	232
Appendix B	241
Appendix C	245
Appendix D	251
Appendix E	256
References	266

List of Tables

1.1.	2000 Series Test Matrix	8
1.2.	2002 Series Phase 1 and 2 Test Matrix	8
1.3.	2002 Series Phase 3 and 4 Test Matrix	8
1.4.	Flow Conditions	9
2.1.	Vortex Shedding Patterns	31
3.1.	Vane Geometric Parameters	42
3.2.	Position of Pressure Tapping on the LSTPC's nozzle blades	69
3.3.	2000 Series Phase 1 DAQ	74
3.4.	2000 Series Phase 2 DAQ	74
3.5.	Matrix of Completed 2000 Series Tests	80
3.6.	Matrix of Completed 2002 Series Phase 1 and 2 Tests	80
3.7.	Matrix of Completed 2002 Series Phase 3 and 4 Tests	80
4.1.	Order of Curve Fits applied to Different Data Sets	92
4.2.	Summery of Percentage of Shedding Cycle Lengths	97
4.3.	Summery of Percentage of Shedding Cycle Lengths	97
4.4.	Summery of the Number of Records Used	110
6.1.	Boundary Layer Results	222
D1.	Transducer Specifications	252

List of Figures

2.1.	Features of the Vortex Shedding Mechanism and Compressible Flow Regimes	32
2.2.	Vortex Movement and Energy Separation Mechanism	33
3.1.	Cut away of the U-66 facility	37
3.2.	Schematic of 2-D working section	37
3.3.	Photograph of the Working Section Looking Upstream	38
3.4.	Photograph of 2-D Test Section Looking Upstream	39
3.5.	Schematic of the LSTPC	42
3.6.	Photograph of the LSTPC with Wake Probe	43
3.7.	LSTPC Nozzle Vanes	43
3.8.	Angular Position Convention	50
3.9.	Assembly Drawing of IAR 1 ¹ / ₂ " Aluminium Cylinder	50
3.10.	Photograph of Reinforced Wind Tunnel Balance	51
3.11.	Assembly Drawing of 37.26mm Steel Cylinder	51
3.12.	Boundary Layer Probe Traverse Mechanism	52
3.13.	Assembly Drawing of Boundary Layer Cylinder	52
3.14.	Photograph of Boundary Layer Cylinder Centre Section	53
3.15.	Photograph of Boundary Layer Cylinder Centre Section	53
3.16.	Positional Error of Boundary Layer Probe	54
3.17	Calibration Curve of Boundary Layer Probe Position	54
3.18.	Sketch of One of the Total Temperature Probe Bodies	64
3.19.	Total Temperature Probe calibration Curves	64
3.20.	LSTPC with Total Temperature Probe in Prototype Sheath	65
3.21.	Photograph of Wake Sting	66
3.22.	Cutaway Drawing of LSTPC Surface Pressure Tappings	70
3.23.	Scale Drawing of Probe Position Relative to the Cylinder	81
4.1.	Voltage Drop Across Heated Thin film Gauge	87
4.2.	Heated Film Gauge Temperature at 1.85D Above Wake Centre Line	87
4.3.	Low Frequency Heat Flux Through Thin Film Gauges	88
4.4.	Heated Transfer analogue Output	88
4.5.	High Speed Heat Flux Signal	89
4.6.	Fully Processed Total Temperature Trace	89
4.7.	Comparison of Curve Fits to Boundary Layer Data	92
4.8.	Oil Flow Visualisation at Mach 0.5	94

4.9.	Histograms of Vortex Period, 2000 Series Data	98
4.10.	Histograms of Vortex Period, 2002 Series Data	98
4.11.	Phase Reference Signals	110
4.12.	A Reference-Data Set	111
4.13.	Total Pressure Signal	111
4.14.	Time Averaged Wake Total Pressure	112
4.15.	Total Pressure Signal	112
4.16.	Phase Lock Averaged Wake Total Pressure	113
4.17.	Time Averaged Wake Total Pressure	113
4.18.	2000 Series Phase Lock Averaged Wake Total Pressure	114
4.19.	2000 Series Phase Lock Averaged Wake Total Temperature	114
4.20.	2000 Series Phase Lock Averaged Cylinder Surface Pressure	115
4.21.	2002 Series Phase Lock Averaged Wake Total Pressure	115
4.22.	2002 Series Phase Lock Averaged Wake Total Temperature	116
4.23.	2002 Series Phase Lock Averaged Cylinder Surface Pressure	116
5.1.	Time-Averaged Wake Total Pressure Ratio, Ma=0.6, Oct. 2000	119
5.2.	Close Up of Damaged Data, Total Wake Ratio Oct. 2000	119
5.3.	Comparison of Total Pressure Data From Above and Below the Wake	120
5.4.	Comparison of Uncorrected and Corrected Phase Lock Averaged Data	121
5.5.	Time Averaged Total Temperature Profile After Duplicating Uncorrupted Data	122
5.6.	Time Averaged 2000 Series and 2002 Series Wake Total Temperature	125
5.7.	2002 Series Time Averaged and Root Mean Squared Values	130
5.8.	Phase Lock Averaged Total Pressure Results	131
5.9.	Phase Lock Averaged Total Pressure Results in the Region of 0D to +0.73D	132
5.10.	2002 Series and 2000 Series Raw Total Pressure Data	133
5.11.	2002 Series and 2000 Series PLA Total Pressure Data	134
5.12.	2002 Series and 2000 Series PSD Total Pressure Data	135
6.1.	Pressure Distributions from 2000 Series Data	153
6.2.	Pressure Distributions from 2002 Series Data	154
6.3.	Drag and Base Drag Coefficients Over the Mach Number Range	155
6.4.	Pressure Coefficient Distributions for the 2000 Series and 2002 Series Tests	156
6.5.	Cylinder Surface Discontinuity Due to Pressure Transducers	157
6.6.	Location of Pressure Transducers Within Cylinder Models	157
6.7.	Isentropic Mach Number Distribution for 2000 Series Results	158
6.8.	Vortex Shedding Frequency Across Experimental Range	159

6.9.	Frequency Spectra of Surface Pressure Results	160
6.10.	Frequency Spectrum of Time Resolved Surface Pressure Results, Mach 0.4	161
6.11.	Frequency Spectrum of Time Resolved Surface Pressure Results, Mach 0.4	161
6.12.	Raw Surface Pressure Traces From Around Cylinder Circumference, Mach 0.4	162
6.13.	Frequency Spectrum of Time Resolved Surface Pressure Results, Mach 0.5	163
6.14.	Raw Surface Pressure Traces From Around Cylinder Circumference, Mach0.5	164
6.15.	Phase Lock Averaged 2002 Series Cylinder Surface Results at Mach 0.5	165
6.16.	Frequency Spectrum of Time Resolved Surface Pressure Results, Mach 0.6	166
6.17.	Raw Surface Pressure Traces From Around Cylinder Circumference, Mach 0.6	167
6.18.	Phase Lock Averaged 2000 Series Cylinder Surface Results at Mach 0.6	168
6.19.	Phase Lock Averaged 2002 Series Cylinder Surface Results at Mach 0.6	169
6.20.	Frequency Spectrum of Time Resolved Surface Pressure Results, Mach 0.7	170
6.21.	Raw Surface Pressure Traces From Around Cylinder Circumference, Mach 0.7	171
6.22.	Phase Lock Averaged 2002 Series Cylinder Surface Results at Mach 0.6	172
6.23.	Frequency Spectrum of Time Resolved Surface Pressure Results, Mach 0.8	173
6.24.	Raw Surface Pressure Traces From Around Cylinder Circumference, Mach 0.8	174
6.25.	Frequency Spectrum of Time Resolved Surface Pressure Results, Mach 0.9	175
6.26.	Raw Surface Pressure Traces From Around Cylinder Circumference, Mach 0.9	176
6.27.	Frequency Spectrum of Time Resolved Surface Pressure Results, Mach 0.95	177
6.28.	Raw Surface Pressure Traces From Around Cylinder Circumference, Mach 0.95	178
6.29.	Time-averaged Wake Total Pressure Ratio	187
6.30.	Velocity Drop in the Wake	188
6.31.	Frequency Spectrum of Time-resolved 2000 Series Wake Total Pressure	189
6.32.	A Selection of 2000 Series Phase Lock Averaged Total Pressure Traces	190
6.33.	2000 Series Phase Lock Averaged Total Pressure Ratio	192
6.34.	Time-Averaged Wake Total Temperature Ratio	192
6.35.	Frequency Spectrum of Time-resolved 2000 Series Wake Total Temperature	193
6.36.	A Selection of 2000 Series Phase Lock Averaged Total Temperature Traces	194
6.37.	2000 Series Phase Lock Averaged Total Temperature Ratio	195
6.38.	Time-Averaged Wake Entropy Creation	196
6.39.	Frequency Spectrum of Time-resolved 2000 Series Entropy	197
6.40.	A Selection of 2000 Series Phase Lock Averaged Entropy Fluctuation Traces	198
6.41.	2000 Series Phase Lock Averaged Entropy Creation	199
6.42.	2000 Series Phase Lock Averaged Total Pressure Ratio	204
6.43.	Time-Resolved CFD Total Pressure Distribution	204

6.44.	Time-Averaged CFD Total Pressure Distribution	205
6.45.	2000 Series Phase Lock Averaged Total Temperature Ratio	206
6.46.	Time-Resolved CFD Total Temperature Distribution	206
6.47.	Time-Averaged CFD Total Temperature Distribution	207
6.48.	2000 Series Phase Lock Averaged Entropy Creation	208
6.49.	Time-Resolved CFD Entropy Creation Distribution	208
6.50.	Time-Averaged CFD Entropy Creation Distribution	209
6.51.	CFD Density Ratio Around and Behind a Circular Cylinder	209
6.52.	CFD Total Pressure Ratio Around and Behind a Circular Cylinder	210
6.53.	CFD Total Temperature Ratio Around and Behind a Circular Cylinder	210
6.54.	CFD Entropy Creation Around and Behind a Circular Cylinder	211
6.55.	2000 Series Phase Lock Averaged Total Pressure Ratio	216
6.56.	Total Pressure Ratio in the Wake of a Guide Vane in the LSTPC	216
6.57.	2000 Series Phase Lock Averaged Total Temperature Ratio	217
6.58.	Total Temperature Difference in the Wake of a Guide Vane in the LSTPC	217
6.59.	2000 Series Phase Lock Averaged Entropy Creation	218
6.60.	Entropy Creation in the Wake of a Guide Vane in the LSTPC	218
6.61.	Measured Local Isentropic Mach Number Distribution	219
6.62.	Experimental and CFD Isentropic Mach Number Distribution, Mach 1.16	219
6.63.	Experimental and CFD Isentropic Mach Number Distribution, Mach 0.6	220
6.64.	Circular Cylinder Boundary Layer Profiles	222
6.65.	Mach 0.4 Boundary Layer Profile at 130°	223
6.66.	Annotated Oil Flow Visualisation at Mach 0.5	225
6.67.	Results of FFT on Oil Flow Visualisation at Mach 0.5	225
A1.	Assembly Drawing of 11/2" IAR Aluminium Cylinder	231
A2.	1 ¹ / ₂ " IAR Aluminium Cylinder North Section	232
A3.	1 ¹ / ₂ " IAR Aluminium Cylinder South Section	233
A4.	1 ¹ / ₂ " IAR Aluminium Cylinder North End Cap	234
A5.	1 ¹ / ₂ " IAR Aluminium Cylinder South End Cap	235
A6.	1 ¹ / ₂ " IAR Aluminium Cylinder Wave Spring	236
A7.	1 ¹ / ₂ " IAR Aluminium Cylinder Teflon Spacer	237
A8.	1 ¹ / ₂ " IAR Aluminium Cylinder Base Pressure Tappings	238
B1.	Assembly Drawing of 37.26mm Steel Circular Cylinder	242
B2.	37.26mm Steel Circular Cylinder North Section	243
B3.	37.26mm Steel Circular Cylinder South Section	244

C1.	Assembly drawing of the Boundary Layer Probe Cylinder	246
C2.	Centre Section of the Boundary Layer Probe Cylinder	247
C3.	South Section of the Boundary Layer Probe Cylinder	248
C4.	North Section of the Boundary Layer Probe Cylinder	249
C5.	Boundary Layer Probe Cylinder Traverse Block	250
E1.	Wake Probe Holder Assembly Drawing	257
E2.	Wake Probe Holder Sting	258
E3.	Wake Probe Holder Probe Head	259
E4.	Wake Probe Holder Probe Sheath	260
E5.	Wake Probe holder Delta Wing	261
E6.	Wake Probe Holder Pneumatic Piston Shroud	262
E7.	Wake Probe Holder Delta Wing Body	263
E8.	Wake Probe Holder Location Pin	264
E9.	Wake Probe Holder Sheath Linkage Pin	265

Nomenclature

- C_D = coefficient of drag measured from cylinder surface pressure measurements
- C_{BD} = coefficient of base drag
- Cp = coefficient of pressure
- C_{WD} = coefficient of drag measured from wake traverse measurements
- c = specific heat of probe substrate (*J*/kgK)
- c_p = specific heat at constant pressure (*J*/kgK)
- c_v = specific heat at constant volume (J/kgK)
- D = cylinder diameter (37.26mm)
- Ds = sting diameter (12.7mm)
- D_t = trailing edge diameter
- F_{WD} = drag measured from wake traverse (N/m)
- f_0 = fundamental vortex shedding frequency
- f_n = nth harmonic of vortex shedding frequency
- G =system gain
- H = shape factor
- h =convective heat transfer coefficient and height from surface in a boundary layer
- i =current through film (A)
- k =conductivity of probe substrate (W/mK)
- M_a = free stream Mach number
- M_e = exit Mach number
- M_I = local isentropic Mach number
- N =number of samples
- P_T = total pressure (*Pa*)
- P_{TBL} = total pressure measured by boundary layer Pitot tube (Pa)
- p = static pressure (*Pa*)
- q = heat transfer rate (W/m^2)
- R =film resistance (Ω) and recovery factor
- s = root mean square of fluctuations (standard deviation)
- S = entropy (J/kgK)
- T = temperature and static temperature (K)
- T_T = total temperature (K)
- u =boundary layer velocity (m/s)
- U =free stream velocity (*m/s*)

V = voltage drop across thin film (V)

W =width of wake (m)

dR/dT = resistance/temperature calibration (Ω/K)

$$y =$$
traverse height (m)

Matlab Code

- t = film temperature(K)
- ht = heated probe
- cd = unheated probe
- tim = time vector
- 1c = low speed heat flux no interpolation
- s = low speed data after interpolation
- f = high speed data

Subscripts

- s = as measured by data acquisition or surface measurement
- T = total or stagnation flow conditions
- R =stagnation ratio
- w =wall conditions
- g = as measured at gauge
- 0 =zero reading
- 1 = measured during blow down or free stream measurement

Greek Letters

- δ = boundary layer thickness (m)
- δ^* = boundary layer displacement thickness (m)

$$\gamma = c_p/c_v$$

 θ = boundary layer momentum thickness (m) and cylinder azimuth (degrees)

$$\rho$$
 = density (kg/m³)

Symbols

 $<>_t$ = time averaged $<>_a$ = area averaged

1. Introduction

The work reported in this thesis is an investigation into unsteady energy separation and base pressure in the wake of circular cylinders and other bluff bodies in high subsonic cross flow. The initial context and motivation for this project emerged from research carried out on a high-pressure gas turbine stator design of Pratt and Whitney Canada (P&WC). The blade design had a notably thick trailing edge to allow for cooling passages. This resulted in unexpected distributions of wake total temperature and total pressure. After investigations into the phenomenon using first an annular cascade and then a planar cascade by Carscallen et al. [1,2] vortex shedding was found in the wake. A further investigation involving the time-resolved measurement of total temperature and total pressure in the wake of the cascade blades confirmed that the unexpected distributions were caused by energy separation [1]. The spatial resolution of these measurements was limited by the small (only 6mm) trailing edge diameter.

This work established that the presence of energy separation is a major contributing factor in uncertainties affecting loss measurements in turbine blades. In addition to this it is well known that turbomachine blades with thick trailing edges also suffer from low base pressures and that this is due, at least in part, to the presence of vortex streets [4]. Thus it was clear that these two phenomena were capable of causing significant problems when designing turbine blading and merited fundamental investigation on a larger and less complicated model.

Despite their ramifications for turbine blading design, the problems caused by energy separation and low base pressures are more widespread and generic in nature. Over appropriate Mach number and Reynolds number ranges they are present in the wake of any bluff body. This provided the opportunity to study the problem for a simpler geometry and so reduce the study to the most significant variables and thus address the problem in a relatively pure form. For these reasons it was decided to simplify the boundary conditions to an isolated and rigid circular cylinder in cross flow. The phenomena are known to be strongly exacerbated by compressibility effects and so it was decided to focus on the high subsonic range. Whilst the research initially carried out by Carscallen et al. [3] focused on very high subsonic and supersonic exit Mach numbers the use of high subsonic Mach numbers for this project was not seen as a drawback as these conditions are the prevalent ones for blading in gas and steam turbines.

Each of the subject phenomena will now be introduced in turn pending a more complete subsequent survey of the relevant literature (chapter 2), followed by a more in-depth reasoning behind the choice of a circular cylinder to create the desired flow phenomena.

1.1. Energy Separation

During wartime wind tunnel testing of a thermally insulated circular cylinder in cross flow Eckert and Weise [5] observed that the temperature on the surface of the leeward face of the cylinder was significantly lower than that of the free stream. This phenomenon was attributed to the phenomenon of the shedding of a von Kármán vortex street into the wake. In this situation the vortices transport energy from the core of the wake to the edge. When measured on a time-averaged basis, as performed by Eckert and Weise [5] with thermocouples, this transport of energy results in the observation of a cold wake core and heated outer wake and is referred to as the Eckert-Weise effect. The effect was later seen to propagate downstream of the cylinder by Thomann [6], as would be expected of a phenomenon caused by a vortex street that is itself convecting downstream. More recent experimental, theoretical and numerical work by Kurosaka et al. [7] has shown that when measured or modelled on a timeresolved basis the cold wake core and heated wake edge actually display hot and cold spots that convect downstream of the cylinder. The frequency at which the hot and cold spots appear matches that of the vortex shedding, thus confirming their relationship. When measured in a time-resolved fashion the phenomenon is referred to as energy separation.

Early work established the importance of compressibility for energy separation. However, prior to this investigation, no measurement of energy separation behind a circular cylinder in compressible cross flow has been made, despite the academic interest in the subject, particularly over the last fifteen years. One of the two main objectives of this project was to rectify that omission and provide time-resolved measurements of total temperature and total pressure in the wake of a circular cylinder in compressible cross flow and by doing so gain further insight into the mechanism of energy separation.

1.2. Base Pressure

"Base-flow region modelling, especially for turbine blades, is rather important. In subsonic flows the losses are affected directly by thick bases. In supersonic flows the flow over the entire back face is affected," [4].

As well as being of great importance to the performance of turbine blades, base pressure also defines the pressure drag acting on a circular cylinder or any other bluff body. Much

experimental research has been carried out looking for empirical correlations, such as that of Sieverding et al [8], or finding ways to lessen its effect with splitter plates [6] and trailing edge leakage or bleed flow [9] along with work on predicting base pressures using potential flow calculations [10]. The general finding of the experimental research has been that base pressure may be increased towards the free stream static pressure through the use of splitter plates of appropriate length or the introduction of the correct amount of base leakage flow into the wake. Splitter plates, however, are impractical for most situations where bluff bodies are used and if too much base leakage is introduced into the wake it can cause the base pressure to fall rather than rise. Potential flow theory can also predict base pressure with a reasonable degree of accuracy, however the theory requires accurate profiles of the boundary layers at separation, usually only available via experimental work or the laborious use of boundary layer theory, and do not actually use the local flow mechanics.

Base pressure may be predicted, the problems caused by it are known and it is known how to overcome them. There is, however, a lack of understanding of mechanisms involved when there is a vortex street present. The second main objective of this project was to rectify this lack of knowledge of the mechanisms involved and so gain a better understanding of the relationship between vortex shedding and base pressure.

Since this project is based around circular cylinders in cross flow, base drag rather than base pressure will be used when investigating the overall time-averaged effect of changing Mach number and Reynolds number. Time-resolved analysis will use either pressure coefficient, surface pressure normalised by the free stream dynamic head, or isentropic Mach number, so that areas of subsonic and supersonic flow can be analysed.

1.3. Moving Away From Turbomachinery

As stated above, although the phenomena of energy separation and base pressure are important to turbomachinery and the initial motivation for this project came from research into a turbine blade, this project is going to concentrate on the flow around a circular cylinder. There are a number of reasons for this; turbine blade boundary layers at separation can be almost as thick as the trailing edge; they are also often asymmetrical in relation to thickness and state. Thus, the vortex streets formed tend to be diffuse, the vortex row shed from the suction surface of the blade being more so than that from the pressure surface. In addition to this the shock waves from neighbouring blades interfere with the flow of any blade under inspection; the trailing edge shock from one of the neighbouring blades will often contact the suction surface of the blade under inspection. This causes flow separation, transition (if it has

not already occurred) and reattachment just before the trailing edge, whilst that from the blade on the other side will interact with the wake. In addition to this the diameter of the trailing edges of turbine blades is small even when scaled up for use in large cascades. The probes used are not particularly small (probe body diameter is 3mm and the transducers are 1mm wide) and this results in poor spatial resolution. Vortex shedding frequency is inversely proportional to the diameter of the body shedding the vortices and this leads to poor temporal resolution when measured behind turbine blades.

Clearly then, to gain a better understanding of the wake flow phenomena a simpler, cleaner model was needed; ideally one with thin and roughly symmetrical boundary layers at separation and no interference from neighbouring bodies. A circular cylinder studied in isolation, in a wind tunnel large enough to prevent any problems associated with blockage, meets these criteria. The boundary layers at separation are thin with respect to the model diameter and are roughly symmetrical, although some difference will occur due to the separation points on the two sides moving periodically fore and aft with a 180° phase difference. This leads to the production of a symmetrical vortex street containing tightly rolled up vortices. In addition to this, aside from the floor and ceiling of the wind tunnel, there is no interference from shock waves interacting with the boundary layers or wake because there are no neighbouring bodies. Furthermore, the base pressures will fluctuate in a similar manner to those of a turbine blade because the separation points are not fixed. Finally, the problems with spatial and temporal resolution are reduced because an isolated circular cylinder can be made significantly bigger for a given facility than a turbine blade that will have to be used in cascade.

A principal difference between taking measurements behind a circular cylinder and a turbine blade is the measurement of lost performance. This is measured as loss for turbomachinery and drag for a cylinder, which are different but related concepts. The problems arise when trying to compare the two; losses cannot be calculated for an isolated circular cylinder as it is not in a passage and therefore there are no limits of integration for the loss calculation. Drag is a difficult concept to apply to turbomachinery blading since the direction in which it acts is unclear, but the work of Denton [11] offers a solution. As described in more detail later, he states that loss in turbomachinery may best be described by entropy increase. Given that a relationship between loss and drag exists it follows that the creation of drag acting on a cylinder may also be expressed in terms of entropy increase. Denton goes on to define entropy loss coefficients. In an unsteady flow field, the location of entropy increase can be used to provide valuable physical insights into the loss mechanisms involved.

1.4. Aims and objectives

The aim of this project was therefore, to perform an experimental study on unsteady wake energy separation and surface pressure behind a circular cylinder in cross flow at high subsonic Mach numbers. The surface pressure and energy separation results were to then be compared to those from behind a turbine blade taken by Carscallen et al.[3] and the CFD results of Rona and Bennett [12], Bennett et al. [13] and Brooksbank [14] and those of Currie presented in Carscallen et al. [3] In addition to the base pressure and energy separation, measurements were also taken of boundary layer thickness at separation and oil flow visualisation carried out to gain an insight into separation.

As an auxiliary aim to the work, the opportunity was taken, whilst at NRC, to take measurements of the surface pressure distribution around the turbine nozzle used by Carscallen et al. [3] to provide data for CFD validation. The results will be presented here to give an extension of the main body of work to turbine blading.

To meet the aims of the project two series of experiments of circular cylinders in cross flow, each split into a number of phases, and one test programme on the Large Scale Transonic Cascade (LSTPC) as used by Carscallen and Oosthuizen [1], were conducted.

The circular cylinder tests planned were limited to high subsonic Mach numbers, $0.4 \le Ma \le 0.95$, by the facility used. This was the 1.5m Trisonic Blowdown Wind Tunnel (TBWT) at the National Research Council of Canada (NRC) U-66 facility in Ottawa, Ontario. The turbine nozzle pressure surveys were carried out over a Mach number range of 0.4 to 0.95 to increase the knowledge of the performance and at Mach 1.16 to allow for validation of CFD developed by Brooksbank [14].

The circular cylinder testing was carried out over the course of two series of tests, the 2000 series, conducted in October 2000 and the 2002 series, carried out in March 2002. The 2000 series tests were limited to time-resolved wake total temperature and total pressure measurements (phase 1) and surface pressure measurements (phase 2). The results of phase 1 have been used to investigate energy separation whilst those of phase 2 have been used to investigate the effect vortex shedding has on drag and base drag as well as how vortex shedding changes with increasing Mach number. In addition to rerunning phases 1 and 2 the 2002 series of tests included time-averaged boundary layer measurements (phase 3) and oil flow visualisation (phase 4) to gather more information regarding the relationship between

vortex shedding and base pressure. The Mach number ranges were chosen to allow unsteady energy separation and base pressure to be observed over a range of different vortex shedding regimes. As can be seen from the 2000 series test matrix (table 1.1) three different Reynolds numbers were chosen for the 2000 series tests. The Reynolds numbers were chosen so that at each one, a range of Mach numbers could be tested and also when it was necessary to increase Reynolds number in order to raise the Mach number an overlap could be achieved. The Reynolds number for the 2000 series tests. However an error in setting up the facility resulted in a slightly different Reynolds number being used. This was not problematic however as at the Mach numbers used separation, vortex formation and vortex shedding are considered to be unaffected by Reynolds number [15]. The flow conditions for the tests can be found in table 1.4.

The time-resolved data collected has been phase lock averaged, a method pioneered by Gostelow [16] for unsteady flows. Phase lock averaging is a powerful tool that allows for the removal of the effects of random turbulence and noise from signals while simultaneously determining the correct phase relationship between data taken at different spatial locations in the same flow. This allows for the flow field to be reconstructed using experimental data and to be presented as contour and surface plots. In addition to providing intelligible time-resolved data the use of phase lock averaging here will provide future researchers with a practical guide to applying this tool to data in a simple, straightforward manner.

Through the application of phase lock averaging the first time-resolved plots of wake total temperature and total pressure, along with those for the cylinder surface pressure, will be presented. This, in turn, will provide the first time-resolved experimental evidence of the existence of energy separation in the wake of circular cylinders at high subsonic speeds and will provide further insight into how this happens.

This thesis will comprise of the following chapters:

Chapter 2, An introduction to vortex shedding, energy separation, the research carried out into them on circular cylinders and turbomachinery blades and the instrumentation used to measure them.

Chapter 3, The facilities, models, instrumentation, data acquisition and experimental procedure used for this thesis.

Chapters 4 to 5. Data processing methods,

Chapter 6. Experimental results and their comparison with previous results and computational work,

Chapter 7. Conclusions and suggestions for further work.

Ма	$Re \times 10^5$	Phase 1		Phase 2		
		Readings	Steps	Readings	Steps	
0.5	6.9	T_T and P_T with P_{ref}	3 <i>mm</i>	P_s with P_{ref}	5°	
0.6	6.9	T_T and P_T with P_{ref}	3 <i>mm</i>	P_s with P_{ref}	5°	
0.7	6.9	T_T and P_T with P_{ref}	3 <i>mm</i>	P_s with P_{ref}	5°	
0.7	7.9	T_T and P_T with P_{ref}	3 <i>mm</i>	P_s with P_{ref}	5°	
0.8	7.9	T_T and P_T with P_{ref}	3 <i>mm</i>	P_s with P_{ref}	5°	
0.8	8.9	T_T and P_T with P_{ref}	3 <i>mm</i>	P_s with P_{ref}	5°	
0.9	8.9	T_T and P_T with P_{ref}	3 <i>mm</i>	P_s with P_{ref}	5°	
0.95	8.9	T_T and P_T with P_{ref}	3 <i>mm</i>	P_s with P_{ref}	5°	

Table 1.1. 2000 Series Test Matrix

Ма	$Re \times 10^5$	Phase 1		Phase 2		
		Readings	Steps	Readings	Steps	
0.4	6.8	T_T and P_T with P_{ref}	*	P_s with P_{ref}	5°	
0.5	6.8	T_T and P_T with P_{ref}	**	P_s with P_{ref}	5°	
0.6	6.8	T_T and P_T with P_{ref}	†	P_s with P_{ref}	5°	
0.7	6.8	T_T and P_T with P_{ref}	+	P_s with P_{ref}	5°	

* 1.44D to 0.18D in steps of 0.068D

** 1.94D to 0.68D in steps of 0.061D

† 2.79D to 1.41D in steps of 0.082D, 1.60D to 0.84D in steps of 0.04D, 0.84D to 0.07D in steps of 0.048D, -2.49D to 0.05D in steps of 0.157D and -4.01D to -2.2D in steps of 0.123D
‡ 2.12D to 0D in steps of 0.075D

Table 1.2.	2002 Series Phase 1	and 2 Test Matrix
------------	---------------------	-------------------

Ma	$Re \times 10^5$	Phase 3	Phase 4
		Pitot Probe Position	
0.4	6.8	130	
0.5	6.8	120	Yes
0.6	6.8	105	
0.7	6.8	100	

Table 1.3. 2002 Series Phase 3 and 4 Test Matrix

Year	Ма	$Re \times 10^5$	P_0 (kPa)	<i>p</i> (kPa)	<i>T</i> ₀ (K)
2000	0.5	6.86	179.20	151.07	≈ 292
2000	0.6	6.86	156.45	122.66	≈ 292
2000	0.7	6.86	141.14	101.70	≈ 292
2000	0.7	7.85	160.52	115.77	≈ 292
2000	0.8	7.85	149.55	98.12	≈ 292
2000	0.8	8.9	167.34	102.87	≈ 292
2000	0.9	8.9	158.86	93.84	≈ 292
2000	0.95	8.95	155.48	86.74	≈ 292
2002	0.4	6.75	216.09	193.54	≈ 292
2002	0.5	6.75	175.41	147.83	≈ 292
2002	0.6	6.75	152.45	119.56	≈ 292

2. Vortices Behind Cylinders and Turbomachine Blades

2.1 Vortex Shedding and Vortex Streets

While this thesis does not deal directly with the formation of vortices or with vortex street structure a brief explanation is necessary to understand some of the results.

There have been a number of explanations of how vortex streets are formed in the wake of circular cylinders. One of the most recent, by Cicatelli and Sieverding [17], which draws heavily on the work of previous authors, explains the formation and structure of the streets at free stream velocities of up to around Mach 0.8. The model proposed involves a vortex forming on one side of the cylinder being fed by the circulation of the oncoming shear layer. The vortex, and the shear layer upstream of it, entrains fluid from the flow on the other side of the cylinder. This can be seen in figure 2.1a where the growing vortex (A) is being fed from the upper shear layer with clockwise circulation while entraining fluid from the lower shear layer with anti-clockwise circulation (B). In this way the vortex grows until the quantity of entrained fluid is large enough to cut off the supply of circulation to the vortex. This happens because the circulation of the entrained fluid is in the opposite direction to that feeding the vortex. Once cut off the vortex is shed and the process starts again on the other side of the cylinder. The shedding of vortices from alternate sides of the cylinder creates a street of staggered vortices in the wake called a von Kármán vortex street. It is this mechanism of vortex shedding that causes the surface pressure, including the base pressure, of cylinders and other bluff bodies to fluctuate periodically.

There are a number of factors that affect the formation of vortices and vortex streets. Gerrard [18] indicates that the two controlling factors are the length of the formation region (C on figure 2.1a) and the thickness of the shear layers emanating from the surface of the body (D on figure 2.1a). The length of the vortex formation region is dependent on the Reynolds number. As Reynolds number increases so does the rate of entrainment of fluid into the vortex being formed, thus shortening the distance and the time required for the vortex to cut itself off. This also leads to an increase in the vortex shedding frequency. The thickness of the shear layer is a strong function of Reynolds number since it is dependent on the thickness of the boundary layers at separation. However the rate of entrainment is inversely proportional to the thickness of the shear layer. This is because the thicker the shear layer the more diffuse it becomes and more time is needed for the fluid it contains to cross the wake and be entrained into the forming vortex. Thus the vortex shedding frequency is dependent

on a balance of the length of the formation region and the thickness of the shear layers. As a result of this the Strouhal number (equation 2.1) remains fairly constant at Reynolds numbers where the shear layers remain laminar. It also contributes to the large changes in Strouhal number once the shear layers have undergone transition. Once the boundary layer has become turbulent there are two contrary mechanisms affecting the Strouhal number. The later separation of the turbulent boundary layer results in a thinner wake and hence closer spacing of the vortices and an increase in shedding frequency while the increasingly diffuse nature of the boundary layer results in a lower rate of entrainment into the forming vortices and thus a longer formation period and lower shedding frequency.

$$St = \frac{f_0 D}{U} \tag{2.1}$$

This mechanism works well while the free stream Mach number remains below 0.4, i.e. is sub-critical, however some modification of the mechanism may be necessary once the flow has become critical. As Zdravkovich [15] notes, once the flow has become critical separation of the flow is caused by the presence of the shockwaves and supersonic regions around the surface of the cylinder. As Mach number is increased changing the Reynolds number independently of free stream velocity has less effect up to just over Mach 0.6 after which it makes no notable change to the flow. Despite this the general principles of the mechanism seem to still apply. As the Mach number increases so does the vortex shedding frequency while the Strouhal number remains fairly constant from around Mach 0.5 to Mach 0.8. In addition, from the schlieren flow visualisation of the flow behind a turbine blade at high Mach number in Cicatelli and Sieverding [17] (although no Mach number is given it is possible to judge from the pattern of the shockwaves that it is probably between 0.7 and 0.8 by reference to the work of Zdravkovich [15]), the flow pattern fits in with the schematics of the mechanism presented in that paper.

Beyond Mach 0.8 however the mechanism for vortex formation becomes unclear. The schlieren flow visualisation by Carscallen et al.[2] and the CFD modelling by Brooksbank [14] indicate that the shear layers shed from behind turbine nozzle vanes cease to be parallel at high Mach number and converge to a node some distance downstream of the trailing edge. It is from the node that the vortices are shed. This is supported by the flow visualisation by Dyment and Gryson [19] of the flow behind a circular cylinder at Mach numbers above 0.8. The mechanism of vortex formation is unclear from these works, however the CFD developed by Brooksbank [14] does reveal the presence of what appear to be Kelvin-Helmholtz waves present in the shear layers shed from the vanes. It has been speculated that these may be in

some part responsible for the vortex shedding at the higher Mach numbers, however the investigation of this goes beyond the remit of this thesis.

In his work on how Reynolds number affected the drag, base pressure and Strouhal number of a cylinder in cross flow, Roshko [20,21] found that through the use of a splitter plate, vortex shedding could be suppressed. Thomann [6], in his experimental study of the recovery temperature in the wake of circular cylinders and wedges in cross flow, also found this to be the case, as did Bearman [22]. The reason for the suppression of the vortex street by a splitter plate, given by Morkovin [23], is that it allows the separation shear layers to grow so increasing the local vorticity with respect to the net vorticity across the wake and by allowing the three dimensional secondary flow effects in the shear layers to grow. The result of this, and further proof that base pressure is related to vortex shedding and thus energy separation, is a significant increase in the base pressure coefficient, Roshko [21] found it increased from 0.6 to 1.4) and an increase in the recovery factor in the wake was found by Thomann [6].

Bearman [22] also found that the formation of the vortex street could be suppressed by injecting air into the wake flow through a base bleed slot. The suppression of the vortex street caused it to form downstream of the cylinder, the greater the base bleed the further the vortex formation area moved away from the body. He also found that the coefficient of base pressure was directly and linearly proportional to the downstream distance between the trailing edge and the vortex formation region. Motallebi and Norbury [9] took this work further and did a study specifically on the effect of base bleed on base pressure and the wake flow at low supersonic Mach numbers (Mach 1.06 and 1.3). For this they used a bluff nosed plate that narrowed in cross section towards the downstream edge. The body had a trailing edge through which base bleed flow could be injected into the wake. They found that at Mach 1.06 a small amount of base bleed delayed the formation of the vortex street and so caused a significant increase in base pressure. Further increase in the amount of base bleed increased the base pressure up to a maximum and destroyed the formation of the vortex street. When the base bleed was increased beyond that which caused the maximum base pressure the subsequent drop was accompanied by the formation of a couplet vortex street, i.e. a vortex is shed from both sides of the body simultaneously, see table 2.1. As the base bleed velocity approached that of free stream the couplet vortex street is replaced by two von Kármán vortex streets shed from the trailing edges formed by the material between the base bleed slot and the upper and lower surfaces of the plate. They found that this trend was repeated at Mach 1.3 although the amount base pressure recovery and where the maximum occurred with respect to the ratio of the bleed and free stream velocities were different to those at Mach 1.06.

Sieverding [24] has repeated this work using turbine blade cascades with very similar results. Cicatelli and Sieverding [17] also repeated the experiments using a water table and a bluff body with a square trailing edge and a gate that could be opened to allow flow through the centre of the body simulating base bleed. The flow visualisation thus produced clearly shows the formation of a von Kármán vortex street when there is no base bleed, followed by the couplet vortex street, no vortex street and the formation of two von Kármán vortex streets as the gate is moved from closed to fully open. This work, however, has not considered what effect the ejection of base bleed fluid has on the losses of a turbomachine.

Xu and Denton [25] do investigate the effect of base bleed, introduced via passive devises, on losses in their study of a family of four turbine blades. The passive devices, ducts and slots, allow flow from the surfaces of the blade upstream of the trailing edge to enter the wake directly. They conclude that, although a low level of base bleed does increase the base pressure it also significantly increases the losses produced in the wake and it is unclear whether the increased base pressure is sufficient to compensate for this. However in a later paper Denton and Xu [26] use theory and CFD to predict the losses of choked cascades of turbine blades and flat plates. In this they simulate the ejection of cooling fluid into the wake in a more realistic manner than the passive devises in the previous paper. They find that as the base pressure increases due to the ejection of base bleed flow the wake losses drop significantly.

There have been a number of theories put forward regarding the form of the von Kármán vortex street. Cicatelli and Sieverding [17] present a comprehensive summery of these and summarise them into a theory that explains most experimental data produced, including that produced in this thesis. An abridged form of the theory is presented here.

A von Karman vortex street can be thought of as a series of coherent structures staggered alternately either side of the wake. The centres of these vortices contain the peak levels of coherent spanwise vorticity and are referred to as "centres" while the minimum spanwise vorticity is located, in the stream wise direction, between the centres and are referred to as "saddles". The maximum incoherent turbulence intensity is located near the centre of the wake and behind the coherent structures. This is because the incoherent turbulence is created at the saddle points, where the shear rate is greatest, and is then accumulated behind the coherent structures. The presence of the maximum rate of shear at the saddles is due to the stretching process caused by the spanwise vortices. Because there is little spanwise

vorticity at the saddles the vorticity of any turbulence created there should aligned, for the most part, longitudinally. Thus the ribs that connect the vortices are themselves smaller scale longitudinal vortices. Since the vortices forming the ribs are non-isentropic they will create entropy and so time-resolved measurements of entropy in the wake should show their presence.

2.2 Energy Separation in the Wake of Circular Cylinders

Redistribution of total energy, or energy separation, caused by vortices was first noted by Ranque [27] in 1933 and then later by Hilsch [28] through the use of what is now known as the Hilsch tube. They noted that the temperature of the air in the core of the vortex in the tube was lower than that at the periphery.

In 1943 Eckert and Weise [5] discovered that the surface temperature on the rearmost part of a circular cylinder in cross flow dropped by as much as 20K compared to upstream total temperature. This resulted in a negative recovery factor, equation 2.2, at the rear most point of the cylinder (about -1 at M_a =0.65 and $Re = 140 \times 10^3$). While unsure of the cause of the negative recovery factor they did feel that it might have had something to do with vortex shedding. Interestingly Prandtl didn't believe the results and wrote "questioning whether our results were not caused by extraneous influences or by errors of measurement," Eckert [29].

$$R = \frac{(T(\theta) - T_1)}{(T_{T_1} - T_1)}$$
(2.2)

The findings of Eckert and Weise [5] were confirmed by experimental work conducted by Ryan [30] who went on to demonstrate that the effect spread downstream into the wake as well. Ryan [30] also suggested that vortex streets shed from the bluff bodies might, in some way, be responsible for the phenomena. This supposition led to the potential-flow theory pioneered by Ackeret [31] (section 2.2).

At this time considerable experimental work was being done on the flow around and behind cylinders at both subsonic and supersonic speeds over varying Reynolds numbers. Roshko [21] investigated how supercritical Reynolds number, i.e. Reynolds numbers higher than those at the drag crisis, was related to the coefficient of drag, coefficient of base pressure (which he defined as the "average pressure over 20° or 30° on either side of the rear most point.") and Strouhal number. He also, as described above, looked into how the introduction of a splitter plate on the leeward side of the cylinder affected the flows properties. Roshko

[21] went on to combine and compare his results with those of Ribner and Etkin [32], Relf and Simmons [33], Delany and Sorensen [34] and Kovasznay [35] to build up a comprehensive picture of time-averaged coefficient of drag, coefficient of base pressure and Strouhal number over a Reynolds number range of 10 to 10^7 . He found that as the Strouhal number rose the coefficient of drag fell. The results of his splitter plate work showed that it suppressed the vortex shedding which increased the base pressure of, and hence reducing the drag acting on, the cylinder.

What Roshko [21] found with regard to the effect of the splitter plate is supported by the work of Thomann [6]. The work carried out by Thomann [6] involved measuring the recovery factor distribution along the endwall of the wind tunnels in which he mounted circular cylinder and wedge shaped models, both with and without splitter plates, over a range of high subsonic and supersonic Mach numbers. Thomann [6] also measured the recovery factor at the leeward-most point of the models. The endwall recovery temperature results were qualitatively similar to those that would have been found by taking measurements in the wake of the models at the mid-span position in the test section. The results were only qualitatively similar because of the presence of the boundary layer over the endwall and secondary flow phenomena created at the juncture between the cylinder and the endwall. He found that the recovery factor on the wall between the centres of the two vortex rows fell significantly below one, showing that the flow in that region had cooled. He then went on to use the potential flow theory of Ackeret [31] and introduce another theory by Schultz-Grunow [36] (section 2.2) to explain the cooling of the flow between the vortex rows. The results of Thomann [6] were the first to demonstrate that the low time-averaged recovery factor on the rear of a circular cylinder first measured by Eckert and Weise [5] propagates downstream. In effect these are the first measurements of energy separation in the wake of circular cylinders.

The work with splitter plates by Thomann [6] showed that they suppress, completely if they are long enough, the formation of the wake vortex street. He used this to show that the cooling in the centre of the wake did not happen when a vortex street was not present. His work at supersonic Mach numbers also showed this.

Following Thomann [6] little was done with regard to temperature measurements behind circular cylinders until the further work of Eckert [29] 1984 after which Kurosaka et al. [7] and Ng et al. [37] provided more experimental and computational evidence for the Eckert-Weise effect, now referred to energy separation when dealing with time-resolved wake measurement, and the relationship between it and vortex shedding. Experimentally they

showed that cold spots existed in the centre of the wake, appearing at the same frequency as the vortex shedding. They did this by using an acoustic lock to intensify the strength of the vortex street at certain Mach numbers and traversing the wake with an aspirating thin wire total temperature probe. They also predicted energy separation, including the presence of hot spots in the edge of the wake, using CFD. In addition to this they put forward a possible mechanism for energy separation (section 2.3).

Sundaram et al. [38] did more computational work in 1991. In this work they successfully modelled three different unsteady flows involving vortices. These models predicted the presence of energy separation in the flow.

2.3 Energy Separation Theories

A number of theories have been proposed to explain the Eckert-Weise effect and energy separation. The earliest of these was the potential flow theory by Ackeret [31]. His theory, based on the energy equation and the potential of a free vortex, considers what an observer at a fixed point would see. Although the potential of a free vortex is meaningless inside the vortex this is not important as the energy separation effect is seen outside of it. This theory shows that the total temperature deficit is located between the two vortex rows and so is proportional to the shedding frequency and circulation of the vortices. Thomann [6] showed that the potential flow theory of Ackeret [31] agreed well with his results although it is inviscid and does not take into account the boundary layer material affecting his measurements.

Another theory put forward at the time by Schultz-Grunow [36] considered turbulent heattransport in the radial pressure field of a vortex. He theorises that if a "lump" of fluid is transported, by turbulent exchange, away from the vortex core it will enter an area of higher pressure thus compressing and increasing the temperature of it. The exchange is assumed to be adiabatic as it occurs very quickly. The lump of air will now only have the same temperature as its surroundings if the static temperature distribution within the vortex matches that found for the free vortex in Ackeret's theory, Ackeret [31]. If this is not the case then the lumps temperature will differ from that of its surroundings and so heat will have been exchanged.

While the theories of Ackeret [31] and Schultz-Grunow [36] do approximate the redistribution of total temperature in the wake quite well, because they are based on potential

flow theory they will not accurately predict the flow. In an attempt to improve the theories for energy separation Kurosaka et al [7] presented another three possibilities.

Central to the first of the dynamic energy separation theories of Kurosaka et al. [7] is the energy equation in the form of:

$$c_{p} \frac{DT_{T}}{Dt} = \frac{1}{\rho} \frac{\partial p}{\partial t}$$
(2.3)

In this theory, which is based in the Lagrangian frame, he states that as a fluid particle moves around a vortex core that is convecting downstream, figure 2.2a, it will move through temporal pressure gradients. The theory states that when the particle is on the downstream side of a vortex it is moving through a negative temporal pressure gradient and so, from equation 2.3, it experiences a negative total temperature gradient. Conversely as it moves around the upstream side of the vortex it sees a positive pressure gradient, and therefore total temperature, gradient. As a result of this the particles total temperature will be at a maximum when it moves from the upstream to the downstream face.

Kurosaka et al. [7] offers an alternative explanation to the above theory by considering the components of the pressure field, $\partial p/\partial r$, which acts inwards towards the centre of the vortex against the centrifugal force caused by the rotation of the particle, figure 2.2a. If the particle is paused in its path at the 3 o'clock position, the left hand diagram in figure 2.2b, and $\partial p/\partial r$ is resolved into its components it can be seen that the tangential component acts against the direction of movement while the normal component acts against the centrifugal force acting on the particle. Since the particle's tangential velocity is being retarded its kinetic energy, which is proportional to the square of the particle's tangential velocity, is similarly reduced and thus the dynamic head and dynamic temperature, both directly proportional to the kinetic energy, will fall. By inspection of the particle's path it can be seen that this will be the case all the way round the downstream face of the vortex.

Conversely, at the 9 o'clock position the resolving of the radial pressure gradient shows that the tangential component acts in the direction of the particle's movement, thus increasing the tangential velocity and so causing a rise in the dynamic head and dynamic temperature. Again, by inspection it can be seen that this will occur all the way round the upstream face of the vortex. Thus when the particle is moving from 12 o'clock to 6 o'clock clockwise its energy is falling to a minimum and when it passes from 6 o'clock back to 12 o'clock its

energy is increasing to a maximum and so energy is transported from one side of the vortex to the other creating energy separation.

Kurosaka et al. [7] also presents a complementary theory based on the entrainment and ejection of fluid particles from the vortex street. The argument basically states that the entrainment of fluid will reduce the total temperature in the vortex street and its ejection will increase it. The mechanism for the increases and decreases in total temperature is the same as that for his alternative theory above, however because the path the entrained and ejected particles take is different to those in the vortex the result is different.

The final explanation given by Kurosaka et al. [7] is a kinematical one based on an idealised infinite street of Rankine vortices defined in both relative and absolute terms. He uses this to produce an idealised model that gives instantaneous and time-averaged total temperature separation that compares identically with the methods of Ackeret [31] and Thomman [6].

The theories proposed by Kurosaka et al. [7] show that total temperature separation does occur in real vortex streets where the vortices are not all the same strength nor of constant strength and where the street is not infinitely long nor of constant width.

2.4 Vortex Shedding in the Wake of Turbomachinery Blades

Vortex shedding has been observed behind turbomachinery blades and flat plates by a number of authors. Lawaczeck, Heinemann and Bütefisch published what was probably the first observation of von Kármán vortex streets in the wakes of turbine blades and flat plates mounted in cascade in a series of papers in the mid 1970's [39, 40, 41]. They estimated the vortex shedding frequency and from that calculated Strouhal number for the flat plate and turbine cascades. They found that their calculated Strouhal number over the Reynolds number range of 0.3×10^4 to 1.6×10^5 was 0.2 to 0.4.

Prior to the work with turbine blades Lawaczeck and Heinemann along with Bütefisch [42] had worked with flat plates with both round and square trailing edges and at slightly different Reynolds numbers. They found that the square trailing edge, at a slightly lower Reynolds number for any given Mach number, had a lower Strouhal number at low Mach numbers, below Mach 0.75, than the rounded trailing edge at a slightly higher Reynolds number. However at higher Mach numbers the difference was significantly reduced. Seemingly then at the higher Mach numbers the compressibility effects have a strong influence on the vortex
formation and shedding mechanism removing, or at least reducing, the Reynolds number effects.

The wake flow of turbine blades, as well as circular cylinders, may be modelled using potential flow solutions. Cox [43] developed one such model that incorporated boundary layer solutions. The solution solved for velocity and pressure distributions, took into account the vortex street and calculated the loss produced and the exit angles. It required the input of the boundary displacement and momentum thicknesses, the velocity of the flow at separation and the velocity at which the vortex street convected downstream. While these parameters could be estimated from potential flow calculations and boundary layer theory the solution had to go through a number of iterations in order to find the correct values. As such, unless the parameters could be found experimentally the solution tended to be cumbersome.

More recently the independent work of Sieverding et al. [8, 17, 24, 44, 45, 46], Denton et al. [11, 25, 26, 47] and Carscallen et al. [1, 2, 3, 48, 49, 50] have concentrated on the wake flow behind turbine blades. This thesis represents a continuation of the work of Carscallen et al. [3].

Work published by Denton et al. [25, 26, 47] encompasses experimental, theoretical and numerical studies of turbine blades and flat plates in cascades. A flat plate is also studied in isolation having pressure gradients imposed onto it so that it simulated a turbine blade. Denton [11] is a description of the various sources of loss in turbomachines, their causes and how to calculate and predict them. Mention has already been made of Xu and Denton [25, 26] with regard to base bleed. These papers also look at the sources and effect of trailing edge loss and how it may be predicted and reduced. They find that:

- At transonic speeds the trailing edge loss of a turbine blade accounts for around one third of the profile loss and that about 70% of that is created within 10D of the trailing edge,
- The trailing edge loss is directly proportional to the thickness of the trailing edge and that the constant of proportionality increases with Mach number into the supersonic regime,
- High wedge angles and curvature of the suction surface downstream of the throat may result in increased base pressure and reduced loss,
- Conventional loss prediction theories cannot accurately predict base pressure and trailing
 edge loss as they do not take into account the exact state of the boundary layers at
 separation. For example the potential flow method described by Cox [43] uses the mean
 of the two boundary layer thicknesses,

- Accurate loss prediction requires the accurate prediction of the suction surface pressure distribution so that the boundary layer is estimated correctly,
- Solutions of base pressure and losses for transonic blades with a specified back pressure may be closed without taking into account viscous effects, which are of only local importance. In other words the fully mixed out downstream flow is dependent on the upstream conditions and blade geometry and the viscous effects force the local flow to match this,
- Because of this Euler predictions and time marching Euler numerical codes can accurately predict base pressure and trailing edge losses and even take into account boundary layers and base bleed so long as the thicknesses of the former and the effect both have on the suction surface pressure distribution is known.

In addition to the above, the paper by Roberts and Denton [47] indicates that increasing the ratio of suction surface boundary layer thickness to trailing edge thickness can inhibit the wake vortex street. Since a proportion of the wake loss is created by the vortex street, inhibiting it in this way will result in less loss overall and the rate of loss creation in the near wake is also reduced. They also found that increasing the deviation of the exit flow field inhibits the wake vortex street and so reduces loss. They surmise that this is due partly to a change in the boundary layer characteristics and partly due to the effect that the change in free stream velocity has on the mixing process.

Denton [11] summarises the above, as well as going into other sources of loss such as shockwaves and boundary layers. Importantly though it introduces the idea of a relationship between the creation of loss, drag and entropy. He argues that due to possible radial changes in total pressure and total temperature without any associated loss of efficiency the usual blade row loss coefficients for cascades are not directly applicable to rotating turbomachines. Rather he proposes that loss creation is best determined in terms of entropy increase. This approach is valid because most turbomachines are adiabatic and so only entropy increase by irreversibilities contributes significantly to the loss of efficiency. Additionally entropy increase has the advantage of not being dependent on whether it is viewed from a rotating or stationary blade row so once entropy increase has been calculated for all of the blade rows in a machine they may be summed and the total entropy increase easily found. With the entropy for whole machine found and knowing one other thermodynamic property at exit the state of the fluid leaving is fully defined and the efficiency can be calculated.

Entropy may be calculated, for a single-phase fluid, if two of its thermodynamic properties, i.e. total pressure and total temperature, are known. For a perfect gas the entropy can be calculated thus:

$$S_{2} - S_{1} = Cp \ln\left(\frac{T_{T2}}{T_{T1}}\right) - R \ln\left(\frac{P_{T2}}{P_{T1}}\right)$$
(2.4)

Denton [11] then shows that the difference between the entropy increase loss coefficient and the energy loss coefficient is in the order 10⁻³ and so is negligible. Beyond this he shows that drag, in terms of viscous forces acting in turbomachine passages, is directly proportional to the entropy increase. This thesis extends this concept by looking at the creation of entropy in the wake of the cylinder and using this to discuss the location of drag creation in that region. Through this that it is possible to correlate the findings of this thesis, based on the flow behind a circular cylinder, with those based on the flow behind a turbine blade. As such the concept of entropy increase, through the relationship it has with loss and drag, will be used in explaining the results of this thesis.

As with the work by Denton et al., that by Sieverding et al. also looked at the base pressure of turbine blades and used experimental results to validate theoretical work with much the same results, i.e. potential flow theory worked so long as the state of the boundary layers at separation was known and well defined. In addition to this they developed an empirical relationship between exit Mach number, the gauging angle of the cascade and the base pressure for both convergent and convergent-divergent nozzle passages. They also looked into how the boundary layers effected the trailing edge vortex street. They found that turbulent boundary layers produced lower vortex shedding frequencies than laminar ones, with hybrid boundary layers (one turbulent and the other laminar) falling in between. Sieverding et al. also postulated that it was the state of the separation shear layers rather than the boundary layers that effected the vortex shedding. After the discovery of energy separation in the wake of a turbine vane by Carscallen et al. [2] (see section 2.5), the work of Sieverding et al. moved towards a more detailed study of the unsteady pressure field around the trailing edge of the turbine blades (Sieverding et al. [45, 46]). They carried out a survey of the unsteady base and surface pressure of a turbine nozzle vane. This showed the fairly uniform nature of the time-averaged base pressure around the trailing edge and the low level of fluctuation at the rearmost portion of the trailing edge compared to the separation regions. They also carried out a frequency analysis of the data and performed ensemble averaging on their results. The results of this show that the pressure fluctuations are not purely sinusoidal but that harmonics of the vortex shedding frequency present in the recorded signals are strong enough to significantly affect the waveforms. Following this Sieverding et al. continue to

look at the unsteady base pressure of turbine blades, further elucidating the time-resolved fluctuations, and move on to look at energy separation in the wakes of turbine blades. This will be considered in the next section along with the work of Carscallen et al.

Note that Cicatelli and Sieverding [17] refer to their ensemble averaging as phase lock averaging. This is not strictly the case as they fail to use a phase reference, which is fundamental to phase lock averaging (see section 4.6). Also their sampling rate did not allow for harmonics of the shedding frequency above the fourth to be captured.

2.5 Energy Separation in the Wake of Turbomachinery Blades

Energy separation in the wake of turbine nozzle vanes was first discovered, both unwittingly and unknowingly, by engineers at Pratt and Whitney Canada (P&WC) and the National Research Council of Canada (NRC) during a joint research project in the 1980's. They found that in the wake of a highly loaded gas turbine blade with a thick trailing edge the total temperature was redistributed with respect to the uniform upstream distribution [1]. It was assumed that heat transfer between the test rig and the flow was causing the redistribution of total temperature and a new test programme was initiated to reproduce the results in a new planar cascade and find the causes. The results from the tests in the new LSTPC displayed the same total temperature redistribution as that found in the earlier research programme and a heat transfer theory that accurately fitted the results at low Mach numbers was produced. In response to these findings a number of engineers, notably Epstein, Hennecke and Moore, (communication with Carscallen and Oosthuzen [1] published at the back of that paper) asked if the redistribution could be due to energy separation and if it had ever been measured in the wake of a gas turbine blade before.

Although it was considered unlikely that energy separation was the cause of the total temperature deficit, an investigation was carried out to establish whether it was possible. Initially schlieren flow visualisation was used to study the wake flow. It established the presence of vortex shedding over a Mach number range of 0.5 to 1.2 [50]. It was found that up to Mach 0.7 an intermittent von Kármán vortex street was shed from the trailing edge of the nozzle vanes after which it became constant. The change in nature of the vortex street from intermittent to constant coincided with an increase in the total pressure loss, measured both at mid stream and area averaged over the passage, and total temperature deficit. This implied that the vortex shedding and the wake losses/total temperature deficit were directly related.

As the Mach number increased towards and beyond unity the total pressure loss and total temperature deficit both reduced. This was accompanied by another change in the vortex shedding mechanism. From Mach 0.8 up to around 0.9 the vortices, rather than being shed from the trailing edge of the nozzle vanes, were shed from a node downstream of the trailing edge where the parallel separation shear layers roll up in the presence of a normal shockwave that denoted the point furthest upstream that the acoustic waves created with each vortex could move. This change in the shedding resulted in a weakening of the vortex street and hence a reduction in total pressure loss and total temperature deficit.

At higher Mach numbers the separation shear layers converged into the downstream node from which the wake shocks emanated. In this transonic region the vortex street becomes unstable changing from the traditional von Kármán street into a range of other configurations:

- Doublets: two vortices appear to be shed from one side of the trailing edge and then the other in an alternate fashion
- Couplets: vortices appear to be shed from both sides of the trailing edge simultaneously,
- Leaning von Kármán street: the time between the shedding of a pressure side vortex and a suction side vortex is less than that between one being shed from the suction side and one from the pressure side,
- Hybrids: any combination of the above,
- No definable pattern: vortex shedding is occurring but not in any definable pattern,
- No coherent pattern: no vortex shedding is occurring.

The schlieren flow visualisation was used to find out how often the different shedding modes occurred. This was done through the inspection of 170 photographs of the wake flow at Mach 1.16. The photographs were taken over a period of 35 minutes with a 4 to 5 second gap between each one for the spark source to recharge and the camera to wind on. The results of this can be found in table 2.1, reproduced from Carscallen et al. [2], along with graphical descriptions of the vortex shedding configurations.

From table 2.1 it can be seen that while in the transonic flow region the structure of the wake is constantly changing. This leads to a further weakening of the vortex street and so a reduction in the losses and total temperature deficit. Carscallen et al. [2] also show that the coefficient of base pressure also increases in this region again showing the relationship between it and vortex shedding.

With the existence of a relationship between vortex shedding and the increased total pressure loss and total temperature deficit found the next step was to acquire time-resolved total temperature and total pressure measurements in the wake. This was accomplished through the use of a Kulite XCQ-062-25D Ultraminiature pressure transducer and a thin film total temperature probe (sections 2.7 and 3.3) mounted on a downstream traverse. They were positioned so that the probe tips would be approximately $6D_t$ downstream of the trailing edge of the third nozzle blade, Carscallen et al. [3, 51]. The measurements were phase lock averaged, using a phase reference transducer mounted to one side of the trailing edge of the nozzle blade under inspection, and from that the local entropy increase was calculated. The results of this can be found in section 6.2 where they are compared to the results of this project. The phase lock averaged results show the presence of areas at the edge of the wake where the total temperature and total pressure increase above the free stream level and areas in the wake centre where they are reduced below the free stream level. By itself this confirms the presence of energy separation in the wake of this turbine vane, however, the calculation of the local entropy production using equation 2.4 provides further evidence. The entropy contours take on the shape of the vortex street showing where most entropy, and therefore loss, is created within the wake. The results also show the shortcomings of measuring total temperature and total pressure in the wake of turbine blades: the high vortex shedding frequency and small trailing edge diameter which result in poor spatial and temporal resolution.

The poor resolution of the wake data prompted the use of CFD to gain a more detailed understanding of the wake flow. Two CFD investigations into the wake flow behind the LSTPC blades have been carried out by Currie [3] and Brooksbank [14]. The CFD used by Currie implemented a quasi-three-dimensional form of the Reynolds-averaged Navier-Stokes (RANS) equations over an unstructured grid. Turbulence was modelled with a "zonal $k-\omega/k-\varepsilon$ Sheer Stress Transport formulation" that used the $k-\omega$ model near walls and the $k-\varepsilon$ everywhere else [3]. Brooksbank [14] used an inviscid Reynolds Averaged Navier-Stokes (RANS) code; the choice of an inviscid code being justified by the high Reynolds number of the flow and the work by Denton and Xu [26]. The results of both sets of CFD results agreed well with those from experimentation adding detail, particularly in the near wake, to the understanding of the wake flow. To support this and to help validate his CFD Brooksbank [14] compared the surface isentropic Mach number distribution calculated by his code to the that measured as part of this project ([14] and section 6.5). The results of this show that the inviscid RANS CFD code accurately matched the surface isentropic Mach number distribution providing evidence of the codes validity. Sieverding et al. [45, 46] have also looked at the time-resolved wake total temperature and total pressure behind a turbine blade. They took time-resolved base pressure readings and used smoke, holographic interferometry, white light interferometry and schlieren flow visualisation techniques to picture the wake. The flow visualisation has provided a detailed picture of the wake, notably the interferometry showing clearly the distribution of density within the vortex street. Unfortunately the Mach number Sieverding et al. chose for their experiments was significantly lower than that used by Brooksbank [14] for his CFD, Mach 0.4 and 1.16 respectively, and so no direct comparison is possible.

The time-averaged wake results of Sieverding et al. [46] clearly show the fall in total temperature and total pressure in the centre of the wake as well as the increase at the edge. The time-averaged entropy increase also shows a distinct double peak at around $\pm 0.3y/D_t$ that, judging from the flow visualisation work, is where the centres of the vortices are located. Unfortunately the time-resolved results contain two flaws. Firstly the total temperature data only covers the wake from the suction surface side through the centre and a short way into the pressure surface side due to a probe failure. The second appears to be in the phase lock averaging of the data. As with their earlier work there is no reference made to the use of a phase reference transducer and so it would appear that the data is ensemble averaged, and then all of the data on one side of the wake assumed to have the same phase and all the data in the centre of the wake and, as is shown in section 6.2 of this thesis, the assumption that all of the data on one side of the wake has the same phase is incorrect.

The base pressure results produced by Sieverding et al. [45, 46] show a marked increase in both the time-averaged level and time-resolved fluctuation from the start of the blend point to around $\pm 60^{\circ}$ from the leeward-most point of the blade, after which they both fall off. The increased pressure and fluctuation could be due to the flow decelerating through the fluctuating separation shocks and the decreased level and fluctuation due to the calmer flow present in the base region. These results also show that the shedding of a vortex, shown by a fall in the time-resolved base pressure, occurs faster than its formation, indicated by a rise in pressure.

2.6 Compressible Flow

Compressible flow over the cylinder can be divided into five regimes dependent on free stream Mach number: *shockless, intermittent shock wake, permanent shock wave, wake shock wave and detached bow shock wave*, [15]. Sketches of the main flow features of the compressible flow regimes are shown in figure 2.1.

The *shockless* regime exists when the flow is purely subsonic, below around Mach 0.4 where the flow is sub-critical. As such there are no localised areas of supersonic flow or shock waves, figure 2.1a, and the flow is strongly Reynolds number dependent.

Just above Mach 0.4 the flow becomes critical, i.e. local regions of flow about the cylinder become supersonic, and the flow enters the *intermittent shock wave* regime. The local regions terminate with weak shock waves that cause the boundary layer flow to separate due to the adverse pressure gradient that exists within them. Importantly the formation of the local supersonic regions of flow and the associated shock waves eradicates the sub-critical flow regime allowing the formation and shedding of vortices to commence if vortex shedding had not been present before due to Reynolds number. This can be seen in the flow visualisation of the flow behind a circular cylinder [19].

While in the *intermittent shock wave* flow regime the local regions of supersonic flow periodically oscillate over the surface of the cylinder with the formation and shedding of the vortices. The oscillations result in the flow only being supersonic on one side of the cylinder at any one time leading to increased pressure fluctuations compared to the previous Mach number. This is indicated on figure 2.1b by one of the separation shock waves being drawn with a dashed line.

Beyond around Mach 0.65 the flow enters the *permanent shock wave* regime. Permanent normal shock waves now appear a little downstream of the cylinder attached to the free shear layers. The permanent shocks are located at the point of vortex roll up which now occurs downstream of the cylinder. The permanent shock waves form in addition to the intermittent surface shock waves that were present in the *intermittent shock wave* regime, figure 2.1c. The movement of the location of formation and shedding of the vortices from the cylinder surface into the wake lengthens the formation region; this results in an increased pressure recovery and a slightly earlier separation.

As the flow approaches Mach 0.8 the near wake elongates as the shear layers begin to turn inwards towards each other heralding the *wake shock wave* regime, figure 2.1d. As the flow moves further into this new regime and the free stream Mach number approaches Mach 0.9 a normal shock wave begins to form across the wake at the point where the vortices roll up. This flow regime exists up to Mach 1 however there are changes to the flow within the regime. Up to and including Mach 0.9 vortex shedding is detectable via the pressure fluctuations on the surface of the cylinder, however beyond Mach 0.95 the surface pressure fluctuations are no longer detectable. This is not to say that no vortex shedding is taking place as the flow visualisation of Dyment and Gryson [19] clearly shows that it is.

Once the free stream Mach number exceeds unity the flow enters the *detached bow shock wave* regime, figure 2.1e. The wake flow appears similar to that of the *wake shock wave* flow regime however there is also a detached bow shock present. This has been included here for completion as there was no experimental work carried out in this flow regime.

The changes in flow features from the *shockless* flow regime into the later regimes are accompanied by a significant change in the effect Reynolds number has on the flow. In the *shockless* regime boundary layer separation is governed by considerations of Reynolds number and transition. However once the flow has become critical and passes into the *intermittent shock wave* regime then Reynolds number has an increasing small effect and the surface shock waves become the driving force for separation, i.e. they become the separation shocks mentioned above. Due to this the state of the boundary layers becomes increasingly less important as Mach number increases. Murthy and Rose [51] demonstrate this. They give the surface pressure coefficient profiles from Mach 0.25 to 0.8 at Reynolds numbers of 166×10^3 and 500×10^3 . At the former Reynolds number the boundary layer undergoes transition after separation while in the latter transition takes place before it. The profiles show that at and below Mach 0.4 the pressure distribution for the two Reynolds numbers are significantly different, however at Mach 0.6 there is little difference in the profiles and at Mach 0.8 there is none.

2.7 Total Temperature Instrumentation

Measurement of the total temperature is usually performed with transducers mounted in probes placed into the flow. The transducers most commonly used for this purpose are thermocouples, usually mounted inside a cavity so that the flow is brought to rest around them. Their popularity is due to their simplicity, robustness, cheapness, and reasonable level

of accuracy. However they are also limited to a frequency response of about 1kHz [52]. Since most unsteady flow phenomena in turbomachinery take place at at least 10kHz (i.e. rotor passing events), thermocouples don't have a high enough frequency response. There have been a large number of attempts to compensate thermocouple results to achieve a higher frequency response [53]. Unfortunately as the frequency increases the accuracy of the measurements decreases producing a practical limit above which measurements become unreliable. Constant current hot wire techniques are similarly limited to low frequency responses unless the fluctuations are small compared to the mean level (Bradshaw [54]).

Electronically compensated thin wire resistance thermometers operated at very low overheat ratios exhibit less sensitivity to velocity fluctuations than constant current hot wires and have been used to measure temperature fluctuations at 5 to 10 kHz most recently by Dénos and Sieverding [55].

Ng and Epsein [56] have gone a step further, developing an aspirating probe that can be used in unsteady, compressible flows, such as found in turbomachinery. Their probe consists of two constant temperature hot wire devices mounted in a cylindrical cavity upstream of a choked orifice. The hot wires are kept at different temperatures so that the readings produced may be used to solve equation 2.5 simultaneously for total pressure and total temperature.

$$V_i^2 = \left[C_i \left(\frac{P_0}{\sqrt{T_0}} \right)^{n_i} + D_i \right] \left(T_{w_i} - r T_0 \right)$$
(2.5)

Where C, D and n are constants to be determined by calibration and i refers to the wire number, 1 or 2.

This new aspirating probe had a much higher bandwidth of around 20 kHz. The problem with this probe is that beyond an acceptance angle range of $\pm 12.5^{\circ}$ any measurements are flow angle sensitive [57].

The next development in probe design came from Buttsworth and Jones [58]. Their total temperature probe is based on transient thin film heat transfer gauge technology. The probe comprises of two hemispherical quartz probes, each with a thin film heat transfer gauge painted onto them operating at different temperatures so that total temperature can be measured in a variety of different compressible flows. Versions of this probe have been used

on a high-pressure turbine stage simulator [59] and in a planar transonic turbine cascade [3]. This new probe design has a number of advantages over aspirating probes:

- 1) Considerably higher bandwidth, around 85 kHz;
- 2) More robust as it does not have any delicate wires to break;
- 3) No need for heat transfer law calibration;
- 4) Ease of operation in compressible flows of arbitrary composition.

However the spatial resolution of the probe is similar to that of the aspirating probe, around 3 mm, due to the separation of the films by being on separate hemispherical mountings. There is no information regarding the acceptance angle of this probe.

One way of improving the spatial resolution is to mount both thin film gauges on the same hemispherical mounting significantly improving the resolution to 1mm [58]. In this arrangement a pulse of high current heats the hot film just before and during the run. There is lateral conduction between the hot and cold films causing the cold films temperature to rise, however the temperature difference between them remains constant and the effect can be corrected for. Because there are two films, the measurements are not made at exactly the stagnation point. However it can be shown that the measured temperature will be within 1% of the actual total temperature. Therefore it is reasonable to claim that this probe does measure total temperature.

Additionally there have been advances in using fibre optics in total temperature and pressure probes by Barton et al. [60]. The probes developed incorporate interferomic optical fibre sensors. Like the thin film gauges of Buttsworth and Jones [58] the total temperature probe incorporates two such devices each mounted at the stagnation point of a hemispherical probe. Again like the Buttsworth and Jones probe one of the sensors is heated prior to a test run so that total temperature may be derived from the readings. The total pressure probe incorporates just one sensor mounted on a wedge probe. The total temperature probe can be calibrated to have a linear calibration curve in the range of 20 to 180 °C. Within this temperature range it has a noise floor of ~50 mK RMS at a measurement bandwidth of 200 kHz. The total pressure probe was operated in the pressure range of 0-5 bar absolute exhibiting ~5 mbar RMS noise in a 1 MHz sampling bandwidth.

The total temperature probe chosen for use in this thesis is the original thin film total temperature probe developed by Buttsworth and Jones [58]. This was used instead of the more advanced thin film probe, which was being held back for use at Oxford University and QinetiQ, or the optical probes of Barton et al. [60], which were still in development.

2.8 Summary

The existing state of knowledge on energy separation was based upon theoretical, experimental and computational work on the flow around cylinders in incompressible flow, while what little work that has been done in compressible flows had been based entirely on turbine vane wakes. To gain a better understanding of energy separation in compressible flows experimental work on cylinders at high subsonic speeds was required. The aim of this project is to investigate energy separation behind, along with base pressure fluctuations on the surface of, circular cylinders at high subsonic speeds. High resolution, time resolved total temperature, total pressure and surface pressure data will be provided along with some boundary layer and flow visualisation work. The investigation will also provide validation of compressible flow computational work.

By increasing the knowledge on energy separation and base pressure at high subsonic speeds it is hoped to provide initial insight into the way in which these phenomena effect the performance of turbomachinery blading and to pave the way for further work in this field.

Pattern	Schematic of Vortex Street	% Occurrence
No Definable Pattern	N/A	35.5
Von Kármán		30.5
Leaning Von Kármán		16.0
No Coherent Pattern	N/A	9.0
Doublets	$\begin{array}{cccccccccccccccccccccccccccccccccccc$	4.0
Couples		3.5
Hybrid		1.5

Table 2.1. Vortex Shedding Patterns

Reproduced with permission from Carscallen et. al





Figure 2.1. Features of the Vortex Shedding Mechanism and Compressible Flow Regimes.

a, Shockless Regime showing entrainment of fluid into a forming vortex,

b, Intermittent Shock Wave Regime, c, Permanent Shock Wave Regime

d, Wake Shock Wave Regime, e, Detached Bow Shock Wave Regime



Figure 2.2. Vortex Movement and Energy Separation Mechanisma, Movement of a Particle Within a Vortexb, Radial Pressure Gradient Resolved Normal to and at a Tangentto the Particles Path

3. Facilities, Equipment and Procedure

3.1. Facilities

3.1.1. 1.5m Trisonic Blowdown Wind Tunnel

The circular cylinder testing was carried out at the 1.5m Trisonic Blowdown Wind Tunnel (TBWT) in the NRC U-66 facility located at the NRC Uplands campus, near the Macdonald-Cartier (Ottawa) International Airport, in Ottawa, Ontario, Canada.

The TBWT is a convergent-divergent blowdown wind tunnel capable of operation over the subsonic, transonic and supersonic flow regimes at high Reynolds numbers. The facility can be used in either a three-dimensional (3-D) $(1.524m \times 1.524m \text{ test section})$ or two-dimensional (2-D) $(0.381m \times 1.524m \text{ test section})$ mode. The circular cylinder testing utilised the facilities 2-D mode that restricted the testing to free stream Mach numbers of below 0.95. A cut away illustration of the facility is shown in figure 3.1 while a schematic of the facility can be seen in figure 3.2 and a photograph of the facility is given in figure 3.3. When operated in this fashion the pressure ratio, and hence Mach number and (because the total temperature is kept constant) Reynolds number, are set by a variable diffuser downstream of the test section.

The 2-D working section is mounted in a modular plenum chamber that is inserted between a flexible nozzle leading from the settling chamber and the variable diffuser. The working section is 3.581m long, with an inlet nozzle that extends a further 1.905m upstream. The inlet nozzle has a contraction ratio of about 4:1. The profile entry of the nozzle into the 2-D test section is displaced from wall by 12.7mm with a 6.35mm gap to the wall, creating a boundary layer bleed. The endwalls of the working section are solid and painted with gloss white epoxy paint while the floor and ceiling are perforated by 60° inclined holes giving a variable porosity of between 0.5% and 6% and are left unpainted, see figure 3.3.

Models can be mounted on a pair of three component balances 2.388m downstream of the inlet nozzle at mid height in the working section. Normally the balances have a maximum loading of 89kN. However, if models are too small to be mounted on the regular balances a smaller version, with a maximum load of around 1.33kN, can be used. The balances can be rotated, either continually or in a step-pause mode, at a rate of $15^{\circ}s^{-1}$ through a range of $\pm 55^{\circ}$ with an accuracy of $\pm 0.03^{\circ}$. Normally the controllers for the balances angular positioning are

coupled together so that models can not have a torque applied to them. However the balances can be decoupled to allow one end of a model to be rotated while the other end is locked in place, assuming that there is provision for this in the model.

Located on the endwalls with the model mounting points in their centre are $0.602m \times 0.452m$ porous boards that facilitate boundary layer bleeding around the model improving the twodimensionality of the flow. The suction required for the boundary layer bleeding is provided in one of two ways depending on the free stream static pressure. If the static pressure is significantly higher than atmospheric then slide valves, located behind the porous boards, are opened to atmosphere, providing the required suction. When the static pressure is not significantly higher than atmospheric, or is lower than it, ejectors are used to provide the suction.

The test section traverse mechanism is located 641mm downstream of the model mounts on the southern endwall (right hand side when looking upstream). The traverse has a stroke of 762mm; 254mm of this is below the wind tunnel mid-height and 508mm above it. The traverse rate is variable depending on what is required. During the course of the project it was found that it took the traverse about 0.35s to move over distances of both 203.2mm and 139.7mm. Pre-test calibrations indicated that the traverse could be located anywhere along the stroke with an accuracy of ± 0.381 mm. The traverse mechanism usually mounts a wake rake containing total pressure transducers. However it could also be used to mount other custom designed probes, as was the case for this project.

One of the distinguishing features of the TBWT is the duration of the blowdown, ranging up to a couple of minutes depending on the Mach and Reynolds number of the flow. This is facilitated by the very large air supply, 4685m³, which can be pressurised up to 2.13MPa by two multistage compressors, operated in series as a single unit and run by an 8.58MW synchronous motor. The compressors supply air at 20.4kgs⁻¹, allowing the tanks to be filled from empty in 32 minutes or from partially charged in approximately 20 minutes.

Another of the notable features of the facility is the ability to operate at an almost constant Reynolds number. This is accomplished through ensuring the air entering the tanks is kept at around 298K through the use of a water-cooling system incorporated into the compressors. The air is kept at approximately this temperature during each blowdown, when expansion would normally cause it to cool significantly, through the use of a 27.432m long thermal storage matrix, with a mass of approximately 200 tonnes, installed in the supply tanks. The

effectiveness of the thermal matrix during the testing for this project tended to drop during the course of a day's continuous testing. It was found during one day of testing in October 2000 that at 11:19am the free stream total temperature dropped by 3K during the course of a blowdown while five runs later, at 2:15pm, it dropped by around 6K with a steady increase in the drop in between. Presumably this is due to the gradual cooling down of the thermal storage matrix during the course of six back-to-back runs.

Throughout this thesis use will be made of the terms "North" or "Northern" and "South" or "Southern" with regard to the sides of the test section and parts of the models used. This usage derives from the facility being built on a roughly east-west axis with the flow moving from east to west. Thus one side of the facility, the left side when looking upstream, is referred to as the "North" or "Northern" side and the other side is referred to as the "South" or "Southern" side. See figure 3.4.



Figure 3.1. Cut away of the U-66 facility



Figure 3.2. Schematic of 2-D working section



Figure 3.3. Photograph of the Working Section Looking Upstream Author for Scale



Figure 3.4. Photograph of 2-D Test Section Looking Upstream

3.1.2. The Large Scale Transonic Planar Cascade

The Large Scale Transonic Planar Cascade (LSTPC), used for the nozzle guide vane pressure distribution tests, is situated in the M-10 building at the NRC Montreal Road Campus in Ottawa. It incorporates six guide vanes producing five nozzle passages, a schematic representation of which is given in figure 3.5. The LSTPC was operated as an in-flow facility in which air was drawn in at 3.83kgs⁻¹ by a 2.0MW compressor.

The inlet to the LSTPC is formed by a bellmouth with an aspect ratio of 6.67:1. This allows the endwall boundary layers to grow to around one tenth of the passage span. Sidewall boundary layers are removed by adjustable bleeds positioned adjacent to the first and sixth nozzle vanes. The reflection of trailing edge shocks back into the stream is prevented through the installation of a perforated (23% porosity) aluminium tailboard. The angle of the tailboard may be adjusted to correct for the blockage of probes inserted into the flow downstream of the guide vanes. A photograph of part of the LSTPC showing the third and fourth nozzle passages is shown in figure 3.6. It clearly shows the nozzle guide vanes and the perforated tailboard.

Exit Mach number is found from the pressure ratio across the passage that is measured from an upstream Pitot tube and downstream static tapping both connected to Scanivalve ZOC remote pressure transducers. The free stream total temperature is found from a thermocouple mounted in the inlet bellmouth.

The LSTPC also has a pitch-wise traverse downstream of the guide vanes that can be used to mount pressure and temperature transducers. There is also provision for vane instrumentation, the leads from which can be routed through holes in the endwalls. A wake probe attached to the downstream traverse is shown in figure 3.6. Also in figure 3.6 the tubettes leading to pressure tappings around the surface of the guide vanes at midspan can be seen extending from the endwalls.

The nozzle profile used in the LSTPC was the midspan profile of an aggressive design for a highly loaded, low wheel speed, gas generator turbine stage from a P&WC aviation gas turbine engine. It had a stage pressure ratio of 3.8 and stage loading of 2.5. The history of this design is laid out in chapter 2. The nozzle used in the LSTPC is 4.3 times engine size; table 3.1 contains the blades geometric parameters. The blades in the LSTPC are designed to

produce a turning angle of 76° and, at a pressure ratio of 2.3, have an isentropic exit Mach number of 1.16. The inlet metal angle was set at -10° to account for leading edge flow effects.

A photograph of the nozzle vanes (figure 3.7) shows the aggressive profile was designed to produce most of the turning in the upstream portion of the nozzle. The thick trailing edge was incorporated to accommodate internal cooling passages.

Chord	175.3 mm	
Chord – Axial	84.6 mm	
Span	112.8 mm	
Pitch	147.6 mm	
Aspect Ratio	0.64	
Solidity	1.19	

Table 3.1. Vane Geometric Parameters



Figure 3.5. Schematic of the LSTPC



Figure 3.6. Photograph of the LSTPC with Wake Probe



Figure 3.7. LSTPC Nozzle Vanes

3.2. Circular Cylinders

Three circular cylinder models were used in the course of the 2000 series and 2002 series of experiments: the Institute of Aeronautical Research (IAR) $1\frac{1}{2}$ " Aluminium cylinder, the 37.26mm Steel Surface Pressure Cylinder and the Boundary Layer Probe Cylinder. The first cylinder had been made for a previous set of low subsonic tests in the TBWT and was on loan for the 2000 series of experiments. The two other cylinders were designed by the author and made in the University of Leicester workshop for the 2002 series of tests. They were required because of pitting experienced by the aluminium cylinder indicated that for any further testing steel models would be needed. Descriptions of the models follow.

The convention for angular positioning that will be used for this thesis is laid out in figure 3.8.

3.2.1. IAR 1¹/₂" Aluminium Cylinder

The IAR 1½" Aluminium Cylinder was originally intended for use at low Mach and Reynolds numbers. It was manufactured from aluminium alloy and designed to be mounted on the TBWT 1.33kN balances. The choice of material made sense for the low Mach and Reynolds number flow it was designed to be used in as any flow debris would have little kinetic energy and so would cause little, if any, damage if it impacted on the soft alloy. Similarly the low drag acting on the cylinder in the design flow conditions meant that the weaker balances could be used. The cylinder had an external diameter of 37.26mm, a span of 381mm and was polished to a mirror finish. To ensure a close fit spring-loaded Teflon spacers were inserted into the ends of the cylinders so that any gap between it and the endwalls would be filled. Manufacturing drawings of the cylinder can be found in appendix A and an assembly drawing is given in figure 3.9.

The design of the cylinder allowed for a single Kulite XCQ-062 transducer to be mounted at midspan on the cylinder. In addition to this, tappings and tubing for remote pressure transducers were incorporated into the cylinder along its span at two different angular positions.

The original design had the Kulite transducer positioned at 100° and the tappings for the remote pressure transducers at 30° and 180°. However due to the symmetry of the cylinder mountings it could be mounted so that the transducer was positioned at 280°. In addition to this modifications were made to the mountings so that the cylinder could be mounted with the

transducer at 10° and 190°. This, along with the ability to rotate the balance through $\pm 55^{\circ}$ allowed the transducers to cover the entire circumference of the cylinder.

Modifications were also made to the balances on which the cylinder was mounted. Due to the higher loading the cylinder experienced at the Mach numbers used in this project the balances on which it was mounted were reinforced. The reinforcement was achieved by taking a pair of balances that had small fractures in them and inserting a thick walled steel tube into the central holes (figure 3.10). While the use of the reinforced balances enabled the cylinder to be used at the higher Mach numbers it resulted in two drawbacks. Firstly the tappings for the remote pressure transducers became impossible to connect due to the reduction in bore of the central hole leading through the balances. Secondly, since the strain gauges had broken when the balances had fractured, no direct measurement of the forces acting on the cylinder could be made. However given the accuracy of the high frequency response pressure transducer used the former drawback was not an issue. Also, it had never been planned to measure the force acting on the cylinder directly from the balances, relying instead on the surface pressure measurements.

The IAR $1\frac{1}{2}$ " Aluminium Cylinder had two drawbacks. Firstly, because it was manufactured from an aluminium alloy, it was susceptible to pitting by flow debris at the high Mach numbers used. This caused roughening of the surface of the cylinder that required rubbing down between wind tunnel blowdowns with a sheet of paper. While this was a suitable short-term solution, concern was expressed regarding what the long term effects of using the cylinder for another set of tests. The other drawback was the solitary high frequency response pressure transducer that could be mounted on the cylinder surface. This meant that measuring the time resolved surface pressure distribution around the circumference of the cylinder required four blowdowns with the cylinder repositioned each time on the balances to be 90° further around the circumference. This was prohibitively expensive and resulted in the surface pressure only being measured between -10° and 190°. To overcome these drawbacks the 37.26mm Steel Cylinder was produced for the 2002 series of experiments.

3.2.2 37.26mm Steel Cylinder

The 37.26mm Steel Cylinder was designed to have the same external dimensions and surface finish as the IAR $1\frac{1}{2}$ " Aluminium cylinder used for the 2000 series of tests. In addition to overcoming the shortcomings of the IAR $1\frac{1}{2}$ " Aluminium Cylinder the 37.26mm Steel Cylinder was designed to incorporate a phase reference transducer. This was a result of the

problems found when trying to take a phase reference from the wake of cylinder (section 3.3.4).

To prevent the pitting of the cylinder experienced during 2000 series of tests the cylinder was manufactured from free cutting stainless steel. The new cylinder, being designed with provision for four high frequency response pressure transducers, solved the problem of requiring multiple blowdowns to make a complete time-resolved surface pressure survey of the circumference. The mountings for the pressure transducers were positioned at 90° intervals around the midspan of the cylinder. In addition to the mountings for high frequency response pressure transducers mounting. The form of pressure tappings positioned next to each pressure transducer mounting. The mountings and tappings were positioned so that when the cylinder was mounted and the balance angle set to zero they would be located at 45°, 135°, 225° and 315°. Thus by rotating the cylinder through $\pm 45^{\circ}$ the pressure distribution around the circumference of the cylinder could be surveyed in a single blowdown.

The incorporation of a phase reference transducer that could be used for the phase lock averaging of both surface pressure results and the wake results into the cylinder presented different challenges. So that the phase reference transducer could be used with the surface pressure data it had to be held in place while the portion of the cylinder containing the mid-span pressure transducers rotated. This was achieved by splitting the cylinder in to two parts, the "North End" (mounted on the balance in the north endwall) containing the midspan pressure transducers, and the "South End", housing the phase reference transducer. The two ends were connected by a bearing. This arrangement can be seen in the assembly drawing of the cylinder, figure 3.11. The bearings used were brass bushes. Manufacturing drawings of this cylinder can be found in appendix B.

The angular position of the reference transducer was chosen by inspection of the 2000 series surface pressure results. The position that was used, 110°, was chosen because the pressure time histories at that location had low noise levels, well formed waveforms and little harmonic content.

The drawings in appendix B are for the cylinder after modifications were made by the U-66 workshop. The modifications, made to the mountings for the high frequency pressure transducers, were necessary because an insufficient number of Kulite XCQ-062-25D

transducers were in stock at NRC. The lead-time for new transducers would have resulted in them being delivered after the tests were scheduled. The only alternative available transducers were Entran EPI-541-50P sub-miniature pressure transducers. Due to the larger diameter of the Entran transducers the mounting holes had to be enlarged from 1.7mm to 2.49mm. This was done in the U-66 workshop. Unfortunately the use of the larger transducers created unforeseen problems that were not discovered until the transducers were fitted and the tests started (section 3.3.3).

3.2.3. Boundary Layer Probe Cylinder

In order to take boundary layer measurements at separation for the 2002 series of tests another cylinder, incorporating a flattened head Pitot tube was designed. The Pitot tube was made from 16 gauge hypodermic tubing. The outer dimensions of the flattened head of the Pitot tube were 1.08mm wide by 0.33mm high, while the internal dimensions were 0.75mm by 0.1mm. As with the 37.26mm Steel Cylinder it was made of free cutting stainless steel to the same external dimensions and surface finish as the IAR $1\frac{1}{2}$ " Aluminium Cylinder.

A number of designs for a traversing devise were considered including a ramp, rack and pinion and a gear chain all of which were driven by a stepper motor. Due to size constraints, the mechanism had to be housed within the cylinder, the smallest possible stepper motor, a SAIA-Burgess No. UAG 23NO5RE, had to be used. The small size of the stepper motor resulted in it having little torque and so the gear chain design had to be used, figure 1.5. The gear chain consisted of a 12 tooth, module 0.8, 10.4mm outside diameter drive gear, a 24 tooth, module 0.8, 24mm outside diameter idler gear and another 24 tooth, module 0.8, 24mm outside diameter attached to the threaded rod that drove the traverse. Even with the gear chain doubling the delivered torque the motor had to be run at 5V above the design power supply of 12V. The traverse mechanism allowed the Pitot tube to be extended in steps of 0.02mm up to a height of 3.8mm from the surface of the cylinder, although it was planned to use steps of 0.04mm to help prevent the mechanism sticking.

A stepper motor control card, designed and built in-house at the University of Leicester for a second year undergraduate design module, was loaned to the project to control the traverse. This was initially run by a Labview virtual instrument (VI), written by Paul Williams at the University of Leicester, and was subsequently incorporated into the VI used for control and data acquisition written by Paul Hunt and modified by Steve Totolo at NRC.

In order to incorporate the traverse mechanism the cylinder had to be made in three parts, the South, Centre and North sections, see appendix C. The traverse was housed in the centre section while the south and north sections connected the cylinder to the balances. In addition to this the north section had to be designed to accommodate the static pressure transducer used to find the boundary layer velocity profile. The assembly drawing for the boundary layer cylinder is shown in figure 3.13.

Once the traverse mechanism had been built into the centre section it was tested to ensure it would work in a high subsonic flow. For this the centre section was attached to the outlet of the University of Leicester Transonic Cascade, figures (3.14 and 3.15), and subjected to an exit Mach number of 0.7. In addition to ensuring that the traverse mechanism worked this also provided an opportunity to test the settling time of the transducer, which turned out to be two seconds when a 1m length of tubing was used to connect it to the Pitot probe and static pressure tapping.

Following the cascade test the accuracy of the traverse mechanism was tested in a Baty Shadowmaster shadowgraph. This showed that over the course of the Pitot probe traverse there were areas where the step size varied by as much at 0.02mm, an error of 50%, figure 3.16. The traverse beam becoming stuck on the guide bar caused the error. While there were few erroneous points the overall affect was a positional error of 0.16mm or 5% at the top of the traverse. The test was repeated three times with the same results. Due to the repeatability a calibration factor applied to the data, figure 3.17, could compensate. The calibration factor was found to be 0.942 from a simple linear line fit using Microsoft Excel and confirmed with Matlab.

In addition to the error caused by the traverse beam becoming stuck there was also a systematic error in the position of the actual probe head. From figure 3.12 it can be seen that the Pitot tube is angled down from the support so that it is parallel to the surface under the probe tip. This means that while the probe support moves up normal to the cylinder the probe tip does not. However the error can be calculated using simple geometry, equation 3.1, and the angular position of the cylinder adjusted to compensate.

$$\theta = \arctan\left(\frac{4.6}{18.23 + y}\right) - \arctan\left(\frac{4.6}{18.23}\right)$$
(3.1)

For use at NRC it was decided to introduce a displacement a transducer to measure the position of the Pitot tube. This was due to the uncertainty regarding the repeatability of the traverse positioning after it had been transported to NRC from the UK. The transducer used was the potentiometer taken from a linear variable resistor. This allowed the position of the Pitot tube to be measured to within $\pm 1 \mu m$.







Figure 3.9. Assembly Drawing of IAR 11/2" Aluminium Cylinder



Figure 3.10. Photograph of Reinforced Wind Tunnel Balance



Figure 3.11. Assembly Drawing of 37.26mm Steel Cylinder



Figure 3.12. Boundary Layer Probe Traverse Mechanism



Figure 3.13. Assembly Drawing of Boundary Layer Cylinder



Figure 3.14. Photograph of Boundary Layer Cylinder Centre Section Mounted on Transonic Cascade for Testing Looking from Below and Downstream



Figure 3.15. Photograph of Boundary Layer Cylinder Centre Section Mounted on Transonic Cascade for Testing Looking From Above at Pitot Tube



Figure 3.16. Positional Error of Boundary Layer Probe



Figure 3.17. Calibration Curve of Boundary Layer Probe Position
3.3. Instrumentation 1. Trisonic Blowdown Wind Tunnel Tests

A number of different transducers were used during the course of the 2000 and 2002 series circular cylinder tests and the surface pressure measurements on the LSTPC. There follows a description of the transducers used along with, where necessary, a description of the operating theory. An error analysis of the transducers may be found in appendix D.

3.3.1: Total Temperature Probe

3.3.1.1. How the probe works

The thin film total temperature probe consists of two bodies each tipped with a platinum thin film transducer. The probe works through the measurement of the heat transfer between the flow and the two bodies and the surface temperature of the bodies at their stagnation points. These quantities are measured by the thin film transducers. Assuming viscous dissipation is negligible the relationship between total temperature, surface temperature, heat transfer rate and convective heat transfer coefficient for each probe body is governed by equation 3.2.

$$q = h(T_T - T_w) \tag{3.2}$$

When one of the probe bodies is heated before the probe is exposed to the flow it results in the two bodies having different surface temperatures and heat transfer rates while maintaining the same heat transfer coefficient and experiencing the same total temperatures. Thus when equation 3.2 is solved simultaneously for both probes the total temperature can be found.

The above method allows for the indirect measurement of total temperature through the use of a probe made of two small and nominally identical bodies with easily definable stagnation points. The two bodies have to be positioned at the same streamwise location, facing into the flow and closely enough together so that the flow can be considered two-dimensional.

One of the assumptions made above for the operation of the total temperature is that the convective heat transfer coefficient is the same for both probes despite one of them being heated. Buttsworth and Jones [59] demonstrate that the heat transfer coefficient over the operational temperature range of the probe is constant to within 1% and so is essentially a function of the probes body geometry. Since both probes have nominally identical geometry it can be assumed that they have the same heat transfer coefficient.

The two bodies of the total temperature probe are made of hollow fused quartz rods both with an external diameter of 3mm. Each rod has a hemispherical end upon which is painted a 1mm wide platinum thin film transducer to measure the heat transfer and film temperature. The thin films are connected to leads at the base of the probe via strips of gold painted onto the surface of the quartz bodies. One of the probe bodies contains a small heater made from a length of high resistance wire coiled around a small ceramic tube, enabling it to be heated before each measurement. An annotated sketch of one of the bodies used can be seen in figure 3.18.

The thin films are run in a constant current mode so that the potential drop across them is proportional to the film temperature and thus the probe surface temperature. With the relationship between the film resistance and temperature known the surface temperature can be easily calculated. The high frequency components of the convective heat transfer rate are measured by running the signals from the thin films through a heat transfer analogue [61] while the low frequency components are found by running the digitised film temperatures through a finite difference routine scripted into Matlab [62]. The two signals are recorded separately in accordance with the advice given in Buttworth and Jones [59]. The frequency responses of the two methods of finding the heat transfer rate are around 85kHz and 1kHz for the heat transfer analogue and the finite difference routine respectively.

The need to find the high and low frequency components of the heat transfer rate separately arises from the inaccuracy of the heat transfer analogue at low frequencies [61] and the frequency response of the finite difference routine [63].

The heat transfer analogue output is a voltage proportional to the heat transfer rate. From this the actual heat transfer rate may be calculated from equations 3.3 and 3.4 [59, 63].

$$|q| = \frac{\sqrt{\rho ck}}{3.08} T_{sence} \tag{3.3}$$

where:

$$T_{sence} = \frac{dT}{dR} \frac{v_0}{i_a}$$
(3.4)

Before the total temperature can be calculated from the heat transfer rates and surface temperatures a number of corrections to the data have to be made. Also there are some limitations on the probe that have to be addressed during data acquisition. These are:

- i. Oldfield et al's heat transfer analogue circuit was designed for heat transfer to a flat plate so surface curvature has to be taken into account,
- ii. Equation 3.3 assumes one-dimensional heat transfer normal to the body surface so lateral conduction has to be accounted for,
- iii. Equation 3.3 also assumes that the heat transfer medium is semi-infinite. To accommodate this the body's core temperature must remain essentially constant,
- iv. The Oldfield et al analogue circuit had incorrect impedance for heat flux frequencies below 0.1Hz.

In order for (iii) to be met the probe could only be kept in the flow for very short periods of time. In this case after around 0.7 seconds the body's core temperatures starts to be significantly affected so limiting the probes to this amount of exposure.

The solution to the problems posed by (i) and (ii) was simplified because the high frequency surface temperature fluctuations, while having a significant impact on the overall heat flux level, has a vanishingly small effect on the difference between surface temperature and total temperature. This means that although the high frequency components have to be considered when finding the heat flux, they could be ignored with regard to the surface to total temperature difference. Additionally the small amount of heat transfer involved in the high frequency heat flux means that it has only a local affect and so is not affected by lateral conduction or surface curvature. Only the low frequency heat transfer data, calculated by the finite difference routine, has to be corrected. This was done using Matlab scripts developed by Buttsworth [62].

The final problem, (iv), is easily solved by digitally high pass filtering the high frequency data at the same frequency that was used to anti-alias the low frequency temperature and heat transfer signals. This removes both the data affected by the incorrect impedance of the analogue and the data repeated by the low frequency heat transfer data.

3.3.1.2. Calibration of the total temperature probe

In order to find the surface temperature and convective heat transfer from the time histories of the total temperature probe signals the temperature/resistance relationship, dT/dR, for the thin films had to be known. Ideally the calibration to find dT/dR for the thin films would be carried out in a constant temperature air bath. This is so that the resistance of the thin films over the operational temperature range can be found in the medium in which the probe will be

used. Unfortunately NRC did not have a constant temperature air bath available and so an alternative arrangement had to be made. A Guideline constant temperature water bath Model 9734 S# 46130 was available.

The use of a water bath presented two problems. Firstly, if the probes were calibrated in the water the resistances of the films come out lower than if they had been taken at the same temperatures in air. Any calibration with the probes in the water was therefore erroneous. Secondly it limited the temperature range to between 20°C and 65°C. While nothing could be done about the temperature range the problems created by calibrating in water could be overcome.

Initially the calibration was conducted by inserting the probes into a practice golf ball along with the probe from a Guideline 9540 platinum resistance thermometer being used to get an accurate reading of the local temperature. This in turn was placed inside a small plastic bag along with some ballast and suspended from the lid of the bath into the water. It was found that the bag did not remain waterproof during prolonged immersion so it was replaced with a latex condom. The condom remained waterproof during prolonged immersion so the calibration was carried out without further problems.

The constant temperature water bath required around 30 minutes to reach any given temperature. Once at a set temperature the equipment was allowed to settle for fifteen minutes enabling it to reach a uniform temperature. The resistances of the thin films and attached leads were then taken and the next water bath temperature entered. The temperatures used were, nominally, 20°C to 40°C in steps of 2°C and 20°C to 65°C in steps of 5°C or 10°C for the 2000 series and 2002 series respectively. The results of the calibrations are shown in figure 3.18

3.3.1.3. Using the total temperature probe in the TBWT

The total temperature probe had been designed for use in transient wind tunnels, i.e. shock tubes and the Isentropic Light Piston Facility. When used in these facilities the probe took a measurement at just one spatial position per run. This meant that it could be heated before the flow was started and then used once. When used in long duration facilities such as the TBWT this could not be done and so a method of heating the probe without stopping the flow therefore had to be derived, thus enabling multiple measurements to be taken each run.

The method used comprised three parts used together to ensure a stagnant pocket of air was created to heat the probe in. Firstly an open-ended sheath was extended over the end of the probes. The sheath extended over the end of the probes by 4Ds. This extension had been arrived at through testing the method in the LSTPC (figure 3.19). It was found that by extending an open ended sheath over the end of the probes by a distance of 4Ds and keeping the leakage flow to minimum a sufficiently stagnant pocket of air was created to allow the probe to heat up as if it had been removed from the flow.

Secondly the probe was moved out to the either the upper or lower extreme of the traverse, depending on which side of the wake the measurements were being taken, so as to remove it from the fluctuating wake flow for heating.

Finally the flow was throttled back to between Mach 0.1 and 0.2, depending on how much pressure there remained in the supply tanks. This had two effects. It improved the quality of the stagnant pocket of air created by the sheath and minimised wasted air, so prolonging each blowdown, allowing for more measurements to be made and reducing the overall number of blowdowns, and so expense, required.

3.3.2. Total Pressure Measurement

To take total pressure measurements simultaneously with, and at the same location as, the total temperature readings a small, high frequency response pressure transducer was needed. As well as being sufficiently small to be placed closely enough to the total temperature transducer for the flow to be considered locally two-dimensional the frequency response of the transducer would have to be similar to that of the Oxford probe. These requirements could be met by using either an Entran Subminiature Pressure Transducer or a Kulite Ultraminiature Pressure Transducer. In the event a Kulite XCQ-062-25D Ultraminiature Pressure Transducer that met the required specifications was available and so was used. Specifications for this transducer are in appendix D.

The total pressure transducer had to be aligned on the same spanwise axis as, and with its tip at the same streamwise position as those of, the total temperature probe. To meet these criteria the probe had to be inserted into a thin walled stainless steel tube with a large enough outside diameter to fit into the holes machined into the sting head and long enough to allow the tip of the transducer to be aligned with the ends of the Oxford probes' bodies. The Kulite pressure transducer was referenced to the facility's slugged pressure volume for the 2000 series of tests and the free stream total pressure for the 2002 series of tests. Since both reference pressures were suitable the choice was arbitrary and made no difference to the results.

3.3.3. Surface Pressure Measurement

Another Kulite XCQ-062-25D referenced to the facility's slugged volume took the surface pressure measurements during the 2000 series of tests. The Kulite, when mounted with its face flush with the upstream and downstream edges of the mounting hole subtended an arc of 4.83°.

During the 2002 series of tests the surface pressure measurements were made using Entran EPI-541-50P transducers, appendix D. These transducers have a number of drawbacks when compared to the Kulite XCQ-062-25D transducers. Firstly, the larger diameter of the Entran transducer (2.36mm) compared to the Kulite transducer (1.57mm), an increase of 50%, meant that the Entran transducer took up a greater proportion of the circumference of the cylinder, 7.26° compared to 4.83°, resulting in the readings being spatially averaged over a greater area. It transpired that this does not produce any problems, the results from the two sets of data match very well. The problems arose from the increased length of the transducer. There was adequate room inside the cylinder for four Kulite transducers and their reference tubes to fit without any interference if the tubes were cut down to the minimum practical length of around 6mm. Unfortunately the same was not true of the Entran transducers. Despite both cutting the reference tubes down and bending them as much as possible without causing kinking the reference tubes still interfered. This resulted in three of the lengths the plastic tubing that connected the reference tubes to the slugged volume becoming punctured rendering the three transducers they were attached to useless. Because of this the advantages of having four transducers were negated.

Another drawback of the Entran pressure transducer was the reduced frequency response. The estimated frequency response of the Kulite was around 85kHz while that of the Entran was 35kHz (from manufacturers estimates). However, the highest vortex shedding frequency from the cylinders used in 2000 series and 2002 series test was 1.49kHz (at Mach 0.9). Even the lower frequency response of the Entran was sufficient to cover any possible harmonic of vortex shedding.

Remote pressure transducers were not used for either the 2000 series or the 2002 series of tests. This was because the measurements would have been unnecessary as the time averaged results from the high frequency response pressure transducers were reliable.

3.3.4. Phase Reference Transducers

Initially the phase reference transducer for the 2000 series tests was a Kulite XCQ-062-25D pressure transducer mounted at the tip of sting attached to the northern endwall so that the face of the transducer was 1D downstream and 1.5D below the circular cylinder. This worked well while the Mach number was kept below 0.8. However on the first run at Mach 0.9 the separation shocks from the cylinder impinged upon the face of the pressure transducer and broke it.

Given the short time scale, and a shortage of pressure transducers in stores it was not possible to install a new dedicated phase reference transducer. It was decided to use the wake total pressure transducer, at a traverse position of -0.6D from the wake centre, as the phase reference for further surface pressure measurements and the surface pressure transducer, positioned at 120°, as the phase reference for wake traverse runs. While not ideal this arrangement worked well (sections 4.3, 6.1 and 6.2).

The phase reference for the 2002 series of tests was a dedicated transducer mounted in the cylinder as described in section 3.2.2. The transducer used for this was a Kulite XCQ-062-25D.

3.3.5. Pressure Transducer Calibration

The high frequency response pressure transducers were calibrated by applying a range of reference pressures with the transducer head exposed to atmosphere. The pressure range was worked up and down to check that hysteresis remained within the manufacturers limits.

3.3.6. Boundary Layer Probe Transducers

The boundary layer pressure measurements were all made by remote Scanivalve ESP ZOC 22 pressure transducers in a bank of similar instruments belonging to the U-66 facility and which were referenced to the facilities slugged volume. The transducers used have a range of 1 - 50 PSID. Measurements of probe position were supplied by the potentiometer mounted inside the cylinder body.

3.3.7. Running Conditions and Probe Position

Free stream and total and static pressure were measured at the control valve by remote Paroscientific Digiquartz transducers with a range of 200 PSIA. Free stream total temperature was measured, again at the control valve, by a custom platinum resistance wire thermometer. The position of both the circular cylinder and the wake traverse were measured and recorded by potentiometers built into the wind tunnels working section.

3.3.8. Wake Traverse Probe Holder

The holder of the total temperature probe had to do a number of things. It had to:

- House the three probe bodies as closely together as possible in a non-conductive material,
- Align the three probe bodies in the same spanwise axis in the test section,
- Place the heads of the total temperature probe and total pressure probe at the same streamwise location 6D downstream of the cylinder at the test section's midspan,
- Mount the sheath used to provide a stagnant pocket of air required to heat one of the total temperature probe bodies.

The first two points were met by housing the probes in a probe holder manufactured from G9 glass. The holder was made so that the three probe heads were positioned side by side and separated by a distance of 0.79mm. The non-conductive material was needed due to the thin films being connected to the back of the probe bodies by strips of gold painted onto the surface of the fused quartz rods.

The third point was met by mounting the probe head onto a sting that positioned the tips of the probes 424mm upstream of the traverse mechanism which in turn was mounted on a delta wing that positioned the centre probe body, the heated total temperature probe, at the test section midspan location.

The sheath was mounted onto the sting and was machined to give it a sliding and location fit. This was necessary for two reasons. Firstly the sheath was attached to the pneumatic piston that moved it back and forth on one side, so if it did not have a close fit it would be in danger of jamming. Secondly the close fit resulted in little leakage flow and so a better stagnant pocket. A further innovation, suggested by Simon Hogg, was included in the design to reduce the leakage flow. The idea was to include ram scoops around the circumference of the sheath that would be connected to a ring machined out of the internal surface of the sheath at a location that would always be behind the probes. This would provide a back pressure behind the probes reducing leakage flow. This was implemented by giving the external surface of the

sheath a step change in diameter of 5.08mm at 25.59mm from the end. Eight equispaced holes were drilled into the surface of step change in diameter that was normal to the flow direction providing the ram scoops. The holes then met up with an annular ring machined out from the internal surface of the sheath.

The pneumatic ram used to move the sheath was mounted in the sting holder and was connected to the sheath via a rod. A pin and a pair of jubilee clips held the ram onto the sting holder. The rod was connected to the sheath using a link pin to provide some flexibility and so reduce the likelihood of the sheath jamming.

Full drawings of the sting, sting holder, delta wing, probe holder and ancillary parts are in appendix E while an annotated photograph of the probe is presented in figure 3.20.



Figure 3.18. Sketch of One of the Total Temperature Probe Bodies



Figure 3.19. Total Temperature Probe calibration Curves



Figure 3.20. LSTPC with Total Temperature Probe in Prototype Sheath



Figure 3.21. Photograph of Wake Sting

3.4. Instrumentation 2. Large Scale Transonic Planar Cascade Test

The number 3 and 4 nozzle guide vanes of the LSTPC were instrumented to take time averaged surface pressure measurements. This was done by drilling tappings with a diameter of 0.508mm normal to the blade surface and then drilling in from the side of the vanes parallel to, and 3.2mm down from, the surface so that the tappings could be connected to transducers. A total of twenty-two tappings were drilled into the surfaces of two vanes. Vane 3 was used for the pressure surface tappings and had ten tappings from the leading edge to just before the blend point on the trailing edge. The adjacent vane, vane 4, was used for the suction surface tappings and had twelve tappings, again going from the leading edge to just before the blend point at the trailing edge. The location of the tappings is given below in table 3.2. In this fashion the vane surfaces of the central nozzle passage was instrumented.

As can be seen from table 3.2 the position of five of the new tappings (tappings 10, 14, 17, 19 and 20) coincide with those of the tappings used previously by Carscallen and Oosthuizen and Moustapha et al. This was to enable comparison of the data collected here with the original data if it was deemed necessary. The remaining tappings were arbitrarily positioned around the suction and pressure surfaces at fairly even intervals along the axial chord. However the blade that was to be used for the pressure surface tappings had a large part of its interior missing near the trailing edge as there had previously been a transducer contained within it. As a result there is a large gap toward the trailing edge of the pressure surface blade between tappings. This is unfortunate as the results discussed later show that there is a large and rapid acceleration of the flow in this region. Similarly, due to the limited available metal space in the blade there are few tappings along the suction surface towards the trailing edge. However the tappings that are there are positioned to intercept the shock wave interaction from the adjacent blade.

The tappings were connected to the outside via 1.6mm holes drilled down from the sides of the blades to connect with the tappings. The connecting holes were positioned so that they went through the blade at a distance of 3.2mm from the blade surface and were drilled through to just beyond midspan to ensure a good connection with the tappings. Into these holes 1.6mm outside diameter bulged stainless steel tubulations, manufactured by Scanivalve, were glued. Holes were also drilled into the front plexiglass endwall; these were aligned with the tubulations allowing them to pass through the endwall when the blades were mounted in the cascade. A cut away drawing of the arrangement is shown in figure 3.21 and photographs

of the blades with the tubulations attached are given in figure 3.7. The tubulations were then connected via 1m lengths of plastic tubing, again manufactured by Scanivalve, to a Scanivalve DSA remote pressure transducer.

Pressure Surface Tappings			Suction Surface Tappings		
Tapping	x	Y lower	Tapping	x	Y upper
1	-1.813392	1.912752	11	-1.813392	1.912752
	-1.796688	1.784736		-1.796688	2.017872
	-1.746720	1.675440		-1.746720	2.127312
2	-1.680048	1.596096	12	-1.680048	2.206656
	-1.613376	1.545696		-1.613376	2.260080
	-1.546848	1.512864		-1.546848	2.303712
	-1.480176	1.487952		-1.480176	2.339712
3	-1.313568	1.413936	13	-1.313568	2.402064
	-1.146816	1.314288		-1.146816	2.431296
4	-0.980208	1.179936		-0.980208	2.431584
	-0.813600	1.001808	R/14	-0.813600	2.403792
5	-0.646992	0.775584		-0.646992	2.345184
	-0.480384	0.503569	15	-0.480384	2.250720
6	-0.313776	0.192816		-0.313776	2.108016
	-0.147168	-0.149760	16	-0.147168	1.886976
	-0.063792	-0.331776		-0.063792	1.727424
7	0.019584	-0.520704		0.019584	1.518912
	0.102816	-0.716544	U/17	0.102816	1.253520
	0.186192	-0.919872		0.186192	0.967392
8	0.269424	-1.130832		0.269424	0.675216
	0.352800	-1.350288	18	0.352800	0.378864
	0.436032	-1.578816		0.436032	0.078336
9	0.519408	-1.816848	V/19	0.519408	-0.226656
	0.686016	-2.317968		0.686016	-0.861696
	1.019232	-3.411072	W/20	1.019232	-2.157264
	1.185984	-3.986352	21	1.185984	-2.844144
P6/10	1.269216	-4.280688		1.269216	-3.196800
	1.310976	-4.386096		1.310976	-3.376368
	1.352592	-4.417200		1.352592	-3.556080
	1.385856	-4.426416		1.385856	-3.701664
	1.419264	-4.425840		1.419264	-3.848400
	1.452528	-4.415328		1.452528	-3.996288
	1.485792	-4.390992	22	1.485792	-4.145184
	1.502496	-4.369104		1.502496	-4.220208
	1.519200	-4.308480		1.519200	-4.308480

Table 3.2. Position of Pressure Tapping on the LSTPC's nozzle blades



Figure 3.22. Cutaway Drawing of LSTPC Surface Pressure Tappings Not to Scale

registrophed pressure transforms and the low-speed total temperature channels) and the entialiaping filter (all other electrophe). Officie were tradied along whit the pre-filter gains by the ext-straining filter that reach up part of the M-10 DAQ specer. The ext-straining filter used was a Procluter instrument 6 pole elliptical filter capable of high, ion and band pain filtering and adjudging pro-filter state page-filter points and affects. A fill-stateing was applied to the shares a solution of the state page-filter points and affects. A fill-stateing was applied to the shares a solution of the state page-filter points and affects. A fill-state and filtering frequencies for shares a state of the state page-filter to a filter and affects will filter and filtering frequencies for

The M-10 high-spinst DAC system used two linked Mutional Instruments PCI-611CH 12 bit DAC parts each espekte of emopting 4 analogue objects of belocken Differ and DMHz via a SUR-64 to eaged bes. The DAC cards were invalided by a PC heaving a 300kHz Pentrari H preserver and S12MB of RAM. All the phononic on core and but for be delayed a some selection of S12MB of RAM. All the phononic on core and but for be delayed a some selection relationship in programmed by Paul Hunt, way used to card of the data consisters and concentrations of the DM programmed by Paul Hunt, way used to card and inightly cather of vertices of the Victoria could be the TBWT symptom. Phates, 1 and 2 and 1 algorithy cather on vertices of the Victoria could be the requirements of tends phone.

3.5. Data Acquisition

3.5.1. 2000 Series

Data acquisition (DAQ) for the 2000 series of tests was carried out using a combination of the Trisonic Blowdown Wind Tunnel's (TBWT) own system and a high-speed system developed at the NRC M-10 Facility by Paul Hunt.

Phase 1 of the tests required seven channels of data acquisition for the signals from the probes, four high-speed (two for the heat transfer analogue's output, one for the total pressure transducer and one for the phase reference transducer) and three low-speed (two for the total temperature transducer and one the for trigger that provided communication between the two DAQ systems). Phase 2 required just two high-speed channels (for the surface pressure transducer and the phase reference transducer) and one low-speed channel (for triggering). This requirement was met by the M-10 high speed system, with the exceptions outlined below. Acquisition of the tunnel running conditions was carried out by the TBWT DAQ system.

Pre-filter gains for the channels were applied by the TBWT DAQ system (in the case of the high-speed pressure transducers and the low-speed total temperature channels) and the antialiasing filter (all other channels). Offsets were applied along with the pre-filter gains by the anti-aliasing filter that made up part of the M-10 DAQ system. The anti-aliasing filter used was a Precision Instruments 6 pole elliptical filter capable of high, low and band pass filtering and applying pre-filter and post-filter gains and offsets. Anti-aliasing was applied to the channels at 40% of the sampling rate. All of the gains, offsets and filtering frequencies for phase 1 and 2 are given in tables 3.3 and 3.4 respectively.

The M-10 high-speed DAQ system used two linked National Instruments PCI-6110E 12 bit DAQ cards each capable of sampling 4 analogue channels at between 1kHz and 1MHz via a SCB-68 terminal box. The DAQ cards were installed in a PC having a 300kHz Pentium II processor and 512MB of RAM. All the channels on one card had to be set to the same sampling rate although the two cards could be set to different rates and remain synchronised. A Labview virtual instrument (VI), programmed by Paul Hunt, was used to control the data acquisition and communication with the TBWT system. Phases 1 and 2 used slightly different versions of the VI each modified for the requirements of each phase.

The TBWT data acquisition system also acquired all of the high-speed data at 1kHz to provide time-averaged data for checking the data collected by the M-10 DAQ system.

The cabling directly attached to the transducers was twisted pair. This was changed to coaxial as soon as the routing allowed and was kept as short as possible. The cabling was routed through a modified external wall plate to avoid using the rather long standard cable runs.

3.5.2. 2002 Series

As with the 2000 series tests the 2002 series phases 1 and 2 used both the TBWT DAQ system and a separate high-speed system, assembled by Steve Totolo of the NRC M-2 Facility. The new high-speed system used two National Instruments PCI-4452 DAQ cards. Each of these cards has four 16 bit channels with built-in anti-aliasing, set to half the sampling frequency, and gains, set by altering the sensitivity of the cards. The built-in anti-aliasing and gains removed the need for applying filtering or pre-filter gains to the data before acquisition. This was the main reason for choosing these cards as the filter used during the 2000 series tests was unavailable in 2002. Both cards had to be set to the same sampling frequency. Since one of the aims of the 2002 series of tests was to increase the temporal resolution of the data the sampling frequency was set to 204.8kHz. This meant that the low-speed data from the total temperature probe subsequently had to be resampled digitally (section 4.2.1). The computer used for data acquisition was the same as that used for the 2000 series of tests.

Again, as with the 2000 series experiments, the data acquisition and communication with the TBWT system was controlled by a Labview VI, this time written by Steve Totolo. All cabling was twisted pair changing to coaxial as soon as routing allowed and kept as short as possible.

Data acquisition for phase 3 was carried out completely by the TBWT system although control of the Pitot tube was carried out by the M-2 system. The control VI used for this was written initially by Paul Williams and later modified and incorporated into a VI which communicated with the TBWT DAQ, written by Paul Hunt and Steve Totolo.

In phase 4 the cylinder was photographed in ultraviolet light taken immediately after the run thus capturing the oil flow visualisation.

3.5.3. Nozzle Pressure Distribution

Acquisition of the pressure data from Scanivalve DSA remote pressure transducer connected to the tappings on the LSTPC third nozzle passage was done through a TPC/IP network link with the data acquisition computer. This was the same as that used for the 2000 series and 2002 series experiments. The atmospheric pressure and temperature, along with the pressure ratio and exit isentropic Mach number, were taken from the facility's transducer readouts and added to the data files. The VI that ran the data acquisition was written by Paul Hunt.

High Speed Card						
Channel	Transducer	Pre-Filter Gains		Offsets	Anti-aliasing	Sampling
		TBWT	Filter	(kHz)	Frequency	Rate (kHz)
					(kHz)	
1	Heat transfer		8		40	100
	analogue,					
	heated					
2	Heat transfer		8		40	100
	analogue,					
	unheated					
3	Total	100			40	100
	pressure					
4	Phase	100			40	100
	reference					
	Low Speed Card					
Channel	annel Transducer Pre-Filter Gair		er Gains	Offsets	Anti-aliasing	Sampling
		TBWT	Filter	(kHz)	Frequency	Rate (kHz)
			·		(kHz)	
1	5V Trigger				0.4	1
2	Total		16	2.5	0.4	1
	temperature					
	heated					
3	Total		16	2.5	0.4	1
	temperature					
	unheated					
4	Not used					

Table 3.3. 2000 Series Phase 1 DAQ

High Speed Card						
Channel	Transducer	Pre-Filter Gains		Offsets	Anti-aliasing	Sampling
		TBWT	Filter	(kHz)	Frequency	Rate (kHz)
					(kHz)	
1	Surface	100			40	100
	pressure					
2	Not used					
3	Phase	100			40	100
	reference					
4	Not used					
Low Speed Card						
Channel	Transducer	Pre-Filt	er Gains	Offsets	Anti-aliasing	Sampling
		TBWT	Filter	(kHz)	Frequency	Rate (kHz)
					(kHz)	
1	5V trigger				0.4	1
2	Not used					
3	Not used					
4	Not used					

Table 3.4. 2000 Series Phase 2 DAQ

3.6. Experimental Procedure

The experimental procedures for the two series of tests in the TBWT are described in the next three sub-sections. While phases 1 and 2 of the two series of tests are largely similar there are sufficient differences for the two series to be described separately. Phases 3 and 4 of the 2002 series tests are described after phases 1 and 2 of that series. A scale drawing of the position of the wake probe, the extents of the traverse planes used in the two series of tests and the approximate extent of the wake relative to the cylinder is given in figure 3.23.

Following the description of the TBWT tests the procedure for the measurement of the LSTPC nozzle pressure distribution is given.

3.6.1. 2000 Series

The wake traverses for phase 1 of the 2000 series tests involved using the TBWT in a semicontinuous blowdown mode, a technique pioneered for these tests. As explained in section 3.3.1.3, a procedure had to be followed before and during each wake measurement to allow the total temperature transducer to be heated in stagnant conditions and to allow for some pretrigger data to be taken. This procedure is laid out in order below:

- 1. The free stream Mach number reduced to $0.1 \le Ma \le 0.2$,
- 2. Wake probe traversed out to approximately $\pm 3D$,
- 3. Sheath extended forward,
- 4. Probe heater switched on,
- 5. Temperature of the heated thin film transducer increased to 120°C,
- 6. Heater switched off,
- 7. Probe traversed into the position required for the measurement,
- 8. Flow brought back up to the required free stream conditions,
- 9. Trigger given to begin measurements,
- 10. Sheath retracted after 0.2 seconds of data acquisition,
- 11. Data acquisition continued for another 1.7 seconds (2000 series) or 0.7 seconds (2002 series).

Note that for the first traverse position of each blowdown the procedure started with no flow rather than reduced flow.

This process was repeated until all of the measurements for a blowdown were completed. A complete traverse from -3.46D to 3.27D in steps of 3mm required six blowdowns with

measurements taken at fifteen traverse positions in each. The first traverse position of each blowdown was a repeat of the last from the previous to ensure repeatability.

Initially it had been planned to carry out wake traverses at all of the Mach and Reynolds numbers in the test matrix. However at an early stage of the testing the heater in the total temperature transducer burned out due to fatigue. Due to the length of time required for the repairs phase 2 was advanced leaving only a single day to carry out phase 1. During the course of each day of testing only one complete traverse could be carried out. The Mach number which produced the strongest periodic surface pressure fluctuations, Ma=0.6, was therefore chosen as this was considered to produce the strongest vortices and hence potentially the greatest energy separation.

During phase 2 the TBWT was used in a continuous blowdown mode and the model was rotated in a step-pause manner so that data was collected at each angular surface position for 2 seconds and then the cylinder was stepped to the next position. Since the transducer used was mounted so that the pressure sensitive head was at the surface of the cylinder no settling time was required.

As with the wake traverses it had been planned to carry out surface pressure measurements with a phase reference at all of the Mach and Reynolds numbers in the test matrix. However, as described in section 3.3.4, the phase reference transducer became damaged during the first set of measurements at Mach 0.9. As a result all of the initial set of reading from phase 2 lacked a phase reference. So that some phase referenced surface pressure measurements could be taken and analysed with the wake traverse results it was decided to carry out the surface pressure measurements at Mach 0.6. The wake pressure transducer was used as a phase reference for this final set of phase 2 measurements, after the wake measurements had been completed on the last day of testing.

The corrected test matrix for the 2000 series tests is given in table 3.5

Two rates of data acquisition were used during the 2000 series of tests. The higher rate of 100kHz was used for the high frequency response pressure transducers and the outputs of the heat transfer analogues. A lower rate of 1kHz was used to sample the film temperatures.

3.6.2. 2002 Series

Phases 1 and 2 of the 2002 series tests were to be copies of those from the 2000 series. There were, however, differences between the methods used in the two series that are described below.

The phase reference was provided for phases 1 and 2 by a dedicated phase reference transducer integrated into the surface of the 37.26mm Steel Cylinder (sections 3.3.2 and 3.4.3).

The most significant difference between the 2000 series and 2002 series phase 1 test procedures was that the spatial distribution of wake measurements for the latter was nonuniform; above the wake centre line it was denser towards the middle of the wake while below it the spacing was uniformly coarse. Also, whereas in the 2000 series the same number of measurements were made per blowdown, in the 2002 series this was altered so that the maximum possible number of traverse positions was used in each run, dependent on Mach number. The number of positions was also affected by wind tunnel logic only allowing for one step size per blowdown. This meant that if the number of steps at a given spacing was lower than the maximum number of possible steps the run would be terminated prematurely. See table 3.6 for details of the traverse step size.

Another significant difference between the two series was that for the 2002 series the compressor for the shop air supply was switched off as it caused a significant amount of electrical interference at 2kHz during the 2000 series tests.

It turned out that the wake data from all the Mach numbers apart from 0.6 were insufficient to describe the profile and so they will not be presented in this thesis.

With regard to phase 2 of the 2002 series of tests, originally it had been planned to make only one blowdown at each Mach number in the test matrix as the four Entran pressure transducers should have captured the entire surface pressure profile in just a rotation of $\pm 50^{\circ}$ in steps of 5°. However due to the problems described in section 3.3.3 this did not happen and a direct copy of the 2000 series phase 2 experiment had to be used. The only differences then were the phase reference transducer and the decoupling of the balance drives allowing one end of the cylinder to rotate while the other was kept in place.

The test matrices for the 2002 series tests, corrected for the changes made during testing, are given in tables 3.6.

The sampling rates for all of the high frequency response transducers were set to 204.8kHz for this series of tests. Again the gains and channels used for the data acquisition system are explained in section 3.5.

For phase 3 of the 2002 series tests the boundary layer cylinder was set up by rotating it on the test section balance so that the tip of the Pitot tube was at the separation point, determined through inspection of the phase 2 time averaged results. The wind tunnel was started and once the flow had reached the desired condition measurements were taken. This was done by moving the Pitot tube out in steps of 0.02mm, correcting the angular position of the cylinder as described in section 3.2.3, and pausing after each step for two seconds to collect data. The movement of the Pitot probe was controlled by the data acquisition system set up by M-2 and using components from the University of Leicester. This system communicated with the TBWT control system allowing for synchronisation of the movement of the Pitot tube with the movement of the test section balances, and so the cylinder, and the data acquisition. In addition to the planned boundary layer traverses an addition one was made at Mach 0.6, see table 3.7. The separation point for each Mach number was chosen, as described, by inspection of the phase 2 results as they were produced. Unfortunately the locations were erroneous and all of the traverses were of separated boundary layers.

The oil used for the flow visualisation in phase 4 of the 2002 series of tests consisted of a mixture of 20 weight engine oil and T-100/05-43 Fluorescent Tracer made by Shannon Luminous Materials Inc. The fluorescent tracer was included so that, when viewed under ultraviolet light, the oil would show up clearly. It was applied to the cylinder by spattering it over the windward face. When the wind tunnel was then run at Mach 0.5 the oil was redistributed over the surface of the cylinder by the localised flow features. Digital photographs of it were taken, under ultraviolet light, of the redistributed oil using the boundary layer probe as a reference for position. From the photographs it was then possible to estimate the position of flow separation.

The final corrected test matrix for phases 3 and 4 of the 2002 series of tests is given in table 3.7.

3.6.3. Large Scale Transonic Planar Cascade Testing

With the testing on the Large Scale Transonic Planar Cascade (LSTPC) reduced to the nozzle pressure distribution this was completed in a single day of testing. For this the pressure tappings in the third and fourth guide vanes were attached to the Scanivalve DAS pressure transducer via 1m lengths of plastic tubing. The nozzle distribution was measured over a exit isentropic Mach number range of 0.4 to 0.95 in steps of 0.05 and at 1.16. The pressure measurements at each Mach number were taken over a six second period to ensure an accurate time average that would not be affected by variations in pressure due to unsteady flow features or short duration variations due to the compressor. The measurements were taken approximately thirty seconds after the flow had been set to the required conditions.

Ma	Re×10 ⁵	Phase 1		Phase 2	
		Readings	Steps	Readings	Steps
0.5	6.9				5°
0.6	6.9	T_T and P_T with P_{ref}	3mm	P_s with P_{ref}	5°
0.7	6.9			P _s	5°
0.7	7.9			P_s	5°
0.8	7.9			P _s	5°
0.8	8.9			P_s	5°
0.9	8.9			P_s	5°
0.95	8.9			P_s	5°

Table 3.5. Matrix of Completed 2000 Series Tests

Ma	Re×10 ⁵	Phase 1		Phase 2	
		Readings	Steps	Readings	Steps
0.4	6.8			P_s with P_{ref}	5°
0.5	6.8			P_s with P_{ref}	5°
0.6	6.8	T_T and P_T with P_{ref}	+	P_s with P_{ref}	5°
0.7	6.8			P_s with P_{ref}	5°

⁺ 2.79D to 1.41D in steps of 0.082D, 1.60D to 0.84D in steps of 0.04D, 0.84D to 0.07D in steps of 0.048D, -2.49D to 0.05D in steps of 0.157D and -4.01D to -2.2D in steps of 0.123D

Table 3.6. Matrix of Completed 2002 Series Phase 1 and 2 Tests

Ма	Re×10 ⁵	Phase 3 Completed	Phase 4 Completed
0.4	6.8	130°	
0.5	6.8	120° and 125°	Yes
0.6	6.8	105°	
0.7	6.8	100°	

Table 3.7. Matrix of Completed 2002 Series Phase 3 and 4 Tests



Figure 3.23. Scale Drawing of Probe Position Relative to the Cylinder

4. Data Processing

4.1. Raw Pressure Signals

All pressure data recorded from the Kulite and Entran pressure transducers during both series of tests were processed in the same manner:

- Gains and offsets were removed where they had been applied during data acquisition
- Zero offsets recorded during data acquisition were added to the signals
- The calibration factors, in PSIA/V/V, were applied to the data
- Reference pressures were added
- Units were converted into Pa.

All of the above were done as part of four Matlab scripts, one each for the 2000 series wake results, 2000 series surface pressure results, 2002 series wake results and 2002 series surface pressure results. Each Matlab script was fully automated requiring no user input once running and would process all the data in the set of results it was written for.

Once this had been done to the data it could be normalised (sections 6.1 and 6.2) and phase lock averaged (section 4.6).

4.2. Raw Total Temperature Signals

In order to calculate the flow total temperature from the measurements made with the thin film total temperature probe a significant amount of data processing had to be applied. While the general theory of the probe's operation was described earlier in section 3.3.1 what follows is a step-by-step description of how the data was processed. The processes used for the 2000 series and 2002 series data were largely similar there were some minor differences and these will be highlighted as and when required.

4.2.1. Low Speed Data

The first step in converting the voltage outputs from the total temperature probe and its heat transfer analogue circuit into total temperature is to deal with the measurements of voltage drop across the thin film recorded directly by the data acquisition system. These signals are processed into film temperature and, from that, into low frequency heat transfer signals.

The method used for converting the voltage output into film temperature is the biggest difference between the processing methods used for 2000 series and 2002 series data. First consider the 2000 series data.

The 2000 series data was recorded at 1kHz with a 400Hz analogue anti-aliasing filter applied to the signal prior to acquisition. As such the data could be processed into film temperature without further preparation.

Firstly to find the voltage drop across the gauge from the recorded voltage, the zero measurements of the voltages and the gain, the following was used:

$$V_{g1} = \left(\frac{V_{s1} - V_{s0}}{G}\right) + V_{g0}$$
(4.1)

From the film voltage the film resistance may be calculated. The zero reading for the current was used because the thin film gauge power supply provides a constant current.

$$R_{g1} = \frac{V_{g1}}{I_{g0}}$$
(4.2)

83

And then finally the film temperature may be calculated:

$$T_{g1} = \left(\frac{R_{g1} - R_{g0}}{dR/dT}\right) + T_{g0}$$
(4.3)

Now that the 2000 series data has been dealt with 2002 series data needs consideration. The 2002 series low speed data were recorded at the same sample rate as the high-speed data, 204.8kHz. An example of a film voltage trace is given in figure 4.1. Since it is advised that the sample rate for the low speed data is kept below 1kHz [63], in order for the conversion into heat flux to work the 2002 series low speed data needed resampling.

When resampling the data, in order that the Nyquist criterion was met the signals had to be digitally low pass filtered at half of the resampling frequency. Due to the limitations of digital filter's frequency response one could not be designed that would low pass the data collected at the original sampling rate of 204.8kHz at 500Hz, the maximum anti-aliasing frequency for data recorded at, or resampled to, 1kHz. So the resampling had to be done in two stages. These were from 204.8kHz to 6.4kHz with anti-aliasing at 1.6kHz and then down to 1.28kHz with anti-aliasing at 500Hz. A final sampling rate of 1.28kHz was chosen over the recommended 1kHz because it was the closest to 1kHz that could be reached in two steps.

With the 2002 series data resampled it could then be converted into film temperature. This was a simpler conversion than for the 2000 series data because the gains and offsets were not applied to the data prior to sampling but during it by altering the sensitivity of the data acquisition cards. Since the film's voltage drop was directly recorded all that was needed was to find the change in resistance of the probe, to apply the calibration factor and to add on the film temperature zero-reading i.e.:

$$V_{s1} = V_{g1}$$

$$T_{g1} = \left(\frac{V_{s1}}{I_{s1}} - R_{g0}\right) \frac{1}{dR/dT} + T_{g0}$$
(4.5)

The film temperature calculated from the film voltage drop trace in figure 4.1 is presented in figure 4.2.

Once the thin film temperature has been found for both the heated and unheated films the next step is to calculate the low frequency heat flux going through the gauge. For both 2000 series and 2002 series data the temperature to heat flux conversion was done by applying the Odot.m Matlab function, written by David Buttsworth of Oxford University, to the time histories. Odot.m used a one-dimensional finite difference method to perform the conversion and corrected for errors caused by surface curvature, a description of which is given in Buttsworth [62]. After *Qdot.m* had been applied to the data to create heat transfer fluxes the data needed correcting for lateral conduction. This correction was applied using another Matlab function, *Postqd.m*, again written by David Buttsworth. It is at this stage that the total temperature data is effectively zeroed. Since it is the lateral conduction that will affect the reading, taking it away from the actual total temperature, the correction is found by taking a reading in the free stream and iteratively applying this correction until the final processed total temperature is equal to the free stream total temperature in the facility. For both series of tests the bottom most point of the traverse was taken to be in the free stream and so was used for this purpose. The heat flux time histories calculated from the temperature time histories in figure 4.2 are given in figure 4.3

Minor modifications were made to *Qdot.m* to remove the user inputs required to tell the script where to start the calculations and what sort of calculations to perform. This was done because of the very large amount of data that needed processing, all requiring the same calculations to be carried out from at the same starting point.

With the low speed data from both the heated and unheated thin film gauges converted into film temperature and low frequency heat flux the high-speed data needed attention.

4.2.2. High Speed Data

As described in section 3.3.1 the high speed heat flux signals, recorded from the output of the heat transfer analogue boxes, were directly proportional to the high frequency heat flux through the thin film gauges. As such little needed doing to the signal.

The first step in processing the data was to change the sign convention so that it matched that of the output from the finite difference method routine applied to the low speed data. Also at this point any gain applied to the signal may be removed. An example of a high-speed heat flux signal before gains are removed and the sign convention reversed is given in figure 4.4.

With this done the data needed to be high pass filtered to remove the low frequency data. This was done using a sixth order Chebyshev type 2 high pass filter with the cut off set to 400Hz designed in Matlab using the *cheby2* function and implemented using the *filtfilt* function. The *filtfilt* function was used because it does not affect the phase of the signals it is applied to.

Now all that needs doing to convert the signal from a voltage to heat transfer is to apply equation 3.3. An example of a fully processed high speed heat flux signal is given in figure 4.5.

With High and low speed data processed the next step is to add the low frequency and high frequency data together and then, finally, to calculate the total temperature.

4.2.3. Calculation of Total Temperature

The first step in adding the low and high frequency heat fluxes and film temperatures together was to interpolate the low frequency data up to the high frequency sampling rate. This was done in Matlab through the use of the *interp1* function, i.e.

```
%Interpolate low speed data onto high speed time line
qhts=interpl(tims,qhtlc,timf);
```

With the interpolation done the low and high speed heat fluxes were added together in Matlab to create a heat flux signal including all of the frequency components that should be present, i.e.

```
qhtt=qhts+qhtf;
qcdt=qcds+qcdf;
```

Once this was done the total temperature was calculated by the simultaneous solving of equation 3.2. for both probes, i.e.

```
To(:,i)=((qhtt.*tcds)-(qcdt.*thts))./(qhtt-qcdt);
```

An example of a fully processed total temperature trace is given in figure 4.6.



Figure 4.1. Voltage Drop Across Heated Thin film Gauge at 1.85D Above Wake Centre Line



Figure 4.2. Heated Film Gauge Temperature at 1.85D Above Wake Centre Line



Figure 4.3. Low Frequency Heat Flux Through Thin Film Gauges at 1.85D Above Wake Centre Line



Figure 4.4. Heated Transfer Analogue Output at 1.85D Above Wake Centre Line



Figure 4.5. High Speed Heat Flux Signal Taken at 1.85D Above Wake Centre Line



Figure 4.6. Fully Processed Total Temperature Trace at 1.85D Above Wake Centre Line

4.3. Boundary Layer Data

The pressure data from the flattened Pitot tube and static pressure tapping were converted into a velocity ratio using equation 4.5:

$$\sqrt{\frac{P_{TBL} - p}{P_{T1} - p_1}} = \frac{u}{U}$$
(4.5)

This assumed that the flow was incompressible so the density was constant through the boundary layer. While this was not the case, readings were taken at a low enough Mach number for the level of compressibility to be considered small enough to ignore.

Normally the boundary layer, displacement and momentum thicknesses would be calculated directly from equations 4.6, 4.7 and 4.8.

$$\delta = (h)_{u=0.99U} \tag{4.6}$$

$$\delta^* = \int_0^{\delta} \left(1 - \frac{u}{U}\right) dh \tag{4.7}$$

$$\theta = \int_{0}^{u} \frac{u}{U} \left(1 - \frac{u}{U} \right) dh$$
(4.8)

However due to mistakes made when choosing the angle at which to measure the boundary layer profile it was not entirely captured. To overcome this, polynomial curve fits were applied to the latter half of the Mach 0.5, 0.6 and 0.7 boundary layer data and extrapolated up to u/U=1. This was done in Matlab:

%BL05_120(:,1) is pitot tube height and BL05_120(:,2) is u/U
P=polyfit(BL05_120(15:end,2),BL05_120(15:end,1),6);
y=polyval(P,[BL05_120(15):0.04:1]);

The behaviour of the Mach 0.4 data meant that this method could not be applied to it.

Note that the boundary layer profiles produced in this manner were approximate, as they did not become asymptotic as u/U approached 1. However, given the amount of work required to
apply a power law to the curve fit to make it asymptotic compared to the small reduction in error produced it was not deemed worthwhile.

The order of the polynomial fit depended on the best fit attainable for each set of data, see table 4.1. An example of the different fits for one set of data is given in figure 4.7.

From the extrapolated profiles approximations of the boundary layer thicknesses could be made. Due to the uncertainty in the data collected it was decided not to spend the time to apply corrections for wall proximity and shear flow to the Pitot tube data.

Approximations of the boundary layer thicknesses were found by finding where u/U became equal to one. Approximations for the displacement and momentum thicknesses were found by applying equations 4.7 and 4.8 to the extrapolated data using the trapezium method of numerical integration, i.e.:

$$Y = \sum_{n=0}^{h=\delta} \left(\frac{X^{n+1} + X^n}{2} \right) \left(h^{n+1} - h^n \right)$$
(4.9)

Where Y is either δ^* or θ and X is either 1-(u/U) in the former case or u/U(1-u/U) in the latter. When implemented in Matlab this becomes:

```
$u=1-(u/U); u2=(u/U)(1-u/U);
deltastar=sum(((u(2:end)+u(1:end-1))/2)*(h(2:end)-h(1:end)));
theta=sum(((u2(2:end)+u2(1:end-1))/2)*(h(2:end)-h(1:end)));
```

And from this the shape factor can then be calculated, equation 4.10:

$$H = \frac{\delta^*}{\theta} \tag{4.10}$$

Mach number	Azimuth	Order
0.5	120°	5 th
0.5	125°	4 th
0.6	105°	5 th
0.7	100°	7 th

Table 1 1	Order of Curve	Fits applied to	Different Data	Sate
1 auto 4.1.	Order of Curve	This applied to	Different Data	2012



Figure 4.7. Comparison of Curve Fits to Boundary Layer Data Taken at Mach 0.5 at an Azimuth of 120°

4.4. Interpreting Oil Flow Visualisation

Figure 1 shows the oil flow visualisation on the circular cylinder at Mach 0.5. A number of flow features are shown in this. However their position is not readily notable and must be calculated using the Pitot probe at a reference.

It is known that the tip of the Pitot probe was located at 105° . If *a* is the uppermost edge of the cylinder in the photograph and *x* is the distance from the that location, on the photograph, to the tip of the Pitot probe then the azimuth of the uppermost point is:

$$\theta_1 = 105 - 90 + \arcsin\left(\frac{2x - D}{D}\right) \tag{4.11}$$

From this the azimuth of any given point a distance y from the uppermost position of the cylinder in the photograph may be calculated from equations 4.12 and 4.13:

If 2y < D

$$\theta_2 = \arcsin\left(\frac{D-2y}{D}\right)$$
(4.12)

Else if 2y > D

$$\theta_2 = \arcsin\left(\frac{2y - D}{D}\right) \tag{4.13}$$

And so, using equations 4.12 and 4.13 the location of the flow features may be calculated (section 6.4).



Figure 4.8. Oil Flow Visualisation at Mach 0.5

4.5 Dealing with Jitter

The word "jitter" is being used to denote the difference in arrival time between flow events caused by a nearly periodic flow feature. It has a notable affect on time resolved vortex shedding measurements. The difference in arrival time between the vortices affectively means that each vortex shedding cycle is a slightly different length to it neighbours. This creates a problem when ensemble averaging the data. Ideally ensemble averaging requires that the records of the signal used to perform the averaging all have the same length and are an integer number of shedding cycles long. These two criteria result in each ensemble containing the same amount of information and being of the same length. If, however, there is jitter present in the signal then only one of the criteria can be met at any one time. Since each record must be the same length then some flexibility in the number of cycles per record must be allowed for.

Flexibility in the number of cycles per record was implemented by making the record length equal to an integer number of mean shedding cycles. Any record in which the shedding cycles had a mean length different to the overall mean had the last cycle either truncated or extended by zero padding. While this does allow for some flexibility even this will not work if the level of jitter is too great. Recent work by Sieverding et al. [46] indicates that if the frequency of the data within each record varies by more than 10% from the mean frequency, then the integrity of the ensemble averaged waveform starts to breakdown. To overcome this problem Sieverding et al. [46] performed a frequency analysis on each record and rejected any that fell outside of 10% of the mean shedding frequency. Rather than resort to this method a simple analysis of the data collected during the 2000 series and 2002 series test programmes was carried out to investigate the level of jitter. Due to the 2000 series and 2002 series data being recorded at different frequencies the jitter content of the two sets of data will be handled separately.

4.5.1 Jitter in the 2000 Series Data

The levels of jitter of each of the 2000 series data sets, wake total pressure, total temperature, reference pressure taken from the cylinder surface, cylinder surface pressure and reference signal taken in the wake, were found using the same method. This simply involved taking each signal, using zero-crossing to find the start of each shedding cycle and then using that to

find the length of each cycle. From this the mean shedding cycle length could be simply calculated and histograms drawn. With the length of each cycle known, finding how many of them fell within 10% and 20% ranges about the mean was trivial.

Figure 4.9 contains histograms of shedding cycle length for each of the data sets. The black vertical lines overlaying the histograms show the 20% range about the mean. Table 1 gives a summary of the percentage of shedding cycles that fall within the 10% and 20% ranges.

Figures 4.9 and table 4.2 indicate that the vast majority of the data falls well within a 10% range of the mean shedding frequencies. The only set that does not, the reference pressure recorded in the wake, falls well within the 20% range. Thus the amount of data falling outside of the limit indicated by Sieverding et al.⁴⁶ is insignificant and may be ignored. So the 2000 series results are suitable for phase lock averaging.

4.5.2 Jitter in the 2002 Series Data

The 2002 series data were treated in the same manner as the 2000 series data. Histograms of the 2002 series data are given in Figure 4.10 while the summary of the percentage of shedding cycles that fall within the 10% and 20% ranges is given in Table 4.3. As with the 2000 series data the black lines overlaying the histograms indicate the 20% range about the mean. Note that the proportion of 2002 data falling into each of the bins representing vortex shedding period lengths is roughly half that of the 2000 series data. This is due to the sampling frequency of the 2002 series data being 2.048 times that used for the 2000 series data and so the vortex shedding period bins for the former set of data will be 0.4883 times smaller than the latter and will contain proportionally less data.

As can be seen from the tables there is significantly more jitter found on the surface pressure signals of the 2002 series data than on those from the 2000 series of tests. This is probably due to the difference in the boundary layer states between the two series as discussed in section 6.1. However, despite the increase in jitter in the 2002 series results, only a tiny proportion of the cycles fall outside of 10% from the mean shedding frequency. This means that, as with the 2000 series data the 2002 series results are suitable for phase lock averaging.

Data Type	Proportion of Cycles With a	Proportion of Cycles With a	
	Length Within a 10% (±5%)	Length Within a 20%	
	range of the mean cycle	$(\pm 10\%)$ range of the mean	
	length	cycle length	
Wake Total Pressure	93.52%	98.04%	
Wake Total Temperature	96.12%	98.71%	
Reference Pressure from	98.30%	99.76%	
Cylinder Surface			
Cylinder Surface Pressure	98.30%	99.84%	
Reference Pressure from	86.41%	95.52%	
Wake			

Table 4.2. Summary of Percentage of Shedding Cycle Lengths

that Fall Within the 10% and 20% Ranges About the Mean. 2000 Series Results

Data Type	Proportion of Cycles With a	a Proportion of Cycles With a	
	Length Within a 10% (±5%)	Length Within a 20%	
	range of the mean cycle	$(\pm 10\%)$ range of the mean	
	length	cycle length	
Wake Total Pressure	92.11%	97.61%	
Wake Total Temperature	91.74%	96.70%	
Reference Pressure Taken on	92.11%	97.61%	
Cylinder Surface For Wake			
Data			
Cylinder Surface Pressure,	71.34%	93.54%	
Entran B			
Reference Pressure Taken on	86.14%	94.96%	
Cylinder Surface For			
Cylinder Surface Data			

Table 4.3. Summary of Percentage of Shedding Cycle Lengthsthat Fall Within the 10% and 20% Ranges About the Mean. 2002 Series



Figure 4.9. Histograms of Vortex Period, 2000 Series Dataa) Total Pressure, b) Total Temperature, c) Phase Reference from Cylinder Surfaced) Cylinder Surface Pressure, e) Phase Reference from Wake Total Pressure



a) Total Pressure, b) Total Temperature, c) Phase Reference for Wake Datad) Cylinder Surface Pressure, e) Phase Reference for Surface Pressure Data

4.6. Phase Lock Averaging

4.6.1. Why it was Needed.

The data collected during the course of the experiments all contained noise, specifically as a result of the very high sampling frequencies used, it contained a large proportion of high frequency noise. Also the strength of the vortices shed from the cylinders in cross flow was not constant and the shedding frequency contained some jitter. This resulted in noisy data containing fluctuations of varying amplitude with a slightly varying fundamental frequency. From this it was required to extract clean data with an amplitude equal to the average amplitude caused by vortex shedding and a shedding frequency equal to the mean frequency.

The usual method for removing noise from periodic data is ensemble averaging. However, in its basic form ensembles averaging only works if all of the signals from the various data points spread out in space are recorded simultaneously. If however the signals from the data points are recorded at different times the phase relationship between the various signals, unlike when they are all recorded simultaneously, will be unknown. To overcome this ensemble averaging must be combined with another tool that allows for the phase relationships between the data signals to be found. The name given to such a tool is 'phase locking'.

Phase locking overcomes the problem of the data signal's phase relationships being unknown by introducing a common phase reference signal, taken from a transducer that is fixed in space, that is recorded simultaneously with each data signal. The technique was first developed and applied to fluid flows in turbomachinery by Gostelow [16]. For convenience each set of phase reference and data signals will henceforth be referred to as a reference-data set. Because the reference signals are all recorded in the same location there is zero phase difference between them. Phase locking is then done by phase shifting the phase reference signals so that there is a zero phase difference between them. The data signals that are recorded alongside the phase reference signals are also shifted by the same amount. In doing this phase relationships of the data signals are then arranged properly in time. The term phase locking is used because the phase difference between a phase reference signal and the data signals recorded with it is synchronised, or locked, so that any phase shift applied to the former is also applied to the latter. It is clear that phase locking represents a very useful tool for dealing with measurements of unsteady flow features when the data collected from different points in space are recorded at different times. There are, however, some prerequisites that must be met for phase locking to work:

- The unsteady flow feature must be periodic and contain minimal jitter,
- The unsteady flow feature has a distinct fundamental frequency,
- The phase reference signals are taken from measurements of the same flow feature as the data,
- The phase reference signal for all of the reference-data sets are taken from the same location.

With the above criteria met the implementation of the phase locking process with digitally recorded data must be considered. There are two methods for this. The first method involves going through each of the phase reference signals one at a time and looking for a start point for each cycle, picking one to be the start of the signal and deleting all earlier data from the both it and the data signals recorded with it. In this way the phase difference between the reference signals disappears while the phase difference between the reference and data signals is not affected. Once this has been done to all of the reference-data sets the data signals will be positioned in time with the correct phase relationships between them. While this numeric method is the simplest there is a more elegant analytical method that can be used.

The analytical method involves using cross-covariance to find the phase difference between the reference signals from the various reference-data sets and between the reference and data signals in each set [54, 55]. This phase information can then be used to shift the reference signals in time so that they all have the same phase. With this done the reference-data phase differences can be used to shift each of the data signals, phase locking them, so they have the correct phase relative to both reference signals and the other data signals.

These two methods both have advantages and disadvantages. The numeric method is very robust and will work on any reference-data set, even if the data signals from some points in the flow do not contain the fundamental frequency of the flow feature. However it doesn't calculate the exact phase difference between the signals nor, in its basic form, does it find the frequency components of the signals. While this is important information, especially when ensemble averaging the data, the frequency components and phase of the signals can be calculated separately.

In contrast the analytical method requires all data signals to have a strong fundamental frequency component so that the phase differences can be found. The analytical method also increases the number of individual steps required to apply the phase lock to the data, increasing the CPU time required for it to be implemented. An advantage of this method is that as well as performing the phase locking it also calculates the phase differences and frequency components of the signals.

While the analytical method's calculation of the signal's frequency components would be useful in the ensemble averaging of the data, the method could not be used. This is due to the method's reliance on the data signals having a strong fundamental frequency component. The problem stems from the flow at the centre of a vortex street and at the trailing edge of a body shedding a vortex street. The flow in these regions lacks the fundamental vortex shedding frequency and instead has a strong first harmonic. The disappearance of the fundamental shedding frequency is due to the flow in these regions being affected equally by vortices shed into both sides of the vortex street; vortices are seen at twice the fundamental frequency. As a result of this it was necessary to use the more robust numeric method and to calculate the frequencies separately.

4.6.2. What is Ensemble Averaging?

Normally, if the signals with have no jitter, then ensemble averaging requires that the fundamental frequency of each one be found. Then, taking each signal in turn, an arbitrary start point is chosen and then either consecutive or overlapping records of signal, each an integer multiple of the wavelength long, are copied to form an ensemble. The ensemble is then averaged across the records so giving the average signal waveform. This is complicated somewhat if there is a small amount of jitter in the signal.

In the case that the signal contains jitter the start of each cycle of the fundamental frequency must be found and from these the start of each record be chosen. For example if consecutive records were being used and there were to be four cycles in each record then each would begin at the start of every fifth cycle. Next the length of the records would have to chosen. That would be done by finding the mean fundamental frequency and from that the mean wavelength found. That would then be used to decide upon the length of each record since if the records were just made from a given number of cycles each record would be a different length. Finally the ensemble would have to be constructed by taking copies of the records of data signal. The averaging of the ensemble would then be carried out as before, producing the average signal waveform with the average fundamental frequency.

4.6.3. Phase Locking Averaging

Performing phase lock averaging on signals from a given reference-data set involves finding the start points for each of the cycles in the phase reference signal and then using them to give the start points for the records from the data signals. From there ensemble averaging is except that the length of the records is found using the average shedding frequency taken from the reference signal. This is done to ensure that all of the phase lock averaged data signals have the same length.

4.6.4. How Phase Lock Averaging was Applied

The first step in performing phase lock averaging on the results was to find the start points for all of the cycles of each of the phase reference signals. Due to the amount of data that was to be handled in this step, along with all of the other steps involved in the phase lock averaging, the routine was automated using Matlab. A portion of a phase reference signal is shown in figure 4.11a. Upon inspection of this it became clear that, without further processing, there were no clear starting points in the cycles.

The solution to this was to apply a bandpass filter to the data allowing only the fundamental shedding frequency through. By inspection of the data, using Matlab's power spectral density function, *psd*, it was found that the mean shedding frequency was around 945Hz at a Mach number of 0.6. From this the cut offs of the bandpass filter for Mach 0.6 flow were chosen at 920Hz and 960Hz. The filter used was a second order elliptical digital filter designed and implemented in Matlab with ripples of 0.1 and 35, i.e.:

```
%Create the filter
%fn=sampling frequeny
[Bf,Af]=ellip(2,0.1,35,[(920/0.5*fn) (960/0.5*fn)],'bandpass');
%Apply the filter to the phase reference signal (Phase_ref)
Phase_ref=filtfilt(Bf,Af,Phase_ref);
```

The same filter was used for the results from both the 2000 series and 2002 series tests and for data signals from both the wake and cylinder surface. For other Mach numbers appropriate limits were found using the same method as for Mach 0.6.

By using the Matlab function *filtfilt* to apply the filter to the phase reference signal the filtering could be performed without affecting the signal's phase. It should be noted however that this is not necessary and the *filter* function could have been used. This is because the same filter would have been applied to every reference signal so phase shifting each one by the same amount. That would mean that, although the phase difference between the phase reference and data signals would change the change would be the same for each reference-data signal set. However, since the difference in CPU time required for *filtfilt* and *filter* to do the filtering is very small it was felt that it would be worthwhile using the former function thus retaining the original phase differences.

The portion of reference signal used in figure 4.11a is shown after filtering in figure 4.11b. From that it is clear that the start point of each cycle could be found using a simple negative to positive zero-crossing routine. This routine worked by taking each phase reference signal in turn as a column vector n points long and then create a 2 by n-1 matrix from it. The first column in the matrix would be made from a copy of the reference signal going from first point to the second from last one. The second column would be a copy of the reference signal going from the second point to the last point. The routine then found all the points in the matrix where the value in the first column was less than zero and the value in the second was greater than zero, hence locating where the signal went from negative to positive, the zerocrossing, i.e.

```
% Create copies of Phase_ref in 2 by n-1 matrix
Phase_ref_2=[Phase_ref(1:end-1), Phase_ref(2:end)];
% Find the zero crossings
zero_crossings =find(([phase_ref_2(:,1)<=0)& ([phase_ref_2(:,2)>0));
```

Zero-crossing was chosen as the cycle start points rather than cycle maxima and minima for convenience. A zero-crossing is very easy to define, all that is needed is two consecutive data points one less than zero and one greater than zero. When using maxima and minima a turning point must be defined. To do so you must, in the case of maxima, look for a data point where both of its neighbours have a lower value than it. The code required to define a turning point would have to produce a 3 by n-2 matrix from the reference signal. The first column of the 3 by n-2 matrix would copy the phase reference signal from the first to the third from last data point, the second from the second until the second from last data point and the third from the third until the last data point. The routine would then have to look for rows where the data point in the second column was greater than that in the first and third. This

would increase the amount of CPU time needed by over 50%. The phase lock averaging routine was quite lengthy with zero-crossing used, taking an hour when using the 2000 series data. Using turning points to define the cycle start points, which would take longer, would not have been desirable. It also would not have given any advantage as both methods find the start point of the cycle to within one sample period.

With the beginning of each shedding cycle on the reference signal found, finding the beginning for each record of data signal was simply a case of taking every m+1 cycle starts where *m* is the number of cycles per signal record, i.e.

```
% Index for Record_starts
a=1;
% A for loop going from 1 to the end of zero_crossings adding m to the step
% index every loop so finding every m+1 shedding cycle start point
for i=1:m:length(zero_crossings);
        % Get the record starts
        Record_starts(a)=zero_crossings(i);
        a=a+1;
end
```

With the start of each record found the record length had to be calculated. To find the mean shedding frequency for each reference signal the Matlab *psd* function was used to find the signal's frequency components. The mean shedding frequency could then be found by looking for the strongest peak in the frequency range of 920Hz to 960Hz. This range was chosen as the limits are the cut off that were used for the band pass filtering. i.e.

```
%Perform the psd
```

[Pxx,F]=psd(Phase_ref,length(Phase_ref),fn,2^14,2^12); %Finding limits for the shedding peak search f=find((F>919)&(F<921)); f=f(1); % lower limit g=find((F>959)&(F<961)); g=g(1); % upper limit %Find the cycle length in sample points Cycle_length=round(fn*(1/(F(find(Pxx==max(Pxx(f:g))))))); %Find the length of the records Record_length=Cycle_length*m;

As with the band pass filtering the limits for the fundamental frequency search were changed appropriately for other Mach numbers.

An example of the filtered reference signal shown alongside the total pressure signal, that along with the total temperature signal make up the reference-data set, is shown in figure 4.12. This reference-data set was taken at 91.95mm or 2.47*D* above the wake centre line. Marked out on both signals are the beginnings of each phase reference shedding cycle, red dots, and the start of each record, green circles. It should be noted that the red dots appear at about the same point in each of the data signal cycles so that, while they do not correspond to the zero crossing of each data signal cycle, they do represent a start point for them.

With the start point and length of the records found the next step was to create the ensemble. This was done, as described above, by making copies of records of the data, m mean cycles long, each starting at the predefined record start points. The phase lock average was then found by averaging across the ensemble. i.e.:

```
% Make a for loop from 1 to the number of records to be used in the
ensemble
for i=1:No_records
    %The ensemble = Data signal(record start to record start + record
    %length)
    Data_Ensemble(:,i)=Data_sig(Record_start(i):Record_start(i)...
    +Record_length);
end
% Average across the ensemble matrix to find the ensemble average
Ensemble average=mean(Data Ensemble,2);
```

An example of a record of a raw data signal next to the phase lock average of that signal is given in figure 4.13. The phase lock averaging is taken over 64 records of four cycles each. It clearly shows the affect of the phase lock averaging routine in clearing the data of random noise and in finding the average shape, size and length of the waveform.

While this method worked well with the cylinder surface pressure data it served to highlight a problem with the wake data caused by the method of operation of the wind tunnel when these data were taken. Figure 4.14 shows a comparison of the time averaged total pressure history compared to the time average of the phase lock averaged wake total pressure. It is quite apparent that the two sets of time averaged wake data disagree.

An investigation of the data revealed that the problem was low frequency noise, presumably created by movement of the wind tunnel control valve while it settled down during the 'air on' periods of the intermittent blowdown mode of the wind tunnel. This noise, because it fluctuates about the mean total pressure, cancels itself out when the data is averaged over the 106

whole of the time history. However, when the phase lock averaging does not use the whole of the time history the noise does not cancel as the data is non-ergodic [16].

To overcome the low frequency noise problem the data signals were filtered prior to phase lock averaging. The filter used for the 2000 series data was a seventh order Butterworth bandpass filter with cut offs at 400Hz and 20000Hz while the 2002 series data used a fifth order Butterworth filter with the same cut offs as the 2000 filter. The difference in order is due to the higher sampling rate for the 2002 series tests resulting in a seventh order filter not working. The cut offs were chosen so that all of the low frequency components would be removed along with some high frequency noise leaving just the shedding frequency and the related harmonics. A bandpass filter was chosen over a highpass filter so that some of the high frequency noise could be removed so increasing the effectiveness of the phase lock averaging.

Figure 4.15 is a comparison of the total pressure signal before and after bandpass filtering of the data signals. It shows that a significant amount of high frequency noise has been removed from the signal. However, the time history shown is too short to display the removal of the low frequency noise.

A comparison of the phase lock averaged total pressure data processed with and without bandpass filtering is shown in figure 4.16. The pre-filtered phase lock averaged data, figure 4.16b, is much smoother than the phase lock averaged data that was not pre-filtered. Also the waveforms in the pre-phase lock averaging filtered data are of a more uniform shape and size. Once the data signals have been phase lock averaged in this way the time averaged values can be superimposed recreating the waveforms. This method was also applied to the wake total temperature data.

As a final check on the pre-filtered phase lock averaged data another comparison of the time averaged phase lock averaged data with the time averaged time history was made, Figure 4.17. This time the two wake total pressure profiles agree very well indicating that the phase lock averaging with pre-filtering incorporated into it provides a true representation of the average waveforms.

Using the method described here all of the wake and cylinder surface pressure data were processed, although the latter did not require pre-filtering. The number of cycles used to form the records, how many records were used and if overlapping of records are to be employed

now requires some discussion. That is because different numbers of records were used for the 2000 data, the 2002 data, the cylinder surface data and the wake data. The following describes the selection of the number of records used, the length of the records and the use of overlapping records.

4.6.5. Selection of Record Lengths and Number of Records

The data displayed in figures 4.18 through to 4.23 have had the phase lock averaging routine applied using various numbers of records. The 2000 series wake data shown, figures 4.18 and 4.19, were taken at 50.54mm (1.36*D*) above the wake centre line while the 2002 series wake data, figure 4.11 and 5.12, was taken at 51.82mm (1.39*D*). Both the 2000 series and 2002 series cylinder surface pressure signals were taken at around 110° from the leading edge of the cylinder. The number of records used for the phase lock averaging was chosen so that any improvement in the signal would be readily detectable. 160 records were taken as the upper limit because, with the wake data, there was a maximum of 162 consecutive sets of 4 cycles. The 2000 series cylinder surface data could have been averaged over up to 486 records as those data were recorded for 2 seconds. The 2002 series cylinder surface pressure data were limited to 243 as only one second of data was taken.

From the 2000 series wake total pressure data in figure 4.18 it is clear that neither 16 nor 32 records were sufficient to remove the random noise from the signal and 64 cycles doesn't quite converge with the mean signal waveform. However, more than 96 records resulted in little improvement in the waveform and so 96 were taken as the number of records to use when performing the phase lock average.

The 2000 series wake total temperature signal, figure 4.19, shows a marked and steady improvement in the averaged waveform up until 128 records, after which there is no significant change. 128 records was therefore chosen as the most sensible number to use for these data.

The gradual improvement of the total temperature waveform as the number of records was increased may be explained by the presence of high amplitude noise at 2kHz corrupting the raw total temperature records in the 2000 series data. This noise, which appeared in unpredictable bursts, was not discovered until the data had been processed. The source of the noise was found to be the motor used to drive the compressors that filled the pressure vessels supplying the facility's shop air. This motor would switch on whenever the pressure dropped

below a preset threshold. Fortunately, despite frequency of the noise being close to that of the vortex shedding first harmonic phase lock averaging removed it.

It should also be noted that the total temperature signals also contained occasional very high amplitude spikes of undetermined origin. These had to be removed before the phase lock averaging routine could be applied to the data, as, due to their high amplitude, they survived the signal conditioning process. Since the spikes were of very short duration, only one or two samples wide, they could be easily removed by clipping the data. The thresholds for clipping were set at 250K and 350K. Any data outside of these thresholds were set to 290K. By clipping the data in this way the spikes are reduced to a level that did not affect the average waveform.

The 2000 series cylinder surface pressure signal, figure 4.20, displays a very rapid convergence to the mean waveform so that 64 records were sufficient. The significant difference in amplitude between the phase lock averaged data and the raw data is due to the amplitude of the raw signal varying greatly during the signal's time history. Had a different record of raw data been chosen it could well have had significantly smaller amplitude than the phase lock averaged data.

The 2002 series total pressure data behaves very similarly to the 2000 series results when phase lock averaged and so 96 records were again used. However, due to the absence of spikes in the raw data the 2002 series total temperature signals, the source having been removed, they behave differently to those taken during the 2000 series, converging rapidly as the number of records used for phase lock averaging was increased. Thus only 64 records were required to create a good phase lock average.

The 2002 cylinder surface pressure signal has a similar response to phase lock averaging as the 2000 data. It rapidly converges so that only 64 records are required to find the mean waveform. Using more than 64 records provides no improvement in the mean waveform. The number of records used for the phase lock averaging routines for the various data sets is summarised in table 4.4.

Since none of the data requires more than 160 records no overlapping was required. The data could have been processed with overlapping records, so producing more uniform waveforms. However this was not done because as errors occurring one phase lock averaged cycle would corrupt other cycles.

Data Set	Number of Records
2000:	
- Wake Total Pressure	96
-Wake Total Temperature	128
-Cylinder Surface Pressure	64
2002:	
-Wake Total Pressure	96
-Wake Total Temperature	64
-Cylinder Surface Pressure	64

Table 4.4. Summary of the Number of Records Used for



Phase Lock Averaging





Figure 4.12. A Reference-Data Set,

a) Filtered Phase Reference signal, b) Total Pressure Signal. Red dots are starting points of cycle, Green 'o' are starting points of records



Figure 4.13. Total Pressure Signal a) Prior to Phase Lock Averaging, b) After Phase Lock Averaging







Figure 4.15. Total Pressure Signal a) No Filtering applied, b) Bandpass Filtering applied



Figure 4.16. Phase Lock Averaged Wake Total Pressure, a) Signal Not Pre-Filtered, b) Signal Pre-Filtered



Figure 4.17. Time Averaged Wake Total Pressure



Figure 4.18. 2000 Series Phase Lock Averaged Wake Total Pressure



Figure 4.19. 2000 Series Phase Lock Averaged Wake Total Temperature



Figure 4.20. 2000 Series Phase Lock Averaged Cylinder Surface Pressure



Figure 4.21. 2002 Series Phase Lock Averaged Wake Total Pressure



Figure 4.22. 2002 Series Phase Lock Averaged Wake Total Temperature



Figure 4.23. 2002 Series Phase Lock Averaged Cylinder Surface Pressure

5. Handling Anomalous Data

There are a number of anomalies amongst the results from both the 2000 series and 2002 series tests. Namely, the 2000 series total pressure results below the traverse position of -2.42D, the time-averaged total temperature gradient found in both series of tests and the time-resolved 2002 series wake results.

Each of the above anomalies will be addressed before results are presented.

5.1. 2000 Series Wake Total Pressure Anomalies

Upon inspection of the 2000 wake total pressure data it became clear that there is distinct asymmetry in the time-averaged profile. Below around -2.42D from the wake centreline the time-averaged total pressure profile becomes jagged and fails to reach levels compatible with those achieved above the wake centreline, see figure 5.1.

The difference becomes more apparent when the sides of the wake total pressure profile are superimposed as in figure 5.2. It becomes clear that at distances beyond -2.42D (the black line) from the wake centre line the profile ceases to match that from above it. To elucidate the cause of the asymmetry between the two halves of the profile an inspection of the time resolved data was made, see figure 5.3.

The time resolved total pressure data from below wake centreline at the extremes of the traverse display a low frequency wavy nature while the high frequency content is suppressed, figure 5.3a. This shows up most clearly in the data from around -2.42D from the wake centreline. The data taken above the wake centreline at the same distance as the affected data below it display none of the low frequency waviness or high frequency suppression, figure 5.3b. The overall effect of the corruption can be seen in figure 5.4a. The corruption causes a step change in the size of the fluctuations at -2.42D.

From this it is clear that the data beyond -2.42D from the wake centreline was corrupted beyond repair. Aside from writing the corrupted data off the remaining option for clearing up the damaged data was to replace it with uncorrupted pressure signals from the other side of the wake, making sure that the time dependent component of the data from the other side was phase shifted by 180°. Since the wake behind a circular cylinder in cross flow should be symmetrical, allowing for the time dependent components on the two sides of the wake to be 180° out of phase from each other, this method for correcting the corrupted is considered to be reasonable.

Rather than do this with the raw data and then reapply the calibrations and phase lock averaging it was decided to first try the mirroring and phase shifting of data with copies of the time-averaged and phase lock averaged total pressure data.

The duplicating and phase shifting of the data was done in Matlab. It was done by simply creating a new matrix with the data from 2.42*D* above the wake centreline. The new matrix was then flipped along its y-axis and, in the case of the phase lock averaged data, shifted along the time axis by 54ms (half the vortex shedding cycle rounded to the nearest data point), the last 54ms of data being moved to the start of the signals. The array containing the y-locations of each the signals in the pressure matrix was also updated to contain the correct locations for the mirrored data. The data was then interpolated onto the original y-axis using the interp1 and interp2 commands for the time-averaged and phase lock averaged data respectively to allow for direct comparison with the total temperature data and the calculation of entropy production. The results of this can be seen in figures 5.4b and 5.5.

Clearly the wake results, after duplication of the uncorrupted data are symmetrical. The timeaveraged results show almost perfectly symmetry between the two sides of the wake while in the time-resolved data the areas of increased pressure are of equal size on each side of the wake and have a phase difference of 180°. The procedure essentially consists of 'patching' a corrupted area with an uncorrupted area. Within the limitations described above it is considered sound.



Figure 5.1. Time-Averaged Wake Total Pressure Ratio, Ma=0.6, Oct. 2000



Figure 5.2. Close Up of Damaged Data, Total Wake Ratio Oct. 2000



Figure 5.3. Comparison of Total Pressure Data From Above and Below the Wake a) Below the Wake Centre Line, b) Above the Wake Centre Line.



Figure 5.4. Comparison of Uncorrected and Corrected Phase Lock Averaged Wake Total Pressure Data a) Uncorrected, b) Corrected



Figure 5.5. Time Averaged Total Temperature Profile After Duplicating Uncorrupted Data

5.2. Time-Averaged Total Temperature Gradient

Figure 5.6 shows the time-averaged wake total temperature ratio data taken at Mach 0.6 in both the 2000 and 2002 series of tests. While it is clear that the results of the two sets are not identical they do bear a strong similarity. The differences between the two sets of data were not unexpected because:

- Two years elapsed between the two series of tests,
- The tests were conducted at different times of the year, resulting in different free stream conditions,
- Different data acquisition systems and sampling rates were used.

These would all be expected to affect the data taken resulting in slightly different results from the two tests. Furthermore the total temperature probe is only accurate to $\pm 3K$ (appendix D) and at no point in the traverse is there more than a 2K difference between the results of the two series of tests. Taking the above into account the two series of results are not inconsistent.

The similarities between the data sets are more interesting than the differences. Both series show a significant and rapid rise in total temperature across the lower side of the wake and the total temperature in neither set relaxes to the free stream value at the upper extent of the traverse (positive y/D). While the difference between the free stream total temperature and the total temperature measured at the upper edge of the traverse is only around 2K, and therefore within the level of accuracy of the probe, such a systematic discrepancy requires further investigation. If the differences in the readings at the ends of the traverse were due to the random errors within the accuracy of the probe then the two sets of results would be expected to show different discrepancies.

Unfortunately there is no obvious cause of the temperature gradient. There is nothing inherent to the facility that should cause such a phenomenon to occur. Also there were insufficient data to conduct an exhaustive investigation into the problem. The data available were taken over the course of the day at slightly different free stream temperatures across a temperature gradient imposed by the flow over the cylinder. In order for a worthwhile investigation to take place, traverses of the flow without the cylinder present would have to be taken not only at the traverse plane used in this project, but also at other locations in the working section. This would allow for any development of the gradient through the working section to be seen and to test whether it is the presence of the cylinder that causes the problem. As a result of this the data has not had any corrections applied to it and has been left to stand as it is.



Figure 5.6. Time Averaged 2000 Series and 2002 Series Wake Total Temperature

5.3. Time-Resolved 2002 Series Results

Figure 5.8 shows the 2002 series time-averaged wake total pressure, total temperature and entropy production profiles superimposed on the root mean squared levels of the time resolved raw and phase lock averaged data.

Upon inspection of the root mean square data the results in the region of 0D to 0.73D display a number of anomalous features:

- The root mean square raw total temperature data in this region rises in a linear fashion away from the wake centre line in a fashion contrary to that from the other side of the wake and the 2000 series results,
- The root mean square of the phase lock averaged total pressure in this region remains at an almost constant value from the wake centre line over a distance of about a cylinder diameter above it before returning to the level expected from the 2000 series results,
- Both of the above anomalies can be seen to be carried through into the entropy creation plot in figure 5.8c
- Overall the root mean square values for raw entropy fluctuations are around twice the level found in the 2000 series results.

Inspection of the raw and phase lock averaged data revealed that the anomalies in the total pressure and total temperature seem to have a common source. Given the commonality of the noise source only the investigation into the total pressure results will be given here. This is because it is significantly easier to demonstrate the problem using the total pressure data, in which each trace is constructed from a single signal, as opposed to the total temperature readings, where each trace is constructed from six separate signals.

Figure 5.9 shows a comparison of the phase lock averaged total pressure data from both the 2000 series and 2002 series of tests. While there are similarities between the two plots in the outer regions of the wake there is a clear difference between the 2000 series and 2002 series results in the data between the wake centre and +0.73D. The 2002 series data in this region lacks the periodic fluctuations at the vortex shedding frequency found in this area both on the other side of the wake and in the 2000 series data. However a close inspection seems to reveal fluctuations at around the first harmonic of the vortex shedding frequency.

To gain a better understanding of what the data looks like in the affected region, plots of the data from the area of 0D to +0.73D taken from both the 2000 series and 2002 series test are
shown in figure 5.10. Figure 5.10a, the 2000 series total pressure results, shows what should be expected in this region; strong signals at the fundamental vortex shedding frequency away from the middle of the wake that fade towards the wake centre line where the first harmonic starts to appear. The appearance of the first harmonic is due to the influence of the vortex row on the other side of the wake. What is worrying about figures 5.10b and 5.10c is that both lack features found in 5.10a although the data in the former shows the least similarity to the 2000 series results.

The data towards the upper edge of figure 5.10b, while being generally of a higher amplitude than the data at the wake centre line, seems to contain little if any periodic structure. Moving towards the lower edge of figure 5.10b the first harmonic appears much stronger than it did in the 2000 series data although is seems to form a less structured pattern. The results shown in figure 5.10c seem to show almost the opposite affect to that of figure 5.10b. Towards the outer edge the data is dominated by a very strong fluctuating signal at the vortex shedding fundamental frequency and, while this signal does become weaker towards the wake centre, the first harmonic of the vortex shedding frequency never seems to appear.

Before conclusions are drawn from this it should be remembered that phase lock averaging can remove a lot of information from the data. Because of the possibility that data was lost in the phase lock averaging of the results it is instructive to inspect representative raw and phase lock averaged traces in figures 5.11 and 5.12 respectively.

Due to the high level of noise present in the 2002 series data Figure 5.11 contains a disappointing lack of information. Clearly, the 2000 series total pressure data is much cleaner than the 2002 series data, shown by the clear signals shown in figure 5.11a. The significant amount of noise in the 2002 series data can be seen to disguise the periodic signals. The increased noise level may be partly due to the higher sampling rate of the 2002 series data (100kHz in the 2000 series tests verses 204.8kHz in the 2002 series) allowing high frequency noise to enter the signal. While one may be able to pick out some periodic nature from the raw 2002 series data this could be illusionary.

The 2002 raw total pressure data was disappointing and the phase lock averaged data must be relied upon to gain insight into the problem. Figure 5.12 shows line plots of the phase lock averaged data that confirm the initial findings from the surface plots of figure 5.10. While the 2000 series data, figure 5.12a, starts with a strong signal with periodic vortex shedding at around +0.73D that fades towards the wake centre as the shed vortex from the opposite

surface interferes this does not occur in the 2002 series data. This can be seen from figures 5.12b and c. They show the lack of first harmonic content above the centre line of the 2002 series data and the lack of the fundamental frequency below it. This supports the conclusions drawn from the surface plots of the 2002 series results, figure 5.10.

To ensure that this is a problem with the signals, and not just an effect of the phase lock averaging, a frequency analysis of the data in the affected region, again for both sides of the 2002 series data and from the 2000 series results, is given is figure 5.13. The frequency analysis was conducted using the Matlab *psd* command. It was performed using 2^{17} samples in widows of 2^{14} data points with an overlap of 2^{12} points for the 2002 series data and 2^{16} samples with windows of 2^{13} data points and an overlap of 2^{12} points for the 2000 series data. The relatively larger overlap for the 2000 series data was to compensate for the smaller number of data points available for the *psd*.

The frequency spectra in figure 5.13 generally support what has already been said regarding the lack of fundamental frequency in the 2002 series data above the wake centre line and the lack of first harmonic below it. Figure 5.13a clearly shows peaks in the frequency spectra at the fundamental shedding frequency at the outer edge of the wake and the first harmonic towards the centre. The lack of fundamental frequency is clear in figure 5.13b although there does seem to be a small peak at the vortex shedding frequency in the traces furthest from the wake centre line. This could alternatively be seen as in increase in the noise at this point. Similarly there is a lack of the first harmonic shown in figure 5.13c although, again in a similar fashion to the data in figure 5.13b, some small peaks at the first harmonic do seem to appear at the towards the centre line. These peaks however are much smaller than would be expected.

The findings from figure 5.13 indicate that the anomalies within the 2002 series total pressure and total temperature data are contained within the raw data and are not a result of the data processing.

Since confidence in the time-averaged results from the 2002 series of tests is high the only conclusion that can be reached with regard to time resolved data is that corruption of the original signal was present. The source of the corruption is difficult to identify. As with the 2000 series total pressure data the source of the noise can appear and disappear between runs with no discernible reason. When looking for a source it should be remembered that the U-66 facility is adjacent to Ottawa International Airport, a source of considerable electromagnetic

noise, and is not designed to be used to take high frequency time-resolved data. As such it does not incorporate shielding against high frequency noise and it is possible that some intermittent source of noise from the airport, or even in the facility, caused the two bad runs during the 2002 series of testing resulting in the problems described here. For example the 2000 series total temperature data contained high level but intermittent noise produced by a compressor used to fill the supply tanks for the facility's shop air. In that case the noise level was reduced sufficiently by clipping that phase lock averaging could remove the remainder. It is possible something similar happened in the 2002 series data that was not susceptible to correction. Thus it is clear that without a further investigation at the facility the source of the noise will remain a mystery.

Clearly then the centre of the 2002 series wake traverse time-resolved data is corrupted to the extent that, by itself, it cannot be used confidently to represent the flow in the centre of the wake. However the edges of the 2002 series results are not corrupted in the same way and are sufficiently similar to the results of the 2000 series wake traverse to be confident that the two sets do support each other. So while confidence in the results from the centre of the 2002 series wake traverse may not be high enough to use it alone as evidence of energy separation the quality of the results at the edges is sufficient to allow it to support the 2000 series time-resolved wake traverse data will be used to base discussion on with the 2002 series results used, where appropriate, to support them.



Figure 5.7. 2002 Series Time-Averaged and Root Mean Squared Values a) Total Pressure Ratio, b) Total Temperature Ratio, c)Entropy Creation



Figure 5.8. Phase Lock Averaged Total Pressure Results a) 2000 Series, b) 2002 Series







Figure 5.10. 2002 Series and 2000 Series Raw Total Pressure Dataa) 2000 Series, b) 2002 Series Above Wake Centre Line,c) 2002 Series Below Wake Centre Line



a

Figure 5.11. 2002 Series and 2000 Series PLA Total Pressure Dataa) 2000 Series, b) 2002 Series Above Wake Centre Line,c) 2002 Series Below Wake Centre Line





6. Results and Discussion

6.1. Cylinder Surface Pressure

6.1.1. Across the Mach Number Range

Figures 6.1 and 6.2 show time-averaged surface pressure distributions for the circular cylinders used in the 2000 series and 2002 series of tests respectively. The surface pressures are presented in the form of pressure coefficient:

$$\left\langle Cp\right\rangle_{t} = \frac{\left\langle p_{s}\right\rangle_{t} - p_{1}}{P_{T1} - p_{1}} \tag{6.1}$$

Superimposed on the mean values, $\langle C_P \rangle_t$, are the maximum and minimum levels of raw pressure coefficient, C_P , and the root mean square (RMS) of the raw and phase lock averaged fluctuations in C_P . The RMS of the pressure coefficient for both raw and time-averaged data is given in equation 6.2:

$$s_{X} = \sqrt{\frac{1}{N-1} \sum \left(X - \left\langle X \right\rangle_{t} \right)^{2}}$$
(6.2)

Where X is the quantity being examined.

When comparing the 2000 series and 2002 series results the pressure distributions at Mach numbers of 0.5 and 0.7 can be seen to be broadly similar; however at Mach 0.6 there are considerable differences. This can best be quantified by finding the coefficients of form drag, C_D , and base drag, C_{BD} , defined in equations 6.3 and 6.4, for the various profiles and plotting them against Mach number, figure 6.3.

$$C_D = \frac{1}{D} \int_{\theta=180}^{\theta=0} CpDd(\sin\theta)$$
(6.3)

$$C_{BD} = \frac{1}{D} \int_{\theta=180}^{\theta=sep} CpDd(\sin\theta)$$
(6.4)

Note that this method of calculating profile drag only includes contributions from form drag and neglects skin friction and drag created by the loss of total pressure across local shock waves emanating from the cylinder's surface. At a Reynolds number of 6.8×10^5 the contribution to profile drag from skin friction drag is very small [64]. Given that the flow is transonic the contribution to drag by total pressure loss through shocks will be small although it will increase, along with the discrepancy caused by neglecting it, as the Mach number approaches unity.

Before considering the differences between the two sets of data an explanation of the changes in C_D over the Mach number range will give an insight into the reason for the differences.

From figure 6.3 it can be seen that both C_D and C_{BD} start low and then rise to a maximum at Mach 0.6 before falling off at Mach 0.7 and then rising again slowly at the higher Mach numbers. These variations over the Mach number range fit in with the compressible flow regimes described by Zdravkovich [15], namely, *shockless*, *intermittent shock wave*, *permanent shock wave* and *wake shock wave* as described in section 2.6. Much of the following discussion is drawn from his work.

At Mach 0.4 the flow is in the *shockless* regime (figure 2.1a) and so is strongly Reynolds number dependent and it is this that determines C_D . In this case, given the Reynolds number used in the test the flow falls into the Turbulent Boundary Layer 3 (TrBL3) subsonic regime [15]. This explains the lack of vortex shedding and low C_D observed at this Mach number: "Further increase in Re [into the TrBl3 regime] brings transition to the primary laminar separation line in an irregular manner. This leads to the disruption and fragmentation of separation bubbles along the span of the cylinder. The irregularly fragmented separation line prevents eddy [vortex] separation..." The lack of vortex shedding allows for the high level in pressure recovery seen in figure 6.2a. This leads to the low C_D .

Just above Mach 0.4 the flow becomes critical, i.e. local regions of flow about the cylinder become supersonic and the flow enters the *intermittent shock wave* regime (figure 2.1b). The oscillating flow field present in this regime, which results in the flow being supersonic only on one side of the cylinder at a time, leads to increased pressure fluctuations compared to the previous Mach number. This can be clearly seen in the change in RMS level and maximum and minimum pressure levels seen in figures 6.2a and 6.2b where the free stream Mach numbers are 0.4 and 0.5 respectively.

As the free stream Mach number increases beyond the critical limit the region behind the cylinder in which the vortices are formed shortens. The increase in C_D leading up to Mach 0.6 is a result of the commencement of vortex shedding, the shortening of the vortex shedding region with increasing Mach number and the formation of the local shock waves as the *intermittent shock wave* regime strengthens.

Beyond around Mach 0.65 the flow enters the *permanent shock wave* regime (figure 2.1c). As described in section 2.6, the *permanent shock wave* regime causes the movement of the location of formation and shedding of the vortices downstream of the cylinder surface so lengthening formation region and increasing the pressure recovery and a slightly earlier separation. This in turn leads to the reduction in C_D at Mach 0.7.

Once the flow enters the *wake shock wave* regime at just below Mach 0.8, see section 2.6, the elongation of the vortex formation region and the growth of the normal shock at the point of vortex roll up, figure 2.1d, the drag on the cylinder increases. This increase can be seen in figure 6.3. As the flow moves further into the regime at Mach 0.95 C_D again increases slightly and no vortex shedding is detected on the surface of the cylinder.

Figure 6.3 also highlights the discrepancy in C_D between the two sets of results at Mach 0.6. Below and above Mach 0.6 the differences in C_D between the two sets of results are 0.08 at Mach 0.5 and 0.07 at Mach 0.7. These differences are small, approximately 7% and 5% of the overall C_D at Mach 0.5 and 0.7 respectively and can be attributed to experimental error and the slight change in Reynolds number as the Mach number has not yet increased sufficiently to remove all Reynolds number effects. However at Mach 0.6 the difference is 0.31, quite considerable when one remembers that at Mach 0.4 C_D is 0.41, suggesting that there is a difference between the boundary layer flow in the 2000 and 2002 series results. To aid the investigation into the C_D discrepancy the 2000 series pressure profiles, with the 2002 series profiles superimposed onto them are shown in figure 6.4 for Mach numbers of 0.5, 0.6 and 0.7.

Inspection of figure 6.4 reveals that the 2000 series surface pressure profiles indicate that for all three Mach numbers there is early laminar separation leading to a small pressure recovery and large pressure fluctuations, particularly below the time-averaged value indicating very strong vortex shedding. In contrast to this the 2002 series results for all three Mach number used in figure 6.3 indicate that the boundary layers remain attached for another ten degrees and there is greater pressure recovery than in the 2000 series results. This would seem to

indicate that the cylinder boundary layer during the 2002 series data is either turbulent or going through transition at separation.

The tripping of the boundary layer into a turbulent or transitional state may have happened in one of two ways. The first possibility is that a change in the running conditions of the facility itself between the two sets prompted the change. However the free-stream Reynolds numbers for the 2000 series and 2002 series tests were almost the same, 6.86×10^5 and 6.80×10^5 respectively, and tests of the free stream pressure fluctuations conducted on the facility indicate that the fitting of a new control valve port ring shortly after the 2000 series tests actually reduced the free-stream turbulence. This means that if the only changes between the tests were those to free-stream conditions the boundary layer is more likely to be laminar during the 2002 series test than the 2000 series tests. Clearly then this is not the cause of the change in separation position and pressure recovery between the two sets of data.

Secondly the presence of four pressure transducers positioning around the midspan of the cylinder in the 2002 series of tests as opposed to the single transducer in the 2000 series experiments may have caused the measurements taken during the former set of tests to be those of a cylinder with a tripped boundary layer. The presence of the pressure transducers on the surface of the cylinders presents discontinuities to the surface curvature. While this was minimised by fitting each transducer so that the face was flush with upstream and downstream edges of the mounting hole, discontinuities were formed, with the larger transducer creating the larger discontinuities. This can be seen by inspection of figure 6.5. The left hand diagram in figure 6.5 shows the geometry of the Kulite pressure transducer, in red, when fitted into the circular cylinder, in grey, so that the face is flush with the surface of the cylinder. The blue chain-dash line extending parallel to the face of the transducer from its edges shows the extent of the discontinuity in surface curvature. The fitting of Entran transducers into the 2002 series cylinder is handled in the same way in the right hand diagram in figure 6.5. Clearly the presence of the transducers creates discontinuities in the surface curvature that are larger for the Entran transducers. By themselves the discontinuities may or may not cause the boundary layer to become transitional or turbulent. However, when one considers that the critical Mach number for a circular cylinder, above which the flow becomes locally supersonic, is around 0.4 then at the higher Mach numbers used these discontinuities may well cause the creation of local shock waves which cause the boundary layer to trip. However during the 2000 series of tests there was only one transducer on the cylinder's surface and the discontinuity caused by it was small. This means that any alteration to the boundary layer as a result of shock waves coming from it occurred after the flow has passed over it. Since any affect this has on the

flow cannot be communicated upstream due to the flow being sonic the readings taken will effectively be those of a laminar boundary layer with shock induced laminar separation. However this is not the case for the 2002 series of tests.

The windward facing transducers on the cylinder used for the 2002 series tests insured that the flow seen by the leeward transducers would always be tripped. Thus the leeward readings are all of a tripped boundary layer with shock induced turbulent separation.

It would seem then that the most likely cause of the differences in C_D and C_{BD} between the series of tests is caused by the presence of discontinuities in the surface curvature due to the extra transducers. While this does mean that the exact flow conditions for the two sets of results differ it also means that data exists for vortex shedding from a circular cylinder with both a purely laminar boundary layer and tripped turbulent or transitional boundary layer. This will be borne in mind during subsequent discussion of the results.

Despite the differences between the drag coefficients and base drag coefficients taken from the 2000 series and 2002 series they both show a similar pattern. As the vortex shedding becomes established at Mach 0.5 and 0.6 there is a significant rise in C_D and C_{BD} . After Mach 0.6 the coefficients fall off at Mach 0.7 and then, in the case of C_D , rise slowly; and in the case of C_{BD} fall slowly. The large difference between the coefficients at Mach 0.6 and Mach 0.7 may be attributed to the change in flow regime from *intermittent shock wave* to *permanent shock wave* at around Mach 0.65. Given that the coefficients do not change much after Mach 0.7 it can be deduced that the change in the coefficients between Mach 0.6 and 0.7 is due to the flow around the cylinder containing supersonic regions throughout the vortex shedding cycle. The slight changes after Mach 0.7 are due to later separation and greater pressure recovery.

Another point of difference between the two sets of data is the RMS levels of the phase lock averaged and raw C_P at Mach 0.6. The 2000 series results have a notable drop in the level of the RMS between the raw and phase lock averaged data that does not occur in the 2002 series data, figures 1b and 2c. The cause of this is the use of wake pressure readings as a phase reference during the 2000 series results. While the wake readings do provide a reasonable phase reference there is a greater level of jitter in the wake pressure reading than those taken on the cylinder surface. This has the effect of slightly smearing the phase lock averaged data resulting in a lowered RMS of the fluctuations. This means that, while the 2000 series phase lock averaged C_P are valid data it is not of such high quality as the 2002 data.

Another flow feature that shows up clearly in figure 6.4 is the drop in the level of pressure fluctuation on the windward side, forward of around the 60° mark, of the cylinders as Mach number increases. An inspection of figures 6.1 and 6.2 show that this is generally true from Mach 0.5 upwards and is caused by the strengthening of the intermittent, and eventually permanent, supersonic regions on the surface of cylinder along with the attendant surface shock waves up to the *wake shock waves* regime. The presence of supersonic regions prevents the movement upstream of pressure fluctuations during the vortex shedding cycle. Thus, in the *intermittent shock wave* regime during the first half of the shedding cycle the pressure fluctuations can move forward over one half of the surface and during the second they can move forward over the other half. The ability to prevent the fluctuations moving forward will be dependent on the size of the supersonic regions and so will increase with free stream Mach number as the regions become larger.

The cessation of pressure fluctuations over the windward side of the cylinder at Mach 0.7 indicates that localised areas of supersonic flow are, or are nearly, permanent. This is evidenced in figure 6.7. At Mach 0.6, figure 6.7a, the time-averaged isentropic Mach number reaches a maximum just above unity and remains there. This indicates that the intermittent shock waves are indeed present for only half of a vortex shedding cycle allowing pressure fluctuations to be communicated upstream during the half period that it is not supersonic, leading to sizable surface pressure perturbations. Note the maximum isentropic Mach number about the leeward side of the cylinder at Mach 0.6 shoots up to an indicated Mach 8 at some points. This is due to the surface pressure at those points tending to zero resulting in a stagnation pressure ratio tending to infinity so giving very high isentropic Mach numbers.

At Mach 0.7, figure 6.7b, the time-averaged isentropic Mach number accelerates to well above unity indicating that the flows on both sides of the cylinder remain supersonic for a significant proportion of the time. While the flows on both sides of the cylinder are sonic there can be no, or in practice very little, communication of pressure fluctuations upstream so reducing the maximum and minimum levels on the windward face.

A more thorough investigation of the proportion of the vortex shedding cycle over which the isentropic Mach number remains supersonic will be covered in the case by case analysis later in this chapter.

The changes in flow features and vortex-shedding mechanisms can be seen from the changes of vortex shedding frequency with free stream velocity and Mach number, figure 6.8a. Figure 6.8a shows that the rate of increase in the fundamental vortex shedding frequency between Mach 0.6 and 0.8 remains linear with a gradient of 4.83Hz/(m/s) or 1558Hz/Ma. Above Mach 0.8 the rate of increase in vortex shedding frequency with free stream velocity increases and below Mach 0.6 initially decreases and then increases down to Mach 0.4. This seems to indicate that either the amount of fluid entrained into each vortex remains the same throughout the Mach 0.6 to 0.8 range or the rate of entrainment and the amount of fluid entrained changes in such a way as to create a linear increase in shedding frequency. Below Mach 0.6 and above Mach 0.8 either the amount of fluid entrained per vortex changes nonlinearly or the rate of entrainment changes nonlinearly, or both.

The apparently linear increase in shedding frequency between Mach 0.6 and 0.8 is interesting as in this Mach number range the flow regime changes twice, from *intermittent shock waves* to *permanent shock waves* and then to *wake shock waves* although the final change in regime has only just occurred at Mach 0.8. The formation of vortices, the subsequent increase, up until just over Mach 0.6, and then reduction in their strength and the increase in frequency at which they are shed is very complex and dependent on a number of variables. From Gerrard⁸ the shedding frequency may be viewed as the result of a balance between the size of the formation region and the thickness and state of the shear layers feeding into it. However since there are no boundary layer readings at separation (sections 4.3 and 6.3) and no flow visualisation from which to determine the size of the formation region then the actual relationship for these results and how they change with changing flow regime will have to be investigated in future work.

A possible reason for the cessation of the linear increase in shedding frequency above Mach 0.8 can be found in the flow visualisation of Dyment and Gryson [19]. From their flow visualisation at Mach 0.8 and 0.9 the vortex formation region can be seen to lengthen by around two and half times. This suggests that when the *permanent shock wave* regime first appears there is initially little change in the formation of the vortices. However as the flow moves further into the regime the differences between it and the *intermittent shock wave* regime become more apparent as the flow features become stronger. It seems reasonable to expect then that the nonlinear increase in shedding frequency to be related to the extension of the vortex formation region. Above Mach 0.9 the vortex formation becomes yet more complex as the shear layers start to converge causing the vortex formation region to thin.

However, as noted below, at this Mach number it is impossible to determine Strouhal number from surface pressure measurements and so the changes here are unknown.

The fundamental shedding frequencies were taken from frequency spectra of the data created using Matlab's *psd* function. A sample of this for each Mach number, each taken at an azimuth of around 85°, is given in figure 6.9.

It is worth noting that there is very little difference in the vortex shedding frequencies found from the 2000 series and 2002 series of tests. For example at Mach 0.6, where the biggest differences between the two series are found the vortex shedding frequencies are 928Hz and 944Hz for the 2000 series and 2002 series results respectively, a difference of just 16Hz or 1.7%. At Mach 0.5 and 0.7 the differences between the two series are 18Hz or 2.1% and 30Hz or 2.7% respectively. This indicates that while the difference in boundary layer state does have some effect on the vortex shedding frequency it is very small.

It should be noted that at the Reynolds number used in these tests there should be no vortex shedding at all when the flow is subsonic as it will fall into the TrBL3 regime [15]. Indeed from a quick inspection of the frequency spectra, figures 6.9a and 6.10, and raw time-resolved data, figure 6.11, it appears that this is the case. However a closer inspection of the data reveals that there is a broad increase in the power spectrum magnitude in the region of around 550Hz to 670Hz at azimuths of around 80° to 90°, ringed in red. Also a closer inspection of the time-resolved data from around 80° to 90° indicates occasional sinusoidal fluctuations with wavelengths that match this broad frequency range, figure 6.12. From this it is assumed that there is weak intermittent shedding of vortices at this Mach number. While this shouldn't be the case it should be recalled that the Reynolds number used is very near the upper boundary of the TrBL2 flow regime within which vortex shedding does occur. Given that the boundary of the regimes are not set and are affected greatly by free stream and surface conditions it seems likely that some vortex shedding may still be occurring.

When trying to find a curve fit for the higher and lower Mach number separately from the mid-range to gain a better understanding of the changes in flow features it was found that there was insufficient data. However further insight can be gained into the behaviour of the vortex shedding frequency through inspection of the non-dimensionalised vortex shedding frequency, Strouhal number (equation 2.1).

When plotted against Mach number, as in figure 6.8b, the changes in Strouhal number confirm the indications given by the changes of shedding frequency regarding the shedding mechanisms. This is because, as well as normalising the data with respect to the cylinder diameter and free stream velocity, Strouhal number is also the product of the first derivative of shedding frequency with respect to free stream velocity and the cylinder diameter. Thus any changes in the rate of increase of the fundamental vortex shedding frequency with the free stream velocity will be shown up when Strouhal number is plotted against Mach number.

As the Mach number increases from 0.4 to 0.5 the Strouhal number rises from 0.182 to 0.192 as the *intermittent shock wave* regime eradicates the subsonic flow features. *St* then falls off significantly from around 0.19 down to about 0.176 between 0.5 and 0.6 as the local supersonic regions become stronger. The Strouhal number then remains fairly constant through the *intermittent shock wave* and *permanent shock wave* regimes confirming the linear increase of shedding frequency in this region, before increasing to 0.217 at Mach 0.9 as the *wake shock wave* regime strengthens.

These findings are supported by the circular cylinder results of Murthy and Rose [51] and the flat plate work of Heinemann, Lawaczeck and Bütefish [42] that are plotted along side the results of the 2000 and 2002 series tests. The results from Murthy and Rose [51] are broadly similar to those from these tests although they do not show an the increase in Strouhal number at Mach 0.5. They did report that their findings at Mach 0.4 showed a broadband increase in the frequency spectra indicating they had similar results to these but interpreted them differently. It is also interesting that at high Mach numbers Murthy and Rose [51] found that the Strouhal number could either rise or fall. This would indicate that the vortex shedding at this Mach number is unstable, confirming the findings of Carscallen et al. [2].

The work of Heinemann, Lawaczeck and Bütefish [42] is presented by way of comparison between the wake flow of flat plates (and by extension turbine and compressor blades) and that of circular cylinders. While it is clear from the patterns formed by the different sets of data that the flow regimes for the two types of flow have different limits, this is to be expected given the low critical Mach number of circular cylinders. Regardless of the differences, the similarity between the two sets of data is encouraging.

Another point of interest is that from the data in figure 6.8b there is little difference in the Strouhal number of data taken at different Reynolds numbers but the same Mach number.

This indicates that once the flow around a circular cylinder has become critical, Reynolds number ceases to be a major determining factor in the flow.

It is also interesting to note that there are no Strouhal numbers recorded in the literature above Mach 0.9. While Zdravkovich [15] states that no vortex shedding is found above Mach 0.9 the flow visualisation that he uses at Mach 0.95, again by Dyment and Gryson [19], indicates that vortex shedding does occur up to that Mach number. However, as presumably with previous work, no periodic pressure fluctuation that would indicate the presence of vortex shedding was found on the surface of the cylinder at Mach 0.95 during the 2000 series of tests. This can be seen from the low RMS level and maximum and minimum pressures in figure 6.1f. However one should note that at Mach 0.95 a strong oblique shock forms at the confluence of the free shear layers from which the vortices are formed and shed. It seems likely then that the supersonic region of flow responsible for this shock prevents pressure fluctuations from moving upstream to the cylinder surface where they could be detected.

The general behaviour of the flow over the Mach number range has been discussed and it is now appropriate to investigate the detailed behaviour of the flow at each Mach number. This will be done through the use of power spectra, raw pressure traces and, where applicable, phase lock averaged data.

6.1.2. Mach 0.4

As has been previously stated, there may be some repressed vortex shedding taking place at this Mach number. However any vortex shedding that is taking place is occurring sporadically and over a range of Strouhal number. An indication of this can be found in figures 6.10 and 6.11. Moving towards the rear of figure 6.10, from around 90° to about 160° a small but recognisable hump can be seen to rise above the background noise. This is made clearer in figure 6.11, where the frequency spectra from around the cyinder are all plotted together. In figure 6.11 the hump in the region of 500Hz to 650Hz and -10dB to 0dB is ringed in red. This suggests that, due to the lack of a distinct spike, any vortex shedding that is taking place varies in frequency and occurs rarely. The sporadic nature of the vortex shedding is further evidenced by figure 6.12. Note that the only azimuths where any periodic functions show is at 95° and even here it is indistinct. The sporadic nature of the vortex shedding results in a high level of pressure recovery with a leeward *Cp* nearing 0 from around 120° on. The high level of pressure recovery leads to the low *C_D* observed at this Mach number.

6.1.3. Mach 0.5

Once the subsonic flow regime has been eradicated and the *intermittent shock wave* regime (figure 2.1b) entered at Mach 0.5, vortex formation and shedding is established. This can be seen by the significant increase in the RMS and maximum/minimum values of pressure fluctuations in figures 6.1a and 6.2b as well as the presence of distinct peaks in the frequency spectra, figures 6.9b and 6.13a and 6.13b, the raw pressure traces in figure 6.14 and the phase lock averaged data presented in figure 6.15. The establishment of the vortex shedding, along with the presence of the shock waves on the surface of the cylinder, is responsible for the marked increase in drag from Mach 0.4.

The frequency spectra in figure 6.9b show that as well as the fundamental vortex shedding frequency coming in at 838Hz and 856Hz for the 2000 series and 2002 series results the first two harmonics are also present for both sets of data. Figures 13a and 13b show that not only are the fundamental frequency and the first two harmonics present but also the third and fourth although the third harmonic only appears between around 90° and 120° and the fourth disappears after around 85° and is very weak in the 2002 series results. The weakness of the fourth harmonic from the 2002 series results is most likely related to the change in boundary layer state between the two sets of data as noted above. The change in boundary layer state can also be seen in the increase in the fluctuations of background noise. While this is not very clear here it becomes far more apparent at Mach 0.6 and 0.7.

The high number of harmonics of the vortex shedding frequency indicates a complex vortexshedding pattern. This is confirmed by the raw pressure traces in figure 6.14. From figure 6.14 it is clear that strong pressure fluctuations occur all the way around the surface of the cylinder although the structure does start to break down to some extent around the leeward face of the cylinder, figure 6.14e, particularly as the azimuth approaches 180°, figure 6.14f. What is clear is that the raw pressure traces from the windward face of the cylinder are made up of distinct saw-tooth waveforms indicating sudden decelerations and gradual accelerations of the local flow. However around the leeward face the signals become more rounded, indicating a more gradual acceleration and deceleration of the flow. The cause of the differences in signal shape between the windward and leeward faces of the cylinder is the presence of the supersonic region as will be discussed below.

The initiation of vortex shedding in the critical flow is triggered by the formation of a shock wave at the trailing edge of the supersonic region. This causes a rapid separation of the flow due the discontinuous adverse pressure gradient it forms. The forward movement of the separation point during the vortex shedding cycle causes an acceleration of the flow creating the supersonic region. As the supersonic region reaches its maximum strength, and the surface pressure its minimum level, the vortex is shed from the surface of the cylinder. What follows is a rapid increase in surface pressure, i.e. deceleration of the flow, over the windward face of the cylinder and a more gradual increase over the leeward face. The more rapid increase over the windward face is due to the sudden disappearance of the supersonic region that had been preventing the more gradually increasing pressure from the leeward face from being communicated forward. This is the cause of the difference in waveforms between the windward and leeward faces.

The deceleration of the flow is then followed by a more gradual acceleration as the vortex is shed from the other side of the cylinder and the shear layers swing back to the side from which measurements were taken. After this the cycle is repeated.

The presence of the saw-tooth waveform supports the findings of Sieverding et al. [45]. They found that, as with the results here, the level of the time-resolved base pressure signals fell faster than they rose.

The relationship between the appearance and disappearance of the supersonic region and the surface pressure of the cylinder can be seen in figure 6.15. Figure 6.15 shows that once the supersonic region has ceased to exist the regions of decelerated flow, or increased surface pressure, move both forward and backwards over the surface of the cylinder. Inspection of the phase lock averaged data enables an estimate of the time taken for the deceleration of the flow to move forwards and back over the cylinder to be made and from this approximate transport velocities found. The time taken for the forward movement of the deceleration is approximately 0.33ms or 0.28 of a shedding cycle while the time taken for it to move backwards was approximately 0.41ms or 0.35 of a shedding cycle. These figures were arrived at by comparing the time at which the peak value of Cp at 84.88°, the middle of the supersonic regions, occurs with the times of peak fluctuation at 20.15° and 165.02°. 20.15° and 165.02° were chosen as the points for comparison as they were the forward-most and rear most locations where the signal was dominated by the fundamental shedding frequency. Thus the forwards and backwards transport velocities were around $3.4 \times 10^3 rad/s$ and $3.26 \times 10^3 rad/s$ respectively.

Clearly then, vortex formation is complex while the flow around the cylinder remains mostly subsonic during the vortex shedding cycle.

6.1.4. Mach 0.6

At Mach 0.6 a simplification of the wave forms, and hence the vortex shedding, occurs. The number of harmonics present in the surface pressure signals has dropped from four to three, although the third harmonic is so weak, virtually disappearing in the 2002 series data as seen in figure 6.16, that it has little impact on the shape of the signals. The vortex shedding frequency increased to 928Hz and 944Hz for the 2000 series and 2002 series results respectively. The simplification of the signals is apparent from raw pressure traces in figure 6.17. While still approximating saw-tooth waveforms the leading edges are not as steep and the signals begin to breakdown much earlier than at Mach 0.5.

The change in the boundary layer state between the 2000 series of tests and the 2002 series shows up quite clearly at this Mach number. The frequency spectrum of the 2002 series results in figure 6.16b is much noisier than that of the 2000 series results in figure 6.16a. The difference is also apparent in the raw signals where the 2002 series traces are less well formed than the 2000 series signals and contain appreciably more noise. The differences stand out most from the phase lock averaged data, where the noise in the 2002 series signals has resulted in the areas of low pressure over the leeward face of the cylinder having irregular edges. Because of this the focus will be on the 2000 series results.

Both the Mach 0.5 and 0.6 results fall into the *intermittent shock wave* regime (figure 2.1b) and so in both cases there is supersonic flow on one side of the cylinder at any given time, thus the vortex shedding mechanism can be expected to be identical in both cases. The simplification of the waveforms, however, is due to the increasingly supersonic flow. Not only does the flow around the separation region become more supersonic, going up beyond Mach 1.2, it remains so for the majority of the time as can be seen from figure 6.18. As well as reducing the complexity of the waveforms produced it has also, as noted for Mach 0.7 previously, reduced the size of the fluctuations on the windward face of the cylinder. This is because, with the flow around separation being sonic for most of the time, very little of the pressure fluctuation can move forward.

As with the Mach 0.5 data the decelerations of the surface flow take time to propagate fore and aft over the surface of the cylinder. Using the same method as before to measure this propagation speed they were found to be 5.5×10^3 rad/s and 4.12×10^3 rad/s respectively.

6.1.5. Mach 0.7

At Mach 0.7 the local flow around the cylinder behaves in a distinctly different manner. This is not a surprise as the flow has now left the *intermittent shock wave* regime and entered that of *permanent shock waves* (figure 2.1c). The first point, taken from figures 6.9 and 6.20 is that the third harmonic has all but disappeared indicating further simplification of the waveform. The next point is the sharp drop in power spectrum magnitude ahead of separation. Whereas at lower critical Mach numbers the power spectrum magnitude dropped off smoothly ahead of separation the rapid drop off at Mach 0.7 shows that almost no pressure fluctuations get through to the windward face of the cylinder. It is also worth noting that at Mach 0.7 the frequency spectrum is significantly noisier than at Mach 0.6. This increase in noise indicates an increased level of aerodynamic noise.

The lack of pressure fluctuations on the windward face of the cylinder, along with the reduced complexity and general lowering in quality of the signals from the leeward face are born out in the raw pressure traces in figure 6.21. Whereas at Mach 0.5 and 0.6 there were strong signals at around 45°, and even at around 10° in the former case, at Mach 0.7 what signals are present there are very weak. At the separation point the signals have become triangular, almost sinusoidal, and the quality breaks down considerably past around 95°. This shows that the temporal discrepancy found at lower Mach numbers, between the time taken for a vortex to form and for it to be shed, reduces and eventually disappears as the Mach number is increased.

The reason for the fall in quality and the lack of pressure fluctuations becomes clear upon inspection of the phase lock averaged results, figure 6.22. The flow at separation is now supersonic throughout almost the entire vortex shedding cycle, preventing almost all pressure fluctuations from moving forward beyond that location.

In addition to the general fall in quality of the data the strength of the fluctuations has, as observed previously, dropped. This is due to the elongation and movement away from the surface of the cylinder of the vortex-formation region, as was also observed in flow visualisation by Dyment and Gryson. The result of this, with regard to surface pressure fluctuations, is that, along with a drop in level, the decelerations no longer appear propagate forwards and back over the cylinder surface. They appear almost instantaneously around the leeward face of the cylinder, figure 6.22.

6.1.6. Mach 0.8

At Mach 0.8 the flow moves into the *wake shock wave* regime (figure 2.1d). This is accompanied by an even more severe drop in the power spectrum magnitude of the data in the frequency plane at the separation point that occurs over a smaller portion of the cylinders circumference than at Mach 0.7. This is due to the flow accelerating to sonic sooner, at a free stream Mach number of 0.8, than at Mach 0.7 and less spatial fluctuation of the separation point. The shedding frequency has also increased to 1.25kHz. The shedding frequency appears to be independent of Reynolds number as measurements at Mach 0.8 were done at Reynolds numbers of both 7.9×10^5 and 8.9×10^5 each giving the same Strouhal number. The results from the lower Reynolds number are not presented here because the readings were incomplete.

Whereas the change in flow regime from *intermittent shock waves* to *permanent shock waves* was met by a drop in signal quality the change to the *wake shock wave* regime is met by an improvement as can be seen from figure 6.24. The signals from the windward face of the cylinder lack any noticeable perturbations, however at the separation point and beyond, the waveforms become clean and regular. Of note is the waveform at around 85°. Here there are areas of undisturbed signal followed by a rounded triangular waveform and another undisturbed period. This is most likely due to the separation shocks moving fore and aft over this location. While the shock is downstream of 85° no pressure fluctuations can reach that position, as the supersonic flow prevents pressure disturbances moving upstream; the surface pressure is undisturbed. However as the separation shock wave moves forward an increase in pressure was measured as the flow is decelerated through the shock. Then as the shock moves backwards over the cylinder the flow accelerates back up again resulting in a drop in pressure. The cycle is then repeated.

The surface pressures from the leeward face of the cylinder show continual fluctuation. This is because, although the pressure fluctuations cannot move forwards over the cylinders due to the supersonic flow, they can move backwards to be measured over the leeward face of the cylinder.

Unfortunately there was not a phase reference for the Mach 0.8 readings. This is due to the improper location of the phase reference transducer described earlier in section 3.3.4. As a result of the lack of a phase reference it was impossible to phase lock average the data and so

no comment can be made with regard to the propagation speeds of pressure disturbances over the surface of the cylinder.

6.1.7. Mach 0.9

The surface pressure distribution at Mach 0.9 is broadly similar to that at Mach 0.8. The vortex shedding frequency has increased to 1.72kHz, a non-linear increase from the lower Mach numbers as noted before. The drag coefficient has increased slightly due to a slightly delayed separation, as a result there is greater pressure recovery and so the contribution made by base pressure to the profile drag of the cylinder can be seen to have reduced.

The interesting waveform noted at around 85° at Mach 0.8 has moved downstream over the cylinder with the increase in Mach number and is now present at about 95° degrees. This fits in with the slightly later separation at Mach 0.9 with respect to Mach 0.8, see figure 6.1. In general the size of the pressure perturbations has decreased from Mach 0.8, probably due to a strengthening of the wake shock wave.

As with the Mach 0.8 data there was not phase reference at this Mach number and as a result analysis of the flow in the time domain beyond the waveforms is not possible.

6.1.8. Mach 0.95

At Mach 0.95 the vortex shedding, as mentioned above, ceases to be measurable from the surface of the cylinder. This can be seen from the frequency spectra of the pressure signals from around the cylinder circumference, figure 6.27. Also apparent from the frequency spectra is the much sharper and slightly later separation, as identified by the sharp increase in the base level at approximately 90°. Whereas at Mach 0.9 separation occurred over a 20° arc, at Mach 0.95 the arc was reduced to approximately 5°. The result of the later and sharper separation is a slight increase in the drag coefficient.

The very low level of pressure fluctuations, as seen from figure 6.1f, is confirmed to by figure 6.28. Clearly very little pressure fluctuation takes place at this high subsonic Mach number. This is due to none of the pressure fluctuations from the wake being communicated back upstream. In addition, it also indicates that the shock induced separation is quite steady as any movement across the surface of greater than 0.18° (the gap in coverage by the transducer between two data points) would have been detected by the Kulite pressure transducer.

6.1.9. Summary

In summary it may be said that once the compressible flow has fully established itself, at around Mach 0.6, the base drag and drag coefficients begin to fall with increasing Mach number until the flow enters the *wake shock wave* regime. Once there the drag and the base drag coefficients begin to rise again. In a similar vein the Strouhal number remains approximately constant from Mach 0.6 up to Mach 0.8 when the *wake shock wave* regime starts. It would seem then that the mechanism responsible for the formation of the vortex street remains the same through the *intermittent shock wave* and *permanent shock wave* regimes but once the steadier near wake of the *wake shock wave* regime is established the mechanism changes leading to increased base drag, despite an increase in pressure recovery.

The change in mechanism can be seen from the change in behaviour of the time-resolved data both in the time and frequency domains. While the magnitude of the pressure coefficient fluctuations around the surface of the cylinder fall in the Mach number range 0.5 to 0.7 the behaviour remains the same. However at Mach 0.8 a sudden clearing up of the signal, accompanied by a significant drop in the size of the fluctuations and the introduction of a new behaviour, described above under the description of the Mach 0.8 results, indicate a change in mechanism. This is backed up by a disappearance of any pressure fluctuations on the windward face of the cylinder, i.e. before separation, and an increasingly sharp rise in the frequency content during and after separation indicating a reduction in the movement of the separation shocks.

As an unexpected aside the results of this project also show that state of the boundary layer before separation has little effect on the drag and base drag coefficients except at Mach 0.6. A possible explanation of this is the strength of the *intermittent shock wave* regime at Mach 0.6. Below this Mach number the regime is still establishing itself and above it, it is eradicated by the formation of the *permanent shock wave* regime. So then at Mach 0.6 the difference in boundary layer state is going to have the greatest effect on the flow just before, during and just after separation resulting in the greatest, and indeed only significant, difference between the drags measured for the two series of tests.

It would seem, then, that the mechanism for the formation of the vortices has a significant impact on the base drag of the cylinder.



Figure 6.1. Pressure Distributions from 2000 Series Data a) Ma = 0.5, b) Ma = 0.6, c) Ma = 0.7, d) Ma = 0.8, e) Ma = 0.9, f) Ma = 0.95 Symbols: $\cdot \langle C_P \rangle_t$, $\times s_{Cp_raw}$, $\Box s_{Cp_pla}$,

error bars indicate maximum and minimum levels of fluctuation.



Figure 6.2. Pressure Distributions from 2002 Series Data a) Ma = 0.4, b) Ma = 0.5, c) Ma = 0.6, d) Ma = 0.7 Symbols: $\cdot \langle C_P \rangle_i$, $\times s_{Cp_raw}$, $\Box s_{Cp_pla}$,

error bars indicate maximum and minimum levels of fluctuation.



Figure 6.3. Drag and Base Drag Coefficients Over the Mach Number Range



Figure 6.4. Pressure Coefficient Distributions for the 2000 Series and 2002 Series Tests a) Mach 0.5, b) Mach 0.6, c) Mach 0.7 Symbols: \cdot 2000 Series $\langle C_P \rangle_t$, o 2002 Series $\langle C_P \rangle_t$, Dashed line: 2000 Series $(C_P)_{Max/Min}$, Continuous Line: 2002 Series $(C_P)_{Max/Min}$



Figure 6.6, Location of Pressure Transducers Within Cylinder Models



Figure 6.7. Isentropic Mach Number Distribution for 2000 Series Results a) Mach 0.6, b) Mach 0.7



Figure 6.8, Vortex Shedding Frequency Across Experimental Range
a) Fundamental Shedding Frequency as a Function of Free Stream Velocity
b) Strouhal Number Over the Mach Number Range
83×10³<Re>500×10³ (Open Symbols): Murthy and Rose [51]
Flat Plate: Heinemann, Lawaczeck and Bütefish [42]



Figure 6.9. Frequency Spectra of Surface Pressure Results Taken at Azimuths of 83.21° (2000 Series) and 84.21° (2002 Series) a) Ma = 0.4, b) Ma = 0.5, c) Ma = 0.6, d) Ma = 0.7, e) Ma = 0.8, f) Ma = 0.9 and 0.95



Figure 6.10, Frequency Spectrum of Time Resolved Surface Pressure Results, Mach 0.4



Figure 6.11, Frequency Spectrum of Time Resolved Surface Pressure Results, Mach 0.4



Figure 6.12. Raw Surface Pressure Traces From Around Cylinder Circumference, Mach 0.4


Figure 6.13, Frequency Spectrum of Time Resolved Surface Pressure Results, Mach 0.5 a) 2000 Series Results, b) 2002 Series Results



Figure 6.14. Raw Surface Pressure Traces From Around Cylinder Circumference. Mach 0.5





Figure 6.15, Phase Lock Averaged 2002 Series Cylinder Surface Results at Mach 0.5 a) Pressure Coefficient, b) Isentropic Mach Number



Figure 6.16, Frequency Spectrum of Time Resolved Surface Pressure Results, Mach 0.6 a) 2000 Series Results, b) 2002 Series Results



Figure 6.17. Raw Surface Pressure Traces From Around Cylinder Circumference, Mach 0.6





Figure 6.18. Phase Lock Averaged 2000 Series Cylinder Surface Results at Mach 0.6

a) Pressure Coefficient, b) Isentropic Mach Number





Figure 6.19, Phase Lock Averaged 2002 Series Cylinder Surface Results at Mach 0.6 a) Pressure Coefficient, b) Isentropic Mach Number



Figure 6.20, Frequency Spectrum of Time Resolved Surface Pressure Results, Mach 0.7 a) 2000 Series Results, b) 2002 Series Results



Figure 6.21. Raw Surface Pressure Traces From Around Cylinder Circumference, Mach 0.7





Figure 6.22, Phase Lock Averaged 2002 Series Cylinder Surface Results at Mach 0.6 a) Pressure Coefficient, b) Isentropic Mach Number







Figure 6.24. Raw Surface Pressure Traces From Around Cylinder Circumference, Mach 0.8



Figure 6.25, Frequency Spectrum of Time Resolved Surface Pressure Results, Mach 0.9 2000 Series Results

and the second sec



Figure 6.26. Raw Surface Pressure Traces From Around Cylinder Circumference, Mach 0.9



Figure 6.27, Frequency Spectrum of Time Resolved Surface Pressure Results, Mach 0.95 2000 Series Results



Figure 6.28. Raw Surface Pressure Traces From Around The Cylinder Circumference, Mach 0.95

6.2. Wake Results

The wake traverse plane was six cylinder diameters downstream from the cylinder axis. The total temperature and total pressure measurements will initially be considered separately. The general evidence for the presence energy separation will be reviewed. The traverses will then be used to calculate the local entropy creation in the wake. This will be used to locate the sources of wake loss. The results will be compared with the experimental work of Carscallen et al. [3, 51] and the computational work of Bennett et al. [13] in sections 6.3 and 6.4 respectively to show both the similarities between the data sets and, with regard to the experimental work, the improvements in resolution made possible by the use of a circular cylinder.

Throughout this chapter the results presented will be those that have been corrected for anomalies described in chapter 5. As such the time-resolved data from the 2002 series of experiments will not be presented although the time-averaged results from this set will be used to support the results from the 2000 series of tests. Since the only wake traverse is that taken at Mach 0.6 it is this Mach number that shall be considered.

6.2.1. Wake Total Pressure Results

The time-averaged wake total pressure ratio profiles are shown in figure 6.29. Superimposed on the 2000 series time-averaged data in figure 6.29a are the maximum, minimum and RMS values of the pressure ratio fluctuation prior to phase lock averaging. The RMS was calculated in the same way as for the cylinder surface pressure data, using equation 6.2.

The time-averaged total pressure ratio drops towards the centre of the wake (figure 6.29a and b) falling to 79.6% of the free stream total pressure at the wake centre. This represents a significant drop in pressure, almost equivalent to the dynamic head, i.e.:

$$\{(P_{T_{l}}-P_{T_{2}})/(P_{T_{l}}-p_{1})\}_{y/D=0} \approx 1.$$

The effect that the low wake total pressure has on the cylinder can be seen from the drag acting upon it. The drag force per unit length acting on a body in cross flow, when measured from a wake traverse and upstream reading, is normally defined as:

$$F_{WD} = \int_{-W/2}^{+W/2} \rho U_2 (U_1 - U_2) dy$$
(6.5)

Determination of U_2 is normally based on a local static pressure reading. However if it is assumed that the wake is fully mixed out at the traverse plane then free stream static pressure measurements may be used, along with the Bernoulli equation and the gas law to determine U_1 and U_2 and thus the drag per unit length acting on the cylinder.

The drag per unit length can then be normalised by the diameter of the cylinder and the free stream dynamic head to calculate the drag coefficient from equation 6.6. Since the flow for both the 2000 series and 2002 series tests was compressible the drag coefficient was defined as:

$$C_{WD} = \frac{F_{WD}}{(P_{T1} - P_1)D}$$
(6.6)

Note that the dimensions of drag per unit length are Nm⁻¹. This only needs to be normalised by the dynamic head and cylinder diameter to make it dimensionless.

Given the discrete nature of the wake data a numerical integration method was required to calculate the drag force on the cylinder; the trapezium method of numerical integration was used.

When this is applied to the 2000 series and 2002 series time-averaged results the coefficients of drag are found to be 1.47 and 1.45 respectively. A plot of the velocity deficit in the wakes is presented in figure 6.30. Note that the drag coefficients are different to those calculated from the surface pressures at this Mach number, which were 1.67 and 1.35 for the 2000 series and 2002 series results respectively. There are a number of reasons for this discrepancy. As stated in section 6.1 the coefficients of drag calculated from the surface pressures only considered form drag and ignored drag caused by skin friction. Additionally the assumption regarding the fully mixed out wake is not fully met at 6D downstream of the cylinder resulting in erroneous wake velocities and thus drag coefficients. So neither drag measurement gives an exact measure of the drag on the cylinder. However, due to the high Reynolds number and Mach number of the flow the contributions to the profile drag by skin friction are small. The drag coefficient calculated from the cylinder's surface is therefore the

more reliable. The coefficients of drag calculated from the wake readings are reasonably close to those from the surface of the cylinder and so can be used in support.

Also of interest from the drag calculation is the distribution of wake velocity. It clearly supports the general shape of the total pressure ratio profile and gives further insight on what is happening in the wake centre. Remembering that the wake velocities are approximate, due to the flow not being fully mixed out, it is possible to get an idea of how retarded the flow in the centre of the wake is. The maximum drop in velocity at the wake centre is by 76% of the free stream velocity. To summarise, the total pressure undergoes a considerable drop in the cylinder wake resulting in a large drop in flow velocity and hence high drag acting on the cylinder. To gain more information about the flow the time-resolved results need consideration.

To better see how the total pressure in the flow is fluctuating the frequency spectra of the raw data and the phase lock averaged results are presented in figures 6.31 through 6.33. In figure 6.32 the pressure ratio fluctuations are shown so that waveforms from different traverse positions may be compared on the same scale.

The frequency spectra show that the wake signals are noisier than those from the surface of the cylinder. This is to be expected; the vortices have had to convect downstream and so have stretched, undergone some viscous dissipation and the shear strains in the wake flow will have created small-scale turbulence. The frequency spectra also indicate that the waveforms in the wake are somewhat simpler than those from the cylinder surface. While the two cases are different and cannot be directly compared, if the data from the cylinder surface between azimuths of 85° and 180° are compared with the results from one side of the traverse from the outer edge to the wake centre then similarities do become apparent.

At the outside edge of the of the wake the fundamental frequency is dominant with a small first harmonic, smaller second harmonic and just a hint of the third harmonic present, figures 6.31a and 6.31b. This results in a slightly skewed triangular waveform, figure 6.32a, similar to the saw-tooth wave found at an azimuth of around 85° on the cylinder's surface. Moving towards the centre of the wake the base level of the frequency spectra rises; this tends to be dominated by the fundamental frequency, which remains at a fairly constant strength until about 0.25D from the wake centre where it fades out and then reappears on the other side of the wake. Similar behaviour occurs on the leeward face of the cylinder. The first harmonic also behaves in a similar manner to that around the leeward face of the circular cylinder in 181

that it exists quite strongly at the outer edge of the wake and then fades out at around 2D from the wake centre before reappearing at around 0.75D and then repeating this on the other side of the wake. In contrast to the surface pressure data the second harmonic only survives until around 3D from the wake centre before either disappearing or being drowned out by the background noise. However the third harmonic, of which there is only a hint at the edge of the wake, disappears completely once beyond 3.5D from the wake centre. This is similar to the behaviour after 85° on the cylinder surface.

When viewed in the time domain the effect the changes in harmonic content have on the waveforms can be seen in the traces of phase lock averaged data in figure 6.33. The increase in background noise can be seen to result in an increase in noise on the traces. The waveform remains largely triangular until inboard of around -1.5D, when it becomes more sinusoidal. Closer to the wake centre the reintroduction of the first harmonic creates a plateau just after each peak. On the centreline the disappearance of any peak in the spectra, aside from the first harmonic, results in sinuous behaviour at twice the vortex shedding frequency.

It is these triangular and sinusoidal waveforms that would be expected if the modified first theory put forward by Kurosaka et al.⁷ holds. As such the shape of the waveforms does support this theory.

The dominance of the first harmonic at the centre of the wake is due to both vortex rows having an equal influence there. In the centre of the vortex rows the only dominant periodic feature is the passing of the vortices on that side of the wake and so only the fundamental frequency is present. The harmonics are present at the edges of the wake due to the presence of ribs connecting the vortices [17]. At the edge of the vortex street these ribs are clearly defined while further in they are masked by the turbulence that both they and the vortex core produce. The random noise seen in the wake is the result of the shear stresses within the vortices and ribs acting on the flow.

The overall affect that the vortex street has on the wake total pressure can be seen in figure 6.33. At the edge of the wake the areas of high pressure are separated by very linear pressure variations resulting in the slightly skewed triangular waveform. The areas of high pressure lean in the direction of increasing time as they move out of the wake indicating that they are created as the vortex reaches the location of the probe. This pattern is continued into the centre of the wake. In the centre of the wake there are small areas of lowered pressure. In keeping with the findings of previous research this is expected in a vortex street.

6.2.2. Wake Total Temperature Results

The time-averaged wake total temperature profiles for both the 2000 series and 2002 series tests are presented in figure 6.34a and b. From this it can be seen that there are similarities and differences between the total temperature and the total pressure profiles. In common with the total pressure results the total temperature profile falls in the centre of the wake, dropping to around 98.5% of the free stream level, a drop of 4.23K. However, unlike the total pressure results there is a rise in the total temperature at the edges of the wake indicative of total temperature, and energy, separation. On the bottom half of the traverse this increase is around 3.37K or 1.1% of the free stream total temperature. When expressed as a recovery factor (equation 2.2, modified so that $T(\theta)$ is replaced with T_{T2}) for comparison with the work of Thomann [6] the minimum time-averaged value is 0.77. While this is significantly higher than the 0.45 that Thomann measured at 6D downstream of a circular cylinder at a similar Mach number (0.556) it should be recalled that Thomann's measurements were taken from the endwall of the wind tunnel. As Thomann admitted in his paper, these are only qualitatively comparable to measurements taken at mid span due to the presence of a thick wall boundary layer, secondary flows due to the interaction of the boundary layer and the root of the cylinder and the likelihood of heat transfer between the flow, the wind tunnel and the laboratory atmosphere. Thomann's work also failed to show the rise in recovery factor that would be present at the edge of the wake, again probably due to the boundary layer, secondary flows and heat transfer.

While these reductions and increases in total temperature are small they are important as they demonstrate that energy is being transferred from the centre of the wake to the edges. They also contribute significantly to the increase in entropy in the wake.

Due to the total temperature gradient across the test section the total temperature results are subject to errors described in section 5.2. As with the total pressure data the maximum, minimum and root mean square of the raw total temperature fluctuations for the 2000 series have been superimposed on the time-averaged values, figure 6.34a. The maximum, minimum and RMS values are those found after the data had been clipped to remove spikes, as described in section 5.2. The distribution of the maximum, minimum and RMS of the total temperature fluctuations are, as with the total pressure data, located at around $\pm 1D$. However unlike the total pressure results the RMS of the total temperature fluctuations reaches a plateau in the centre of the wake rather than dropping off. A possible explanation of this is

that there is a greater level of random total temperature noise in the centre of the wake caused by the dissipation of heat from fluid entrained into the vortex street.

To consider at the time-resolved results the details of the frequency spectra, figure 6.35, and the phase lock averaged data, figures 6.36 and 6.37, are discussed next. Note that figure 6.36 is of total temperature fluctuations only, again to allow for the comparison on the same scale of data taken at different traverse positions.

The obvious difference between the total pressure and total temperature frequency spectra is the peaks at just over 2kHz and 4kHz at the edges of the wake. These peaks are the result of noise created by motor switching, as discussed in section 3.6 and 4.4. They were removed from the data by clipping and phase lock averaging. Aside from the noise the other distinguishing feature is the extreme weakness of the second harmonic and the non-existence of the third. The main difference between the two sets of results, however, is the behaviour of the first harmonic across the wake. Whereas with the total pressure signals the first harmonic commences strongly, weakens in the middle of the vortex row and then strengthens again in the centre of the wake; in the total temperature signals it is only present between around $\pm 2D$. Even when present it is, with the exception of close into the wake centre, very weak in comparison to the fundamental frequency. This means that the signals in the wake are initially triangular as before due to the presence of the second harmonic (figure 6.36a). They then become largely sinusoidal in shape in the middle of the vortex row with a frequency equal to the vortex shedding rate, figures 6.36a, 6.36b and 6.36c. Close into the wake centre the first harmonic affect can be seen, first through making the waveform saw tooth like (figure 6.36d), then by the presence of small peaks after each large peak in the signal (figure 6.36e) and finally it takes over the signal completely producing a noisy sinusoidal waveform with a frequency twice that of the vortex shedding rate (figure 6.36f). The filled contour plots of figures 6.37 show how the different waveforms fit together.

The hotspots and coldspots created by energy separation can be seen in figure 6.37. The hotspot centres are located at approximately $\pm 1.3D$ from the wake centre and extend from around the wake centre line out to just beyond the limits of the traverse. They appear in an alternating fashion on either side of the wake, as would be expected from a Von Kármán vortex street. The coldspots appear along the wake centreline and extend out about $\pm 0.5D$ either side of it.

In order to combine the total pressure and total temperature results, as well as to allow for a fuller comparison with the turbine blade results and an investigation into the creation of losses in the wake the amount of entropy created in the wake and boundary layer flow must be calculated.

6.2.3. Losses and Entropy Production

As Denton [11] stated, entropy creation is related to the creation of loss and drag. It may be calculated from two thermodynamic properties of the flow, such as temperature and pressure, if they are known both at the point of interest and upstream of that point (equation 2.4). Since T_{T2}/T_{T1} and P_{T2}/P_{T1} have already been calculated in sections 6.2.1 and 6.2.2 the calculation of the time-averaged entropy creation for the 2000 series and 2002 series results and the time-resolved entropy creation for the 2000 series data was trivial. The time-averaged entropy creation for the 2000 series data was trivial. The time-averaged entropy creation for the 2000 series data was trivial. The time-averaged entropy creation for the 2000 series data was trivial. The time-averaged entropy creation for the 2000 series, again superimposed with the maximum, minimum and RMS levels, is shown in figure 6.38a while the time-averaged values for both series are presented in figure 6.38b.

From figure 6.38 it is can be seen that instead of reaching a distinct peak in the centre of the wake, as with the total pressure and total temperature results, the data instead forms a plateau. This is not entirely unexpected as the time-averaged entropy creation measured behind a turbine blade, but much closer to the trailing edge, by Sieverding et al. [46] showed, not a plateau but two peaks either side of the wake centre. Given that the present data were taken further downstream than those of Sieverding et al. [46] it seems sensible that viscous dissipation would have smoothed the two peaks out into a plateau. The reason for the plateau is that most of the turbulence in the wake, both the large scale vortices and the smaller scale ribs joining them are present in this area. This is further confirmed through the inspection of the root mean square of the entropy fluctuations in figure 6.38a. It shows that the fluctuations peak at around $\pm 0.6D$. To find whether this is occurring in the centres of the vortices or elsewhere an inspection of the time-resolved data will be performed, in the same manner as was done for the total pressure and total temperature, and compared to along with a comparison of the flow visualisation of Dyment and Gryson [19].

The power spectrum of the entropy data is given if figure 6.39. It shares many features with the frequency spectra of the total temperature and total pressure, figures 6.31 and 6.38. The fundamental frequency of the entropy data follows the same pattern as that of total temperature while the first harmonic is strong in the centre of wake, as with the total temperature data, and reappears towards the outer portions of the wake as with the total

pressure data. The noise spikes from the total temperature data are also present in the entropy results but are removed by the phase lock averaging routine.

The entropy waveforms are different from those for both total temperature and total pressure although they incorporate features of both. At the edge of the wake the waveform is triangular as with the total temperature and total pressure signals. Further into the wake the waveform first becomes sinusoidal and then takes on a saw tooth form once into the vortex cores. The steep leading edge of the saw tooth waveform is caused by the sudden appearance of the vortex core at the face of the probes. The gentler trailing edge is a result of the presence of the ribs linking it to the neighbouring vortices in the street and the small-scale turbulence created by the vortices and ribs that follow the vortex core. At the centre of the wake the waveform becomes sinusoidal again, with a frequency equal to that of twice the vortex shedding, due to both sides of the vortex street having an equal effect on the flow there.

The overall affect of this can be seen from the filled contour plot of the phase lock averaged data in figure 6.41. The serpentine shape of the vortex street can be easily made out from figure 6.41, although care has to be taken to remember that the flow features will appear from the opposite direction in the Lagrangian view familiar from flow visualisation. When compared to the flow visualisation by Dyment and Gryson [19] at equivalent Mach and Reynolds numbers the similarities are quite clear, indicating that the majority of the entropy creation takes place in the centre of the vortices. From this it can be seen that the majority of the entropy creation, and hence loss and drag production, within the vortex street occurs in the vortex cores with some being produced in the interconnecting ribs. Since the ribs are themselves, mostly, longitudinally positioned vortices this is to be expected [17].

6.2.4. Summary

In summary, the presence of areas of reduced and increased total pressure and total temperature have been measured in the wake of a circular cylinder in cross flow at a high subsonic Mach number. By itself this provides the first experimental proof of the existence of energy separation in the wake of circular cylinders in compressible cross flow. In addition to this it has been shown that the majority of the entropy created and carried into the wake is located in the centre of the vortices and along the interconnecting ribs.



Figure 6.29. Time-averaged Wake Total Pressure Ratio
a) 2000 Series With (P'_R)_{Max}, (P'_R)_{Min} and (s_{PR})_{Raw}
Symbols: • <P_R>_i, Error bars (P'_R)_{Max}, (P'_R)_{Min}, and × (s_{PR})_{Raw}
b) 2000 Series and 2002 Series



Figure 6.30. Velocity Drop in the Wake



а









Figure 6.33. 2000 Series Phase Lock Averaged Total Pressure Ratio



Figure 6.34. Time-Averaged Wake Total Temperature Ratio a) 2000 Series With $(T'_R)_{Max}$, $(T'_R)_{Min}$ and $(s_{TR})_{Raw}$ Symbols: • $\langle P_R \rangle_t$, Error bars $(P'_R)_{Max}$, $(P'_R)_{Min}$, and $\times (s_{TR})_{Raw}$ b) 2000 Series and 2002 Series



Figure 6.35. Frequency Spectrum of Time-resolved 2000 Series Wake Total Temperature a) Lower Half of Traverse, b) Upper Half of Traverse







Figure 6.37. 2000 Series Phase Lock Averaged Total Temperature Ratio



Figure 6.38. Time-Averaged Wake Entropy Creation a) 2000 Series With $((S_2-S_1)')_{Max}$, $((S_2-S_1)')_{Min}$ and $(s_{(S2-S1)})_{Raw}$ Symbols: • $\langle P_R \rangle_i$, Error bars $(S_2-S_1)')_{Max}$, $(S_2-S_1)')_{Min}$, and $\times (s_{(S2-S1)})_{Raw}$ b) 2000 Series and 2002 Series Time-averaged Profiles



Figure 6.39. Frequency Spectrum of Time-resolved 2000 Series Entropy a) Lower Half of Traverse, b) Upper Half of Traverse






Figure 6.41. 2000 Series Phase Lock Averaged Entropy Creation

6.3. Comparison of Wake Data With CFD

One of the aims of this project was to allow for comparison between experimental wake measurements and results from computational fluid dynamics (CFD). The comparisons made here will be primarily with the work of Bennett et al. [13], although some reference will be made to the earlier work of Kurosaka et al. [7] and Carscallen et al. [3]. Bennett et al. [13] used an inviscid, formally second order, explicit finite volume method to model the flow around both a circular cylinder in cross flow and the nozzle guide vane used in the Large Scale Transonic Planar Cascade (LSTPC). The inviscid code provides an accurate model of the initial, largely inviscid, vortex formation mechanism and a qualitative description of the vortex street created, although the inability of the code to predict viscous dissipation does prevent it from predicting the stretching of the vortices and the growth of the wake.

The comparison with the CFD results will be addressed in the same order as the experimental results of section 6.2, i.e. the total pressure, total temperature and entropy creation comparisons will be considered separately followed by a summary. The results will firstly be viewed in the Eulerian frame, to allow for a direct comparison with the experimental results, before being viewed in the Lagrangian frame to highlight the location of the flow features.

6.3.1. Total Pressure

As can be seen from figures 6.42 and 6.43 the experimental results bear reasonable resemblance to the computational results of Bennett et al. [13] and support the result of Kurosaka et al. [7], although the latter have only presented their results in a Lagrangian frame. When comparing 2000 series results with those of Bennett et al. [13] the latter results had to be clipped for presentation on the same colour scale as the former. It should therefore be borne in mind that the maximum pressure ratio calculated by Bennett et al. [13] was 1.14 and the minimum was 0.58. It should also be remembered that the phase lock averaging of the experimental data would have effectively clipped some of that data as well due to the inclusion of weak and noisy vortices. Importantly both have the same Strouhal number and the maximum and minimum values are similar. Also the appearance of areas of high and low total pressure in the two sets of data do correspond, although those in the computational results appear closer to the centre of the wake than the experimental ones. A brief inspection of the time-averaged computational total pressure at a distance of 6D downstream of the cylinder reveals the reason for this, as shown in figure 6.44. The width of the time-averaged computational wake is around one third of that measured experimentally. This is due to the

use of an inviscid code for the CFD. Because the code is inviscid the wake will not develop fully, due to the absence of viscous dissipation, resulting in the narrow wake discovered here.

6.3.2. Total Temperature

When comparing the experimental total temperature results with the CFD results of Bennett et al. [13] there are, as with the total pressure results, many strong similarities. Again the computational data has been clipped to allow for a comparison to be made. The areas of localised increase and decrease of total temperature, i.e. the hotspots and coldspots referred to by Kurosaka et al. [7], calculated in the CFD and measured experimentally appear in similar positions, spatially and temporally, in the wake. However as with the total pressure data in the CFD results they appear closer to the centre of the wake for the same reason, (see figures 6.45 and 6.46). The other main difference is the location of the coldspots with respect to the hotspots. With the CFD results the hotspots and coldspots are aligned normal to the flow (this is hidden by the clipping of the data), however this is not the case with the experimental results. Rather, when measured experimentally the coldspots appear shortly before or after, depending on interpretation, the hotspots. The most likely cause of this is that, due to the inviscid nature of the CFD, the vortices have not deformed properly as they have convected downstream and it is this deformation in the real flow that causes the lack of alignment. Also, as with the total pressure results, the inviscid code again causes the time-averaged total temperature, figure 6.47, to have a much narrower wake than that measured. Despite this the two data sets do display good agreement providing validation for the CFD.

6.3.3. Entropy Creation

When the time-resolved entropy creation calculated from the experimental results is compared with that from the CFD, figures 6.48 and 6.49, there is good agreement, although the CFD data has again been clipped to allow for a comparison. The comparison shows that despite many features being lost in the experimental results due to noise and phase lock averaging, entropy calculated from the experimental measurements and computational calculations has the greatest similarities of all the properties. This is possibly due to the nature of entropy increase. When the total temperature changes fail to map those of the total pressure, or visaversa, entropy increases. It would seem then that the differences in behaviour between the total temperature and total pressure and that the details of the entropy creation, and hence loss generation, are similar for both experimental and computational results. One notable feature that is shown up in the CFD is the presence of ribs connecting the vortices. The details of this have been lost in the experimental results, although they do suggest it, and so the CFD provides confirmation of the existence of ribs connecting the vortices. In doing so the CFD

displays how the application of numerical computations can provide valuable support to experimental work, once the experimental work has validated the CFD. That is details that have been lost or not resolved within the experimental results show up in the results from CFD.

However, as with the total temperature and total pressure results, a comparison of the timeaveraged CFD and experimental data shows up the principal difficulty in using inviscid codes to calculate the details of the local flow. While the time-resolved CFD data contained higher peak values of entropy increase than the experimental results the time-averaged distributions present a different picture. The time-averaged entropy distributions from CFD contains the double peak measured by Sieverding et al. [46] closer to the source of the vortex street; it also rises to a lower maximum than the experimental data and falls to zero much closer to the wake centre. Additionally, as noted before, the wake when calculated from CFD is noticeably narrower than that measured experimentally (figure 6.50). The differences, as noted before, are due to the inability of an inviscid code to account for viscous dissipation and the effects that has on the wake.

In addition to agreeing well the results also show strong similarities to the computational entropy contours behind a blade in the Large Scale Transonic Planar Cascade by Currie as presented in Carscallen et al. [3]. This provides some confirmation regarding the similarity of the energy separation mechanism present in both cases. It should be noted that CFD code developed by Currie includes turbulence modelling and so the vortex street would be expected to develop a wake in greater agreement with that measured experimentally than is attainable using inviscid codes.

6.3.4. Location of Flow Features

In addition to providing a comparison with the experimental results the computational results also allow for the physical location within the vortex street of the increased pressure, cold spots and entropy creation maxima. This can be done through inspection of the computational data in a Lagrangian frame. The local density, figure 6.51, can be used to determine where the vortices are located in the wake. Then, using the density contours as a reference, the locations of the total pressure, total temperature and entropy creation features (figure 6.52, 6.53, and 6.54) can be found with respect to the vortex cores. From figures 6.52 and 6.53 it can be seen that the maximum total pressure and total temperature occur at the edges of the vortices closest to the edge of the wake while the minima are towards the wake centre. Interestingly the figures show that the maxima and minima do not occur aligned

exactly normal to the flow but the total pressure minima are slightly further downstream than the maxima, while the opposite is true for the total temperature. It would seem then that although this slight offsetting of the maxima and minima can be seen in a Lagrangian frame it is not strong enough to appear when the data are presented in an Eulerian view. Figure 6.54 confirms that the entropy creation maxima are located at the centres of the vortices; that is where the majority of turbulence, drag and energy loss are created.

6.3.5. Summary

The inviscid CFD of Bennett et al. [13] shows good agreement with the experimental results. It does however also display the problems inherent in using inviscid CFD codes to model local flow features. Due to the inability of the code to model the viscous forces acting on the flow, the wake of the cylinder does not develop properly, resulting in it being approximately one third of the width of that measured experimentally. In addition the inviscid code does not accurately predict the stretching of the vortices so that the hotspots and coldspots appear aligned normal to the flow when viewed in the Eulerian frame. However the CFD does provide information regarding details that have been lost in the experimental results. The CFD results show the ribs that connect the vortices far more clearly than the experimental results do and, when not clipped for presentation, do not suffer from loss of information due to noise and phase lock averaging.



Figure 6.42. 2000 Series Phase Lock Averaged Total Pressure Ratio



Figure 6.43. Time-Resolved CFD Total Pressure Distribution Reproduced with permission from W.P.Bennett



Figure 6.44. Time-Averaged CFD Total Pressure Distribution Reproduced with permission from W.P. Bennett



Figure 6.45. 2000 Series Phase Lock Averaged Total Temperature Ratio



Figure 6.46. Time-Resolved CFD Total Temperature Distribution Reproduced with permission from W.P. Bennett



Figure 6.47. Time-Averaged CFD Total Temperature Distribution Reproduced with permission from W.P. Bennett



Figure 6.48. 2000 Series Phase Lock Averaged Entropy Creation



Figure 6.49. Time-Resolved CFD Entropy Creation Distribution Reproduced with permission from W.P. Bennett







Figure 6.51. CFD Density Ratio Around and Behind a Circular Cylinder Reproduced with permission from W.P. Bennett



Figure 6.52. CFD Total Pressure Ratio Around and Behind a Circular Cylinder Reproduced with permission from W.P. Bennett



Figure 6.53. CFD Total Temperature Ratio Around and Behind a Circular Cylinder Reproduced with permission from W.P. Bennett



Figure 6.54. CFD Entropy Creation Around and Behind a Circular Cylinder Reproduced with permission from W.P. Bennett

6.4. Large Scale Transonic Planar Cascade Results

In this section the comparisons will be made between the wake total pressure, total temperate and entropy creation measurements made behind the blading in the Large Scale Transonic Planar Cascade (LSTPC) by Carscallen et al. [3, 50] and those made behind a circular cylinder in this project. Following that an analysis of the measurements of the isentropic Mach number around the blading of the LSTPC, measured as part of this project, and a comparison of it with the computational fluid dynamics predictions of it made by Bennett [67] and Brooksbank [14] will be made. The comparisons are included as the data has been used by both Bennett [67] and Brooksbank [14] to validate their CFD codes.

6.4.1. Comparison of Wake Results

The time-resolved total pressure results (figure 6.55) bear a close resemblance to the total pressure ratio found in the wake of a NGV mounted in the LSTPC (figure 6.56) by Carscallen et al. [3, 50]. It should be noted that the time axes of the contour plots presented by Carscallen et al. [3, 50] were reversed so that it would more closely resemble the Lagrangian view of the flow visualisation it was being compared to. The positioning of the areas of increased pressure at the edges of the wake is very similar to those behind the circular cylinder if the asymmetry of the NGV wake is allowed for. In addition to this the actual minimum and maximum values are similar. The minimum phase lock averaged total pressure behind the NGV is around 68% of free stream while that behind the cylinder is around 77.5% of free stream. The maximums are around 103% and 102.5% of free stream behind the NGV and cylinder respectively. Taking into consideration the differences in running condition, Mach 0.95 versus 0.6, and the relatively thick boundary layers on the NGV these results show that there is indeed a similar mechanism for the redistribution of total pressure in the wake. The results also bear a close resemblance to those of Sieverding et al. [46] although insufficient detail could be extracted from that paper for a comprehensive comparison.

Similarly the time-resolved total temperature results (figure 6.57) reveal a strong similarity to those of Carscallen et al. [3, 50]. (figure 6.58) bearing in mind the considerations described above. The total temperature profile from Carscallen et al. [3, 51] shows the presence of periodic hotspots at the edge of the wake and cold spots in the centre although the pitch wise locations differ from those in the cylinder wake due to the asymmetrical boundary layers at separation. Additionally they are also similar to the results of Sieverding et al. [46]. This further supports the hypothesis that unsteady energy separation is occurring in wakes behind

both a circular cylinder in compressible cross flow and a turbine blade with a thick trailing edge.

As with both the total temperature and total pressure the entropy increase contours (figure 6.59) also agree with the results of Carscallen et al. [3, 50] (figure 6.60). The entropy increase contours from behind a circular cylinder take on a similar serpentine form to that found behind the NGVs, although the latter is distorted due to the asymmetry of the boundary layers and wake and the relatively poor resolution when compared to the measurements behind a circular cylinder. There is however, enough similarity to confirm that the same mechanism is at work and so that, as with the wake of a circular cylinder, the majority of the entropy in the wake of a turbine blade is created in the vortex cores. The main difference between the circular cylinder and turbine results is that, in the latter case, the loss creation in the pressure surface side of the wake occurs in tightly rolled up vortices whereas on the suction surface side the thicker boundary layer resulted in a more diffuse distribution.

In summary, there is good agreement between the experimental results behind a circular cylinder and those behind a NGV, allowing for the different flow conditions. This indicates that it is indeed energy separation that was measured by Carscallen et al. [3, 50] and also indicates that similar mechanisms are present.

6.4.2. Comparison of Isentropic Mach Number Distributions

The measured surface pressures from around the LSTPC nozzle passage were converted into isentropic Mach number using equation 6.7 and are shown in figure 6.61.

$$M_{I} = \sqrt{\frac{2}{\gamma - 1} \left(\left(\frac{P_{T1}}{P_{s}} \right)^{\frac{\gamma - 1}{\gamma}} - 1 \right)}$$
(6.7)

For subsonic isentropic exit Mach numbers below 0.7 there is a plateau of increased local isentropic Mach number between around 40% and 65% axial chord on the suction surface. This increase in the local isentropic Mach number indicates the presence of a laminar separation bubble. This agrees with the published local isentropic Mach number distribution and oil flow visualisation by Moustapha et al. [48] at $M_e = 0.7$. The laminar separation bubble is instigated by an adverse pressure gradient present in the boundary layer due to the

strong diffusion on the suction surface of the blades at around 40% axial chord. The flow reattaches as a turbulent boundary layer at around 65% axial chord.

For the exit Mach numbers over 0.7 the plateau seems to have been replaced by a spike. This can be explained by an inspection of the CFD models (figures 6.62 and 6.63) and the flow visualisation of Moustapha et al. [48] Once the trailing edge shock wave pattern appears a shock will impinge on the suction surface of the neighbouring blade causing the flow to separate and an isentropic Mach number spike to form. After the shock the flow reattaches as a turbulent boundary layer. The suction surface spike at $M_e = 1.16$ appears further downstream than that at the $0.76 \le M_e \le 0.96$ because once the flow passes unity the trailing edge shock becomes oblique causing it to meet the neighbouring blade further downstream.

It should be noted that the local isentropic Mach number distributions at $M_e = 0.76$ and $M_e = 0.81$ are almost identical and so cannot be distinguished on figure 6.61.

The interaction between the impinging shock wave and the separation bubble has a significant effect on the state of the boundary layer after the flow reattaches, and on the wake of the blade. The strength of the impinging shock wave affects the rate at which the reattached boundary layer thickens. Generally the stronger the impinging shock wave the more rapidly the boundary layer will thicken resulting in a thicker wake with stronger vortices and greater losses.

Moustapha et al. [48] observed the increasing wake loss with impinging shock strength as an increase in area-weighted averaged total pressure loss in the wake of the blades as the isentropic exit Mach number increased towards unity. However once the isentropic exit Mach number has passed unity the losses fall. This is because the now oblique trailing edge shock is impinging in the blade further downstream, delaying flow reattachment and so giving the boundary layer less distance over which to develop. The thinner boundary layer results in a thinner wake and so in weaker vortices and lower losses.

With regard to the validation of the CFD models developed by Brooksbank [14] and Bennett [67] (figure 6.62 and 6.63) it can be seen that the comparison between them and the measured surface isentropic Mach number distribution is generally very good. However along the suction surface of the blade the inviscid CFD models suggest a greater acceleration of the flow leading up to the impinging trailing edge shock. This is caused by the inability of the models to predict flow separation, thus responding to the reduction in local surface pressure by accelerating the flow.

However, aside from the minor discrepancies in the inviscid CFD codes, the models do an excellent job of predicting the flow around the blade. As discussed above, the model accurately predicts the impingement of the trailing edge shock from the neighbouring blade on the suction surface. Indeed the models give a clear display of what the flow is doing close to the shock and indicate that the flow reattaches earlier than is suggested by the experimental data. This is because the coarse spacing of the pressure tappings in this region of the blade means that if the flow reattaches between tappings this will not be detected until the flow crosses the next transducer.

In summery the experimental measurement of the LSTPC isentropic Mach number distribution has provided an increased knowledge of the flow around the blade and has provided validation data for two different CFD codes.



Figure 6.55. 2000 Series Phase Lock Averaged Total Pressure Ratio



Figure 6.56. Total Pressure Ratio in the Wake of a Guide Vane in the LSTPC



Figure 6.57. 2000 Series Phase Lock Averaged Total Temperature Ratio



Figure 6.58. Total Temperature Difference in the Wake of a Guide Vane in the LSTPC



Figure 6.59. 2000 Series Phase Lock Averaged Entropy Creation



Figure 6.60. Entropy Creation in the Wake of a Guide Vane in the LSTPC



Figure 6.61. Measured Local Isentropic Mach Number Distribution



Figure 6.62. Experimental and CFD Isentropic Mach Number Distribution, Mach 1.16



Figure 6.63. Experimental and CFD Isentropic Mach Number Distribution, Mach 0.6

6.5. Boundary Layer Results

6.5.1 Mach 0.5 to 0.7

The boundary layer velocity profiles measured during the 2002 series of tests are shown in figure 6.55. Poor choices of the azimuths used had the result that the data has been extrapolated up to u/U=1, as described in section 4.3. The boundary layer, displacement and momentum thicknesses and shape factors for all four data sets are presented in table 6.1.

The separated flow is most apparent from the Mach 0.5 data collected at an azimuth of 120°. The very thick boundary layer suggests that the data has been collected in the vortex shedding region. Interestingly the data that was collected at 125 degrees shows that the boundary layer is significantly thinner, 9.5mm thick, when compared to the profile at 120°, which has a thickness of 22.8mm. Despite this the displacement thickness at 125° is slightly greater than that at 120° due to the shape of the profile.

The data collected only gives an estimate of what the flow is doing. It can be seen from the Mach 0.6 and 0.7 data that before separation the boundary layers should be thin enough for the 3.8mm of traverse available to the boundary layer Pitot tube to capture it entirely if the experiment was repeated. However as the results stand there is insufficient data to test the potential flow theories that require this information, such as that of Cox [43].

6.5.2 Mach 0.4

The Mach 0.4 data indicates that the boundary layer at 130° contained a recirculation region out to around 1mm, figure 5.56. Since there is no regular vortex shedding at this Mach number, section 6.1, this would seem to indicate that there might be eddies attached to the leeward face of the cylinder. If these eddies broke away in an unpredictable fashion that would explain the apparently irregular vortex shedding noted from the surface pressure measurements at this Mach number.

Ma	Azimuth	$\delta(mm)$	$\delta^{*}(mm)$	$\theta(mm)$	Н
	(Degrees)				
0.5	120	22.8431	1.8518	1.3342	1.3880
0.5	125	9.4996	2.1224	1.2930	1.6415
0.6	105	5.4659	1.2495	0.5925	2.1088
0.7	100	4.3127	1.2193	0.4747	2.5687

Table 6.1. Boundary Layer Results



Figure 6.64. Circular Cylinder Boundary Layer Profiles



Figure 6.65. Mach 0.4 Boundary Layer Profile at 130°

6.6. Oil Flow Visualisation

Figure 5.57 is an annotated photograph of the cylinder after the oil flow visualisation run at Mach 0.5. The top line shows the azimuth of the top edge of the cylinder in the shot, the second indicates where flow started to separate and the third shows where fluid entrained from the other side of the wake is pulled into the vortices forming on this side. Towards the bottom of the photograph a horizontal line is formed on the surface of the cylinder at 180°. Note that the two separation lines indicated by the flow visualisation are time averaged due to the nature of the oil flow visualisation and would have moved fore and aft during the flow period.

The way in which the streamlines formed by the oil flow visualisation move, roughly, into the centre of the area over which they are spread indicates that the vortex shedding is a three dimensional phenomenon although the regularity of the surface pressure and wake readings indicate that it is safe to assume local two dimensionality.

There was some concern at the regularity of the streamwise lines created by the flow visualisation. To confirm or disprove the presence of any regularity a short investigation making use of a fast Fourier transform tool, created by Nathan Barry using Matlab while on placement at NRC, was carried out. The results of this can be seen in figure 5.58. The data used for this was a one pixel wide spanwise strip of the bitmap shown in figure 6.57 from approximately 60° shown in the top plot in figure 5.58. The bottom plot in figure 5.58 shows that there are no dominant frequencies. The distribution of the streamwise lines then is simply dependent on where the spots of oil fell when they were flicked onto the surface of the cylinder.

Oil flow visualisation offers a very useful tool for finding the time-averaged separation point and, if it had been conducted during the phase 1 or 2 of the tests it would have prevented the poor choice of azimuths for phase 3. It would also have been of interest if the oil flow visualisation had been carried out at higher Mach numbers.



Figure 6.66. Annotated Oil Flow Visualisation at Mach 0.5



Figure 6.67. Results of FFT on Oil Flow Visualisation at Mach 0.5

7. Conclusion

Of the two main aims of this project the first to be considered was the analysis of timeaveraged drag coefficient, base drag coefficient, Strouhal number and, for the first time, timeresolved unsteady surface pressure on the cylinder using phase lock averaging over a range of high subsonic Mach numbers. This has been accomplished, although the analysis of the timeresolved surface pressure through phase lock averaging was limited to the Mach number range of 0.5 to 0.7 due to the failure of the phase reference transducer during the 2000 series of tests.

The analysis of time-averaged results has shown that as the flow moves into the *intermittent shock wave* regime the drag coefficient and base drag coefficient increase significantly as the vortex shedding is re-established and strengthens. Given that most of the drag creation is found at the core of the shed vortices it follows that as the vortex shedding becomes stronger the drag will increase. Beyond Mach 0.6 the *permanent shock wave* regime replaces the *intermittent shock wave* regime and the drag coefficient is seen to fall significantly before rising slowly as Mach number increases into the *wake shock wave* regime. The base drag coefficient behaves in a similar manner although it tends to fall as Mach number is increased beyond 0.7. The increasing drag coefficient may be attributed to the later separation of the flow around the cylinder while the reduced base drag coefficient is due to increased pressure recovery.

As with the drag coefficients the Strouhal number increases between Mach 0.4 and 0.5 as the vortex shedding is re-established. However the Strouhal number falls between Mach 0.5 and 0.6 and then remains fairly constant until Mach 0.8 when it rises again. The behaviour between Mach 0.4 and 0.6 is due to the re-establishment of the vortex street in the wake, between Mach 0.6 and 0.7 the value is fairly constant because, although the flow regime changes from *intermittent shock wave* to *permanent shock wave*, the vortex shedding mechanism remains the same. There then seems to be little change in Strouhal number until Mach 0.9 when it significantly increases, the *wake shock wave* regime having become fully established. However the *wake shock wave* regime is entered at around Mach 0.8; although no change in Strouhal number is detectable at Mach 0.8 the new flow regime has only just been entered and so the changes are small enough to escape detection. At Mach 0.95 there is no measured shedding frequency, however this is because the pressure fluctuations created by the vortex street do not move upstream to the surface of the cylinder due to the shocks present

in the wake. Thus the shedding of the vortex street is not detectable from the surface of the cylinder. This is not to say that no vortex shedding is taking place as vortex shedding has been observed in approximately the same flow conditions [19].

The time-resolved results support the idea of the vortex shedding mechanism remaining constant throughout the *intermittent shock wave* and *permanent shock wave* regimes as both the raw and phase lock averaged results show that the surface pressure fluctuates in a similar manner between Mach 0.5 and 0.7, although the number of harmonics present in the signals is reduced from four strong harmonics to two strong and one weak harmonic between Mach 0.5 and 0.6 due to the increasingly compressibility of the flow. Once into the *wake shock wave* regime at Mach 0.8 however, the raw surface pressure signals change markedly. The general wave forms remain the same at Mach 0.9, although the change in the point of separation results in some of the signals being shifted around the surface. As noted with regard to Strouhal number, at Mach 0.95 there are no recognisable waveforms.

The phase lock averaged results allow the changing flow regimes to be monitored over the Mach number range of 0.5 to 0.7. The inability to phase lock average the Mach 0.4 data shows that any vortex shedding present is sporadic in nature. Between Mach 0.5 and 0.6 the strengthening of the intermediate shock wave regime can be seen and then at Mach 0.7, the beginning of the *permanent shock wave* regime, the surface isentropic Mach number remains greater than one at some point on the windward face of the cylinder throughout the vortex shedding cycle. It should be noted that the permanent shock wave regime appears as a development of the intermediate shock wave regime rather than a distinct change. This explains why the vortex shedding mechanism does not change when the flow regime changes here. Unfortunately there is a lack of phase lock averaged data at Mach 0.8 and so the change from *permanent shock wave* to *wake shock wave* cannot be observed.

The surface pressure results highlight the usefulness of phase lock averaging for elucidating the changing flow patterns over the Mach number range. In addition a practical guide to implementing the method has been provided along with an explanation of one of the most significant problems faced when trying to implement it: jitter. The results of the phase lock averaging have also been compared with those of Sieverding et al. [46] to show the importance of using a phase reference and not just ensemble averaging the data.

The other main aim of this project was to measure the time-resolved redistribution of energy, or energy separation, in the wake of a circular cylinder in compressible cross flow for the first

time. Innovative methods of total temperature measurement and phase lock averaging were deployed to achieve this. The aim has been accomplished at a free stream Mach number of 0.6. In addition an analysis has been performed on the wake flow locating the features associated with energy separation and the areas of greatest entropy increase. The results were then compared with existing theories, principally those of Kurosaka et al [7] and Cicatelli and Sieverding [17], with which they agree. In addition, the results have been compared to the previous experimental and computational work of Carscallen et al. [3, 49, 51], Bennett et al. [13], and Bennett [65].

Analysis of the time-resolved wake results showed the hot spots occurring at the edge of the wake and the cold spots appearing in the centre. This was the first demonstration of these time-resolved features for the flow around a circular cylinder at high subsonic Mach numbers. The calculation of entropy increase in the wake showed that it was concentrated at the cores of the vortices, indicating that most of the drag created by the wake occurs in the vortex cores. The contoured surface plots made from the entropy increase calculations also showed the pattern of the vortex street and suggest the presence of the ribs that connect the vortices. When compared to experimental work performed on turbine cascades by Carscallen et al. [3, 51] there was good agreement, considering the differences in boundary layer conditions, indicating that the same mechanisms are present in both flows.

When compared to the computational fluid dynamics of Bennett et al [13] and Bennett [65] the results show some interesting similarities and differences. The main flow features of the experimental and computational work are similar; both exhibit areas of increased total temperature and total pressure at the edges of the wake and decreased total temperature and total pressure at the centre. Both sets of results also showed that the majority of the entropy increase occurs in the vortex cores and both also show the presence of ribs interconnecting the vortices. Despite the similarities there are also significant differences. The most positive of the differences is the retention of detail by the computational results that is, to some extent, lost within the experimental measurements. The best example of this is the ribs that join the vortices together. While they are hinted at in the experimental results they are clearly present in the contoured surface plots of the CFD calculations. The nature of the invicid Euler CFD code used by Bennett et al. [13] and Bennett [65] was the cause of the other differences. The Euler code does not allow the wake to develop as it would if viscous shear stresses were present. This has the result that while experiments indicate that associated areas of increased and decreased total temperature and total pressure have a temporal offset from each other, they appear simultaneously in the computational work. In addition to this it is clear that the

width of the computational wake when time averaged is only a third of that measured experimentally. While the formation of the vortices is primarily an inviscid mechanism, which the inviscid code accurately calculates, it does not realistically predict the development of the wake. This is because, once the wake has formed, the shear stresses present in the wake cause the vortices to be stretched and additional small-scale turbulence to form. So while inviscid codes do quantitatively predict the pattern of the wake vortex street and, when analysed at the exit of the control volume, will accurately predict the overall effect on the flow from the wake [26] they do not accurately predict the local wake flow at any distance from the cylinder. To do this a turbulence model is required.

The main innovations in experimental procedure and data analysis were the adaptation of the thin film total temperature probe, initially designed to be used in short duration facilities, for use in a long duration blowdown wind tunnel and the development of an automated phase lock averaging routine that could be used over a range of Mach numbers.

To support the main aims of the project boundary layer measurements and oil flow visualisation were also conducted. However the results of the boundary layer measurements were disappointing, primarily due to the incorrect choice of azimuthal location for the measurements. As a result the only useful information to come out of the boundary layer measurements was the possible presence of recirculation on the leeward face of the cylinder at Mach 0.4. Nevertheless the boundary layer probe worked well and the design can be recommended for future use. The oil flow visualisation results show that if used over the entire Mach number range it would have provided information regarding separation points. This would have prevented the incorrect azimuthal choices for the boundary layer traverses.

There were a number of problems caused by equipment failures encountered during the project. Notable amongst the problems were:

- Probe failures that delayed testing, required the adaptation of other instrumentation and reduced the number of Mach numbers at which time-resolved wake data could be collected,
- An apparent vertical temperature gradient in the wind tunnel working section,
- A high level of noise in the 2000 series data that was removed through the careful use of clipping, digital low pass filtering and phase lock averaging,
- Irreparably corrupted data from the 2002 series tests,

• The failure of three of the four pressure transducers mounted in the cylinder to take surface pressure measurements so increasing the number of blowdowns required and reducing the proportion of the surface surveyed.

Despite these problems the main objectives of the project have been successfully accomplished.

In addition to the work on circular cylinders an auxiliary aim of this project was to use the surface isentropic Mach number distribution measured for a nozzle passage in the Large Scale Transonic Planar Cascade (LSTPC) to validate CFD codes developed by Bennett [65] and Brooksbank [14]. As well as validating the CFD codes the CFD itself elucidated the presence of a plateau in the readings on the pressure surface of the blade. When compared to the CFD it was discovered that the plateau was in fact the point on the blade where the wake shock from the neighbouring blade impinged upon it. Due to the distribution of the surface pressure transducers this was not evident from the experimental results but rather the experimental measurements made the plateau appear much larger than it actually was.

The results of the auxiliary aim, along with the comparison of experimental and computational results from the main aims, highlight one of the useful features of CFD: the ability to fill in details missed in experimental due to the finite resolution of instrumentation.

7.1. Further Work

This project could be expanded in a number of ways. A priority, however, should be given to an investigation on the acceptance angle of the total temperature and total pressure probes under unsteady flow conditions as they were used in this thesis.

A repeat of the boundary layer work would allow for a fuller comparison with the potential flow theories. However a change to the method of operation would be required. Rather than estimating the separation location on the cylinder and traversing the Pitot tube outwards across the boundary layer, the cylinder should be traversed through the available azimuthal travel, ideally from 0° to 180°, at each radial location of the Pitot probe, so capturing the entire boundary layer. While this would require a greater number of blowdowns it would provide a complete picture of the boundary layer behaviour throughout the high subsonic range.

An extension of the wake traverse work would also be beneficial given the lack of information around the change in flow regime from the shockless regime into the intermittent shock wave regime and from the permanent shock wave regime into the wake shock wave regime. This could be achieved by repeating phase 2 of the experiments at Reynolds numbers at which vortex shedding occurs at Mach 0.4 and increasing the number of Mach numbers used to include those just after the flow has become critical, say at 0.42 and 0.45, and at Mach numbers just below and above the threshold of the wake shock wave regime, say 0.75 and Given the possible running conditions of the Trisonic Blowdown Wind Tunnel 0.85. (TBWT) it would not be possible to carry out the full Mach number range at a Reynolds number at which vortex shedding occurs at Mach 0.4, however an attempt should be made to carry out the higher Mach number tests at significantly different Reynolds numbers to ensure that vortex shedding is independent of Reynolds number once the flow has become fully compressible. Also an attempt should be made to locate a wind tunnel having greater availability and lower operating costs to enable a more comprehensive experimental investigation to be undertaken.

With regard to computational fluid dynamics (CFD), a turbulence model should be implemented. This will be included in Bennett [65], however at the time of writing the code was still under development.

Appendix A. $1\frac{1}{2}$ " IAR Aluminium Cylinder Drawings



Figure A1. Assembly Drawing of 11/2" IAR Aluminium Cylinder



Figure A2. 11/2" IAR Aluminium Cylinder North Section








Figure A5. 11/2" IAR Aluminium Cylinder South End Cap







Appendix B. 37.26mm Steel Cylinder Drawings



Figure B1. Assembly Drawing of 37.26mm Steel Circular Cylinder



Figure B2. 37.26mm Steel Circular Cylinder North Section



Figure B3. 37.26mm Steel Circular Cylinder South Section

Appendix C. Boundary Layer Probe Cylinder Drawings.



Figure C1. Assembly drawing of the Boundary Layer Probe Cylinder



Figure C2. Centre Section of the Boundary Layer Probe Cylinder







Appendix D: Transducer Specifications and Error Analysis

D1. Transducer Specifications

A number of different transducers have been used for this project. The details for the transducers used for the models and wake probe are given below in table D1. The accuracy of all other transducers is given in the error analysis.

	Kulite	Entran	Scanivalve	Scanivalve	
	XCQ-062-25D	EPI-541-50P	ESP ZOC 22	DSA3017	
INPUT		· · · · · · · · · · · · · · · · · · ·	.	 ,	
Pressure Range	25PSID	50PSID	50PSID	15/30PSID	
Over Pressure*	50PSI	Not Specified	75PSI	60PSID	
Burst Pressure	75PSID	100PSID	Not Specified	Not Specified	
Pressure Media	All non-conductive and non- All non-condu		All non-conduc	ctive and non-	
	corrosive liquids and gasses.		corrosive gasses.		
Rated Electrical Excitation	10VDC/AC	5VDC	Not Specified	Not Specified	
Maximum Electrical	15VDC/AC	Not Specified	Not specified	Not specified	
Excitation					
Input Impedance	800Ω min.	1200Ω nom.	Not Specified	Not Specified	
OUTPUT		.	•	•	
Output Impedance	1000Ω nom.	1000Ω nom.	Not Specified	Not Specified	
Full Scale Output	100mV nom.	90mV nom.	±2.5VDC	N/A	
Residual Unbalance	±3%	Not Specified	Not Specified	Not Specified	
Combined Non-Linearity	0.1% FS	0.5% FS	0.1%FS	0.05%FS	
and Hysteresis					
Repeatability	0.1%FS	0.25%FS			
Resolution	Infinite	•	••••••••••••••••••••••••••••••••••••••	16bit A/D	
Natural Frequency (kHz)	330	160	Not Specified	Not Specified	
Frequency Response	85	32	Not Specified	Not Specified	
(kHz)**					
Scan Rate (kHz)	Not Specified	Not Specified	20	0.5/channel	
ENVIRONMENTAL					
Operating Temperature	-55°C to 120°C	-40°C to	0°C to 60°C	0°C to 60°C	
Range		120°C			
Compensated	25°C to 80°C	20°C to 80°C			
Temperature Range					
Thermal Zero Shift	±1%FS/56°C	±1%FS/50°C	0.1%FS/°C	Not Specified	
Thermal Sensitivity Shift	±1%/56°C	-2% to -	0.05%FS/°C	0.001%FS/°C	
		6%/50°C			

* No change in calibration

******From manufacturers estimates

D2. General Error Analysis

All percentages are of maximum readings that were taken at:

- Mach 0.4 for Surface Pressure and Wake Measurements,
- Mach 0.5 for boundary layer measurements,
- Atmospheric Conditions for the Large Scale Transonic Planar Cascade.

Free Stream Measurements

1.5m Trisonic Blowdown Wind Tunnel

Paroscientific Digiquartz (Total Pressure):	±0.02PSI	=	0.06%		
Paroscientific Digiquartz (Static Pressure):	±0.02PSI	=	0.07%		
Platinum Resistance Wire Thermometer:	±0.556K	=	0.19%		
(Total Temperature)					
Large Scale Transonic Planar Cascade (LSTPC)					
Scanivalve DSA3017 (Total Pressure)	±0.008PSI	=	0.055%		
Positional Uncertainties					
Wake Traverse	±0.381mm	=	0.05%		
Cylinder Traverse	±0.03°	=	0.0083%		
Pitot Tube Traverse	±1µm	=	0.026%		

Cylinder Transducers

Since the transducers were flush mounted on the cylinder surface, and it was the surface pressure that was being measured, no error for flow angle needed to be included in the error analysis of the cylinder-mounted transducers.

Random Uncertainties

The random uncertainties due to noise and flow angle must be accounted for. The noise levels were estimated by inspecting the pressure and temperature signals after processing, but before phase lock averaging. Peaks of the fundamental frequency were inspected, as the changes here due to vortex shedding would be minimal, and the peak-to-peak amplitude of the local small-scale fluctuations estimated from there. No raw data is available for the boundary layer results and so an arbitrary 1% will be added for noise. Similarly for the LSTPC measurements the Scanivalve DSA provides time averaged measurements and so an arbitrary 1% will again be added for noise. Since there is no information available regarding the flow angle sensitivity for the pressure and total temperature transducers it is felt that an arbitrary 2% should be used.

Kulite XCQ-062-25D	(Cylinder	Surface)):
--------------------	-----------	----------	----

Systematic Uncertainties:

Combined non-linearity and hysteresis:	±0.025PSI	=	0.08%
Repeatability:	±0.025PSI	=	0.08%
Positioning:	±0.03°	=	0.0083%
Random Uncertainties:			
Noise (2000)	±0.105PSI	=	0.34%
Noise (2002)	±0.15PSI	=	0.48%
Total uncertainty:			
2000		=	0.51%
2002		=	0.65%
Entran EPI-541-50P (Cylinder Surface):			
Systematic Uncertainties:			
Combined non-linearity and hysteresis:	±0.25PSI	=	0.8%
Repeatability:	±0.125PSI	=	0.4%
Positioning:	±0.03°	=	0.0083%
Random Uncertainties:			
Noise	±0.15PSI	=	0.48%
Total uncertainty:		=	1.68%
Kulite XCQ-062-25D (Wake):			
Systematic Uncertainties:			
Combined non-linearity and hysteresis:	±0.025PSI	=	0.08%
Repeatability:	±0.025PSI	=	0.08%
Positioning:	±0.381mm	=	0.05%
Random Uncertainties:			
Noise (2000)	±0.105PSI	=	0.34%
Noise (2002)	±0.15PSI	=	0.48%
Flow angle		=	2%
Total uncertainty:			
2000		=	2.55%
2002		=	2.69%

Thin film total temperature transducer (Wal	ke):		
Systematic Uncertainties:			
Transducer accuracy	±2K	=	0.67%
Positioning	±0.381mm	=	0.05%
Random Uncertainties:			
Noise (2000)	±2K	=	0.67%
Noise (2002)	±8K	=	2.7%
Total Uncertainty:			
2000		÷	1.39%
2002		=	3.42%
Scanivalve ESP ZOC 22 (Boundary Layer):			
Systematic Uncertainties:			
CNLH&R for P_{TBL}	±0.04PSI	=	0.17%
CNLH&R for P_w	±0.04PSI	=	0.22%
Positioning	±0.001mm	=	0.026%
Random Uncertainties:			
Arbitrary Addition for Noise		=	1%
Total Uncertainty		=	1.416%

Large Scale Transonic Planar Cascade Blade Measurements

Systematic Uncertainties:			
Scanivalve DSA3017 CNLH&R	± 0.008 PSI	=	0.055%
Random Uncertainties:			
Arbitrary Addition for Noise		=	1%
Total Uncertainty		=	1.055%

Appendix E. Wake Probe Holder Drawings



Figure E.1. Wake Probe Holder Assembly Drawing



Figure E.2. Wake Probe Holder Sting



Figure E.3. Wake Probe Holder Probe Head





Γ





Figure E.6. Wake Probe Holder Pneumatic Piston Shroud



Figure E.7. Wake Probe Holder Delta Wing Body





DO NOT ICALE DALING NEWORT ALL BURCHS TO DESIDE OFFICE 5/16-24UNF-28 x 3/8 DP Ø.430 - . 905 1.155 .625 .03 x 45° CHAMFER-TYP OTHER SIDE -. 06 x 45" CHANFER - . 063 . 125 ------I+I Courti Courte Constil activati DAC-COARC WATCHIAL /WATCHICL TOLERANCES DRILL & REAN FOR 3/16 ROLL PIN-11-478 UNLESS OTHERWISE NOTED SAUF NOTE CONTRAINE DESIGN AND FABRICATION SERVICES SERVICE DE CONCEPTION ET DE FABRICATION HEAT THEAT. FTRAITHENT THEAN. ALL DINENSIONS IN INCHES DINENSIONS (N POULES CANADA OTTAWA .2 ±.015 .33 ±.016 .331 ±.005 fractions < 6* ± 1/64 > 6* ± 1/32 Angle ±.5% Concentricity 0.010 fir f 1815#/f 181 11112/11145 SHEATH LINKAGE HEATED PROBE U-68 »J CONFORMS TO/CONFORME & ASHE TI4 SH-1994 BESISH/CONCEP. B.BOUSSELLD SHEETITENILLE SCALFICHELLE OTV DANEN/BESSINE D.BONDHERM HOBEL DANETHON BE HOBELE 1811/011681 BAEAK ALL SHARP EDGES CASSER CONGES ET ARRONDIS .010 .020 01 2:1 CHECKED/VELIS 1.5.2. MIC 140 1784 : I I OF /DE I APP. 1300. -----BRABING BA. /No. DESSIN PEY. " REY TONE M407PB011 DESCRIPTION ST/PAR DATE APP. BATE 14-249-88 M407GD001 100 10



Г

References

¹ Carscallen, W.E., and Oosthuizen, P.H., 1988, "The effect of secondary flow on the redistribution of the total temperature field downstream of a stationary turbine cascade," AGARD CP-469.

² Carscallen, W.E., Fleige, H.U., and Gostelow, J.P., 1996, "Transonic turbine vane wake flows," ASME Paper No. 96-GT-419.

³ Carscallen, W.E., Hogg, S.I., Gostelow, J.P., and Buttsworth, D.R., 1998, "Time-resolved measurements of the energy separation process in a transonic turbine vane wake flow," AGARD-CP-601.

⁴ Gostelow, J.P., 1984, "Cascade Aerodynamics," Pergamon Press, pp 172-174.

⁵ Eckert, E.R.T., and Weise, W., 1943, "Messungen der Temperaturerteilung auf der ober Fläche Schnell Angeströmter Unbeheizter Körper," *Forshg. Ing. Wesen.* Vol. 13, pp. 246-254.

⁶ Thomann, H., 1959, "Measurements of the recovery temperature in the wake of a circular cylinder and of a wedge at Mach numbers between 0.5 and 3," *The Aeronautical Research Institute of Sweden*, Report 84.

⁷ Kurosaka, M., Gertz, J.B., Graham, J.E., Goodman, J.R., Sundram, P., Riner, W.C., Kuroda, H., and Hankey, W.L., 1987, "Energy separation in a vortex street," *Journal of Fluid Mechanics*, Vol. 178, pp. 1-29.

⁸ Sieverding, C.H., Stanislas, M., and Snoeck, J., 1980, "The base pressure problem in transonic turbine cascades," *Journal of Engineering for Power*, Vol. 102, pp, 711-718.

⁹ Motallebi, F., and Norbury, J.F., 1981, "The effect of base bleed on vortex shedding and base pressure in compressible flow," *Journal of Fluid Mechanics*, Vol. 110, pp. 273-292.

¹⁰ Motallebi, F., 1988, "Base pressure in transonic speeds a comparison between theory and experiment," ASME paper No. 88-GT-132.

¹¹ Denton, J.D., 1993, "Loss mechanisms in turbomachines," Journal of Turbomachinery, Vol. 155, pp 621-656.

¹² Rona, A., and Bennett, W.P., 2001, "Energy separation in a compressible vortex street," AIAA Paper No. AIAA 2001-0601

¹³ Bennett, W.P., Rona, A., Ackerman, J.R., Gostelow, J.P., and Carscallen, W.E., 2003, "Experimental and numerical study of the non-uniform total temperature in a turbulent Mach 0.6 vortex street," AIAA Paper No. AIAA2003-0426.

¹⁴ Brooksbank, E.J., 2001, "A numerical investigation of time-resolved flows around turbine blades," Ph.D. Thesis, University of Leicester, UK.

¹⁵ Zdravkovich, M.M. (1997), "Flow around circular cylinders, Vol. 1: Fundamentals," Oxford University Press, Chapter 16.

¹⁶ Gostelow, J.P., 1977, "A new approach to the study of turbomachinery flow phenomena," *Journal of Engineering for Power*, Jan 1977, pp 97-105

¹⁷ Cicatelli, G., and Sieverding, C.H., 1995, "A review of the research on unsteady turbine wake characteristics," AGARD PEP 85th Symposium, AGARD-CP-571, pp, 6-1 – 6-13.

¹⁸ Gerrard, J.H., 1967, "The mechanism of the formation region of vortices behind bluff bodies," *Journal of Fluid Mechanics*, Vol. 29, part 2, pp 259-272.

¹⁹ Dyment, A., and Gryson, P., 1979, "Study of turbulent subcritical and supercritical flows by high-speed visualisation," AGARD CP 227, Paper No. 28.

²⁰ Roshko, A., 1954, "On the drag and shedding frequency of two-dimensional bluff bodies," NACA TN 3169

²¹ Roshko, A., 1961, "Experiments on the flow past a circular cylinder at very high Reynolds number," *Journal* of *Fluid Mechanics*, vol.10, pp 345-356

²² Bearman, P.W., 1967, "On vortex street wakes", Journal of Fluid Mechanics, vol. 28, part 4, pp. 625-641.

²³ Morkovin, M.V., 1964, "Aerodynamic loads on bluff bodies at low speeds," AIAA Journal, Vol. 2, No. 11.

²⁴ Sieverding, C.H., "The influence of trailing edge ejection on the base pressure in transonic turbine cascades," ASME 82-GT-50

²⁵ Xu, L., and Denton, J. D., 1987, "The base pressure and loss of a family of four turbine blades," ASME Paper No. 87-GT-202.

²⁶ Denton, J. D., and Xu, L., 1990, "The trailing edge loss of transonic turbine blades," *Journal of Turbomachinery*, Vol. 112, pp, 227-285.

²⁷ Ranque, G.J., 1933, "Experience sur la détante giratoire avec productions simultanees d'un echappement d'air chaud et d'air froid", *Journal de Physique et de Radium*, Vol. 4, pp112.

²⁸ Hilsch, R., 1947, "The use of the expansion of gases in a centrifugal fieldas cooling process", *The Review of Scientific Instruments*, Vol. 18, No. 2, pp108-113. (English translation from: Zeits. F. Naturf., Vol. 1, p208, 1946)

²⁹ Eckert, E.R.T., 1984, "Experiments on energy separation in fluid streams," *Journal of Mechanical Engineering*, vol. 106, No. 10, pp 58-65.

³⁰ Ryan, L.F., 1951 "Experiments in Aerodynamic cooling," PhD thesis, ETH, Zurich.

³¹ Ackeret, J., 1954, "Über die Temperaturverteilung hinter angeströmter," *Mitteilungen aus dem Istitut für Aerodynamik*, ETH, Zurich, No. 21.

³² Ribner, H. S., and Etkin, B., 1958, "Noise research in Canada," *Proceedings of the 1st International Congress on Aeronautical Science*, Madrid (published by Pergamon Press, London, 1958).

³³ Relf, E. F., and Simmons, L. F. G., 1924, "The frequencies of eddies generated by the motion of circular cylinders through a fluid," Aerospace Research Council, London, Report and Memorandum no. 917.

³⁴ Delany, N. K., and Sorensen, N. E., 1953, "Low-speed drag of cylinders of various shapes," NACA TN 3038.

³⁵ Kovasznay, L. S. G., 1949, "Hot wire investigation of the wake behind cylinders at low Reynolds number," *Proc. Roy. Soc. A*, vol. 198, pp 174-190.

³⁶ Schultz-Grunow, F., 1951, "Turbulenter Wärmedurchgang im," Forch. Geb. Ing-Wes., Bd. 17, Heft 3.

³⁷ Ng, W.F., Chakron, W.M., and Kurosaka, M., 1990, "Time resolved measurements of total temperature and pressure in the vortex street behind a cylinder," *Phys. Fluids* A2 (6), pp. 971-977.

³⁸ Sundram, P., Kurosaka, M., and Wu, J.M., 1991, "Vortex dynamics analysis of unsteady vortex wakes," *AIAA Journal*, Vol. 29, No. 3, pp 321-326.

³⁹ Heinemann, H.-J., and Bütefisch, K.A., 1978, "Determination of the vortex shedding frequency of cascades with different trailing edge thickness," AGARD CP-227.

⁴⁰ Lawaczeck, O., Bütefisch, K.A., and Heinemann, H.-J., 1976, "Vortex streets in the wakes of subsonic and transonic turbine cascades," *IUTAM Symposium on Aeroelasticity in Turbomachines*, Paris.

⁴¹ Lawaczeck, O., and Heinemann, H.-J., 1976, "von Kármán vortex streets in the wakes of subsonic and transonic cascades," AGARD CP-177.

⁴² Heinemann, H.-J., Lawaczeck, O., and Bütefisch, K.A., 1975, "von Kármán wakes and their frequency determination in the wake of profiles in sub- and transonic regimes," *IUTAM Symposium Transsonicum II*, Göttingen, Germany, Berlin: Springer.

⁴³ Cox, H.J.A., 1972, "Prediction of two-dimensional cascade loss and outlet angle from potential flow and boundary layer solutions," Internal GEC technical report.

⁴⁴ Sieverding, C.H., and Heinemann, H.-J., 1990, "The influence of boundary layer state on vortex shedding from flat plates and turbine cascades," *Journal of Turbomachinery*, Vol. 122, pp, 181-187.

⁴⁵ Sieverding, C.H., Richard, H., and Desse, J.-M., 2003, "Turbine blade trailing edge flow characteristics at high subsonic outlet Mach number," *Journal of Turbomachinery*, Vol. 125, No. 2, pp. 298-309

⁴⁶ Sieverding, C.H., Ottolia, D., Bagnera, C., Cimadoro, A., and Desse, J.-M., 2003, "Unsteady turbine blade wake characteristics," ASME Paper No. GT2003-38934.

⁴⁷ Roberts, Q. D., and Denton, J. D., 1996, "Loss production in the wake of a simulated subsonic turbine blade," ASME Paper No. 96-GT-421.

⁴⁸ Moustapha, S.H., Carscallen, W.E., and McGeachy, J.D., 1993, "Aerodynamic performance of a transonic low aspect ratio turbine nozzle," *Journal of Turbomachinery*, Vol. 115, pp. 400-408.

⁴⁹ Carscallen, W.E., and Gostelow, J.P., 1994, "Observations of vortex shedding in the wake from transonic turbine nozzle vanes," ISROMAC-5, Hawaii, pp 153-169.

⁵⁰ Carscallen, W.E., Currie, T.C., Hogg, S.I., and Gostelow, J.P., 1999, "Measurement and computation of energy separation in the vertical wake flow of a turbine nozzle cascade," *Journal of Turbomachinery*, Vol. 121,

⁵¹ Murthy, V.S., and Rose, W.C., 1977, "Form drag, skin friction, and vortex shedding frequencies for subsonic and transonic cross flows on circular cylinder," *Proc. AIAA 10th Fluid and Plasma dynamics, Albuquerque*, pp. 77-687.

⁵² Forney, L.J., Meeks, E.L., Ma, J., and Fralick, G.C., 1993, "Measurement of requency response in short thermocouple wires," Review of Scientific Instrumentation, Vol. 64, pp. 1280-1286.

⁵³ Boutrif, M.S. and Thelliez, M., 1995, "Determination of Flow Temperature by using the Two Thermocouples Experimental Technique. Application for the Exhaust Flow Gas Engine," *Revue Generale de Thermique*, Vol. 34, No. 400-401, pp. 263-271

⁵⁴ Bradshaw, P., 1975 "An Introduction to Turbulence and its Measurement," Pergamon, Oxford, 1975, pp 86-91
⁵⁵ Dénos, R., and Sieverding, C.H., 1995/97, "Assessment of the cold wire resistence thermometer for high speed turbomachinery applications," *Journal of Turbomachinery*, Vol. 119, No. 1, pp, 140-148.

⁵⁶ Ng, W.F., and Epsein, A.H., 1983, "High-frequency temperature and pressure probe for unsteady compressible flows," *Review of Scientific Instrumentation*, Vol. 54, No. 12, pp. 1678-1683.

⁵⁷ Alday, J., Osborne, D.J., Morris, M.B., Ng, W.F., and Gertz, J., 1993, "Flow randomness and tip losses in transonic rotors," ASME Paper No. 93-GT-189.

⁵⁸ Buttsworth, D.R., and Jones, T.V., 1998, "A fast response total temperature probe for unsteady compressible flows," ASME *Journal of Engineering for Gas Turbines and Power*, Vol.120, pp. 694-701.

⁵⁹ Buttsworth, D.R., Jones, T.V., and Chana, K.S., Oct 1997, "Unsteady total temperature measurements downstream of a high pressure turbine," *Journal of Turbomachinery*, vol. 120, No. 4, pp 760-767

⁶⁰ Barton, J.S., Kilpatrick, J.M., MacPherson, W.N., Jones, J.D.C., Chana, K.S., Anderson, S.J., Buttsworth, D.R. and Jones, T.V., 1999, "Optical fibre probes for total pressure and total temperature measurement in a turbine test rig," *Proceedings of SPIE - The international Society for Optical Engineering*, Vol. 3746, pp 612-615.

⁶¹ Oldfield, M.L.G., Burd, H.J., and Doe, N.G., 1982, "Design of wide-bandwidth analogue circults for heat transfer instrumentation in transient wind tunnels," *16th Symposium of the international centre for heat and mass transfer*, Hemisphere Publishing, Bristol, PA, pp. 233-257.

⁶² Buttsworth, D.R., 2001, "A finite difference routing for the solution of transient one dimensional heat conduction problems with curvature and varying thermal properties," Faculty of Engineering & Surveying Technical Reports, Faculty of Engineering, University of Southern Queensland, ISSN 1446-1846, Report TR-2001-01.

⁶³ Hogg, S.I., 1996, "Fast response total temperature probe how it works!" University of Leicester Internal Report.

⁶⁴ Hanff, E., 2002, Private communication.

⁶⁶ Douglas, J.F., Gasiorek, J.M., Swaffield, J.A., "Fluid Mechanics, 3rd edition," Longman Scientific and Technical.

⁶⁷ Bennett, W.P., 2004, "A time accurate computational analysis of two-dimensional wakes," Ph.D. Thesis, University of Leicester.

⁶⁵ Twiddle, J.A., 2002, Private communication.