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TOTAL PRESSURE LOSS IN A CONICAL DIFFUSER

Peter , Yun Kai , Kwong

*A Thesis submitted to the Faculty of Graduate
Studies and Research in partial fulfillment
of the requirements for the degree
of Master of Engineering*

DEPARTMENT OF MECHANICAL AND AERONAUTICAL ENGINEERING
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Abstract

Data for the static pressure recovery of conical diffusers are readily available in the literature. However, under some circumstances such as in the design of wind tunnel circuits, it is important also to make accurate estimates of the total pressure losses across the diffusers. Handbooks usually suggest that the total pressure loss be taken as the difference between the static pressure recovery in the actual diffuser and that in the equivalent ideal diffuser, where the ideal diffuser has one-dimensional inviscid flow throughout. That is, the shortfall in static pressure recovery in the actual diffuser compared with the ideal diffuser is attributed entirely to total pressure loss. However, as pointed out by Sovran & Klomp (1967), the shortfall in static recovery has two causes: the growth in flow non-uniformity across the diffuser and the total pressure loss. Thus, values of the total pressure loss calculated according to the usual method will tend to be too high. The present thesis describes an experiment in which the total pressure loss was measured in a conical diffuser in order to determine the size of this over-estimate. The results are supplemented with data from an experiment by Pozzorini (1976), the only other source known to the writer of conical diffuser data which are sufficiently detailed to allow total pressure loss values to be extracted.

The present experiment was carried out in a wooden conical diffuser with an inlet diameter of 10.8 inches, an area ratio of 2.22, and an included angle of 16.4 degrees. A tailpipe was attached to the diffuser. The Reynolds Number based on the inlet radius was maintained constant at 3.58×10^5 and only one inlet boundary layer thickness, corresponding to an inlet blockage of $B = \frac{2\delta^*}{R} = 0.0083$, was considered. Measurements of the wall static pressure and boundary layer total pressure profiles were made along the length of the diffuser. The boundary layer profiles were then integrated to obtain the mass averaged total pressure values.

Pozzorini's and the present experiment show that the total pressure loss can account for as little as half of the shortfall in static pressure recovery. Furthermore, the fraction appears to vary from diffuser to diffuser and along the length of a given diffuser. It is

therefore concluded that, based on presently available data, it is not possible to make reliable estimates of the total pressure loss on the basis of the shortfall in static pressure recovery. It is further pointed out that all performance estimates, including that of the static pressure recovery, which are made by reference to the equivalent ideal diffuser involve some ambiguity. The reason for this is that it is impossible to match all inlet conditions for the ideal and actual diffusers. Given the same mass flows, either the inlet static pressures or the inlet mass averaged total pressures can be matched but not both. For typical diffuser area ratios and inlet blockages, the offsets in one or other of the inlet pressures are significant compared with the total pressure loss. A simple correlation for diffuser total pressure loss coefficient, which makes no reference to ideal diffuser, is therefore presented. The loss coefficient appears to be primarily a function of the area ratio of the diffuser and only weakly a function of the inlet boundary layer thickness. Further experiments, with thicker inlet boundary layers, are recommended to confirm the apparent insensitivity to inlet blockage of the loss coefficient.

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Table of Contents

Abstract	ii
Acknowledgements	iii
Table of Contents	iv
Lists of Tables	viii
Lists of Figures	ix
Nomenclature	xiv
1 INTRODUCTION	1
2 THEORY	4
2.1 Static Pressure Recovery	4
2.2 Total Pressure Loss	5
2.3 Diffuser Design Process	5
2.3.1 Flow Stability and Related Geometry	6
2.3.2 The Static Pressure Recovery	6
2.3.3 The Total Pressure Loss	9
2.4 Inlet Conditions of Ideal and Actual Diffusers	20
3 APPARATUS	25
3.1 The Annular Wind Tunnel	25
3.2 The Conical Diffuser	27
3.3 Instrumentation of the Conical Diffuser	29
3.3.1 Computer System	29
3.3.1.1 Data Sampling Program	33
3.3.2 Circular Pitot Probe	33
3.3.2.1 Pitot Probe Diameter	33
3.3.2.2 Misalignment Effect	35

3 3 2.3	<i>Pitot Probe Stem</i>	35
3 3 2.4	<i>Length of Pitot Probe</i>	39
3 3.3	<i>The Traversing Gear</i>	39
3 3.4	<i>Pressure Transducer and Scanvalve System</i>	45
3 3.5	<i>Miscellaneous Apparatus</i>	49
4.0	EXPERIMENTAL METHOD	51
4.1	<i>Scope of Measurement</i>	51
4.2	<i>Experimental Set-Up</i>	51
4.3	<i>Experimental Procedures</i>	51
4.4	<i>Wind Tunnel Operating Point</i>	54
4.5	<i>Data Acquisition</i>	54
4.5.1	<i>The Operation of the 3054A System for Data Sampling</i>	54
4.5.2	<i>Measurement Rate and Averaging Time for Data Sampling</i>	58
4.6	<i>Velocity Profile Traversing</i>	61
4.6.1	<i>Pitot Probe Alignment with Main Flow and Probe Zero Position</i>	61
4.6.1.1	<i>Probe Alignment</i>	61
4.6.1.2	<i>Probe Zero Position</i>	61
4.6.2	<i>Traversing Step</i>	61
4.6.3	<i>Dynamic Pressure Measurement</i>	64
4.6.4	<i>Static Pressure Measurement</i>	67
4.6.5	<i>Effect of Velocity Gradient</i>	68
4.6.6	<i>Effect of Wall Proximity and Viscosity</i>	70
4.6.7	<i>Effect of Turbulence</i>	70
5.0	RESULTS AND DISCUSSION	73
5.1	<i>Static Pressure Measurement</i>	73
5.2	<i>Boundary Layer Traverse Data</i>	77
5.2.1	<i>Velocity Profile Data Reduction</i>	83
5.2.1.1	<i>Near Wall Data</i>	83
5.2.2	<i>Velocity Profiles and Boundary Layer Parameters</i>	86

5.3	Total Pressure Loss Coefficient and Flow Non-Uniformity Coefficient	109
5.3.1	Center-Line Total Pressure Coefficient	110
5.4	Comparison with Pozzorni's Data	112
5.5	Inlet Static Pressure Off-Set and Inlet Total Pressure Off-Set	130
6.0	CONCLUSIONS AND RECOMMENDATION FOR FURTHER STUDY	136
6.1	Conclusions	136
6.2	Recommendation for Further Study	138
	References	140

Appendices

APPENDIX A	Derivation of Kinetic Energy Flux Parameter expressed in terms of Boundary Layer Parameters	143
APPENDIX B	Data Sampling Program	145
APPENDIX C	Inviscid Calculations of the Minimum Length of the Pitot Probe	150
APPENDIX D	Design of Vortex Generators	152
APPENDIX E	Data Reduction Program	154
APPENDIX F	Velocity Profiles Data	171

List of Tables

3.1	Static Tap Co-ordinates	30
3.2	Traversing Hole Co-ordinates	31
5.1	Comparison with other Static Recovery Coefficient Data	82
5.2	Sample Output from the Data Acquisition System	84
5.3	Boundary Layer Parameters (station 1 - station 7)	102
5.4	Boundary Layer Parameters (outlet section)	103
5.5	Boundary Layer Parameters—Pozzorini's Diffuser	116
5.6	Summary of the Comparisons between the Present Diffuser and Pozzorini's Diffuser	129

List of Figures

Figure

2.1	Flow Regime Chart for Conical Diffusers (correlated by McDonald and Fox)	7
2.2	Flow Regime Chart for Conical Diffusers (ESDU data sheet)	8
2.3	Effect of Inlet Blockage on the Performance of Diffusers with an Area Ratio ≈ 2.3 , from Klein(1981)	10
2.4	Conical Diffuser Static Recovery Effectiveness Variation with Inlet Blockage, from Padilla(1982)	11
2.5	Conical Diffuser Static Recovery Effectiveness Variation with Inlet Blockage, from Sjolander(1981)	12
2.6	One-Dimensional Flow in Conical Diffuser	14
2.7	Actual Flow in Conical Diffuser	17
2.8	Inlet Mass-Averaged Total Pressure Off Set in Diffuser	22
2.9	Inlet Static Pressure Off-Set in Diffuser	23
3.1	Annular Wind Tunnel, adapted from Sjolander(1975)	26
3.2	Conical Diffuser	28
3.3	Wiring of Input Channels to the 3497A Controller	32
3.4	Distribution of Displacement and Momentum Thickness Functions (from wall to 0.03125 inches)	34

3 5	Yaw Sensitivity of Pitot Probe	36
3 6	Pitching Misalignment as Probe Approaches Wall	37
3 7	Length of Pitot Probe Stem required to reach Centerline	38
3 8	Actual Pitot Probe	40
3 9	Required Length of Traverse Column to allow Probe to reach Centerline	41
3 10	Traverse Gear Details (figure taken from Velazquez (1983))	42
3 11	Traverse Gear (a)	43
3 12	Traverse Gear (b)	44
3 13	Arrangement of Instrumentation during Calibration of Transducer	46
3 14	Pressure Transducer Calibration Curve (a)	47
3 15	Pressure Transducer Calibration Curve (b)	48
3 16	Scanivalve System	50
4 1	Arrangement of Instrumentation for Velocity Profile Measurements	52
4 2	Arrangement of Wind Tunnel Reference Static Taps	55
4 3	Signal Flow Path of the 3054A System during Experiment	56
4 4	Real Time Scanning Process of Input Analog Signals	57
4 5	Averaging Time for Scanning Inside Shear Layer	59

4.6	Averaging Time for Scanning Free Stream Region	60
4.7	Nulling Probe Yaw Angle	62
4.8	Determination of the Wall Location	63
4.9	Dynamic Pressure Measurement	65
4.10	Static Pressure Variation Along Diffuser	66
4.11	Effect of Velocity Gradient on Effective Measuring Point of a Pitot Probe	69
4.12	Wall Proximity Correction for Pitot Probe	71
4.13	Viscosity Errors of Small Pitot Probes	72
5.1	Static Pressure Variation Curves	74
5.2	Flow Surface in Conical Diffuser	75
5.3	Static Pressure Variation Curves after Installation of Vortex Generators	76
5.4	Static Pressure Variation Curves of Two Sides of the Diffuser Wall	78
5.5	Final Static Pressure Variation Curve	79
5.6	Static Pressure Recovery Coefficient Distribution	80
5.7	Conical Diffuser Static Pressure Recovery Variation with Inlet Blockage, from Sjölander (1981)	81
5.8	Interpolation of Near Wall Velocity Profile Data	85
5.9(a)	Velocity Profile at Station 1 (Inlet Section)	87

5.9(b)	Velocity Profile at Station 2	88
5.9(c)	Velocity Profile at Station 3	89
5.9(d)	Velocity Profile at Station 4	90
5.9(e)	Velocity Profile at Station 5	91
5.9(f)	Velocity Profile at Station 6	92
5.9(g)	Velocity Profile at Station 7	93
5.10(a)	Velocity Profile at Outlet Section (zero deg)	94
5.10(b)	Velocity Profile at Outlet Section (30 deg)	95
5.10(c)	Velocity Profile at Outlet Section (60 deg)	96
5.10(d)	Velocity Profile at Outlet Section (120 deg)	97
5.10(e)	Velocity Profile at Outlet Section (-30 deg)	98
5.10(f)	Velocity Profile at Outlet Section (-60 deg)	99
5.10(g)	Velocity Profile at Outlet Section (-120deg)	100
5.11(a)	Momentum and Displacement Thickness Distribution	104
5.11(b)	Shape Factor Distribution	105
5.11(c)	Kinetic Energy Flux Parameter Distribution	106
5.12	Constant Static Pressure across Diffuser Cross Section	108
5.13	Total Pressure Loss Coefficient Distribution (Present Diffuser)	111
5.14	$(C_{p,u} - C_{p,s})$ vs Area Ratio(Present Diffuser)	111

	(Present Diffuser)	113
5 16	Velocity Profiles Development along the Length of Pozzorini's Diffuser	115
5 17	Total Pressure Loss Coefficient and Non-Uniformity Coefficient Distributions (Pozzorini's Diffuser)	118
5 18	Comparison of Total Pressure Loss Coefficient between the Present Diffuser and Pozzorini's Diffuser	119
5 19	Wall Shear Stress Coefficient Distribution (Present Diffuser)	120
5 20	Wall Shear Stress Coefficient Distribution (Pozzorini's Diffuser)	121
5 21	Comparison of Wall Shear Stress Coefficient between the Present Diffuser and Pozzorini's Diffuser	122
5 22	$\left(\frac{C_{f1}}{C_{f2}} - \frac{C_{f3}}{C_{f4}}\right)$ Vs Area Ratio (Pozzorini's Diffuser)	123
5 23	Comparison of Static Pressure Recovery	125
5 24	Location of the Two Diffusers on the Flow Regime Chart, ESDU(1973)	126
5 25	Center Line Total Pressure Coefficient (Pozzorini's Diffuser)	128
5 26	$I_{0\infty}$ Vs Area Ratio	131
5 27	$E_{0\infty}$ Vs Area Ratio	132

5 28 T_{∞} Vs Area Ratio

134

Nomenclature

A	Cross-sectional area of diffuser
AR	Area ratio, $\frac{A_2}{A_1}$
B_{in}	Inlet blockage factor, $\frac{2\delta_{in}^2}{R_{in}^2}$
C_f	Local skin friction coefficient, $\frac{\tau_w}{\frac{1}{2}\rho U_\infty^2}$
C_{p_s}	Actual static pressure recovery, $\frac{P_{s2} - P_{s1}}{q_1}$
C_{p_i}	Ideal static pressure recovery, $1 - \left(\frac{A_1}{A_2}\right)^2$
$C_{p_{o,cl}}$	Center line total pressure coefficient, $C_{p_s} + \frac{f_L}{q_1}$
D	Outside diameter of pitot probe
d	Inside diameter of pitot probe
E_{os}	Inlet static pressure offset parameter, $\frac{\Delta C_{p_{static}}}{(C_{p_i} - C_{p_{o,cl}})_{ideal}}$
H	Shape factor, $\frac{f}{g}$
I_{os}	Inlet static pressure offset parameter, $\frac{\Delta C_{p_{static}}}{1 - \left(\frac{A_1}{A_2}\right)^2}$
$\frac{L}{R_{in}}$	Length over inlet radius ratio of conical diffuser
m	Mass flow rate
P_s	Static pressure
P_{ref}	Reference plane static pressure
$\bar{P}_0$	Mass-averaged total pressure
$(P_{c1} - P_{c2})$	Wind tunnel reference pressure
q	Dynamic pressure, $\frac{1}{2}\rho u^2$
q_{ma}	Mass averaged dynamic pressure, $\frac{1}{2}\rho \bar{u}^2$
R	Radius of the present conical diffuser
Re_D	Reynolds number based on diffuser inlet section diameter $\frac{U_\infty D}{\nu}$
T_{os}	Inlet total pressure offset parameter, $\frac{\Delta C_{p_{total}}}{C_{p_{o,cl}}}$
u	Velocity in boundary layer
U_∞	Free stream velocity

u	Mass-averaged velocity, $u = 1/A \int^A u dA$
$\overline{v_x^2}, \overline{v_y^2}, \overline{v_z^2}$	Mean squared turbulent velocity component in rectangular co-ordinates
y	Distance from the wall
z	Outward displacement correction by Young and Mass
$\Delta C_{p, inlet}$	Inlet static pressure offset, $(\alpha_1 - 1)$
$\Delta C_{p0, inlet}$	Inlet total pressure offset, $(\alpha_1 - 1)$
ΔP_{pitot}	Dynamic pressure measured by pitot probe
$\frac{\Delta P_s}{P_{s1} - P_{s2}}$	Measured static pressure ratio

Greek Symbols

α	Kinetic-energy-flux parameter $1/A \int^A (u/u)^3 dA = \frac{3}{4} \alpha$
δ	Boundary layer thickness
δ^*	Axi-symmetry boundary layer displacement thickness $\int_0^R \left(1 - \frac{u}{u_\infty}\right) R dr$
δ^{**}	Axi-symmetric energy thickness $\int_0^R \frac{u}{u_\infty} \left(1 - \left(\frac{u}{u_\infty}\right)^2\right) R dr$
η	static pressure recovery coefficient C_{p_s}/C_{p_t}
γ	Non-uniformity coefficient, $C_{p_t} - C_{p_s} = \omega$
ϕ	Divergence angle of diffuser
ρ	Density
θ	Axi-symmetry Boundary layer momentum thickness $\int_0^R \frac{u}{u_\infty} \left(1 - \frac{u}{u_\infty}\right) R dr$
ω	Total pressure loss coefficient $\frac{\overline{P_{0,1}} - \overline{P_{0,2}}}{q_1}$

Subscripts

a	Refers to actual flow situation
actual	Refers to actual flow situation
real	Refers to actual flow situation
I	Refers to ideal flow condition
(t)	Refers to total pressure
c	Refers to center-line flow
inlet or in or 1	Refers to inlet section of diffuser
outlet or out or 2	Refers to outlet section of diffuser
ref	Refers to reference condition
s	Refers to static pressure
pitot	Refers to pressure measured by pitot probe
x,y	Refer to axial and tangential direction of diffuser flow
∞	Refers to infinity or free stream condition

Superscripts

'	Denotes real flow quantity
n	Denotes index of a power law velocity profile

Chapter 1

INTRODUCTION

Diffusers are among the simplest and most widely used fluid mechanical devices. They are used for converting dynamic pressure to static pressure. They are used in many internal flow systems such as wind tunnel circuits, intending to reduce the velocity level so that large losses will not occur. Diffusers also have practical applications as elements of devices such as compressors, turbomachines, jet aircraft engines, combustors and afterburners.

In a diffuser, flow decelerates and the fluid static pressure increases. Therefore, a diffuser is a device that operates in an adverse pressure gradient which can generate flow separation, depending upon the diffuser geometry and flow parameters.

The nature of diffusers has been the subject of many experimental and theoretical investigations: for example, Klein, (1981), Sovran & Klomp, (1967), and Pozzorini, (1976). However, in spite of these efforts, diffuser flow characteristics still are not clearly understood. Also, little gain has been accomplished in building a mathematical model which can predict diffuser performance for all flow regimes. The difficulty can be attributed to the complexity of the flow due to adverse pressure gradient. It is also due to the incomplete understanding of the physics of the interacting shear layer occurring on the centerline of the flow.

At present, diffuser performance is usually expressed in terms of a static pressure recovery coefficient (C_p) or as a static pressure recovery effectiveness (η). C_p and η data are available for most diffuser geometries of practical interest. However, the static pressure recovery gives an incomplete measure of the diffuser performance. In addition to static pressure recovery, users and designers of diffusers may be interested in the total

pressure loss and the velocity change which occurs across the diffuser. Unfortunately few of the references deal with total pressure losses, and measurements of total pressure losses are very rare. More importantly, there appears to be a misconception about the relationship between total pressure loss and static pressure rise in many of the published sources (except Sovran & Klomp, 1967). As will be evident from chapter 2, previous studies have suggested methods to compute the total pressure loss of a diffuser that end up with an excessively conservative answer. Since no measurements of total pressure losses in diffusers are available, the size of the errors is unknown. In certain situations the correct determination of this loss is important. For instance, in a closed circuit wind tunnel design, the mass averaged total pressure loss dictates the power necessary to drive the fan and the pressure ratio which the fan must supply. In the short term, it is therefore desirable to collect data on the total pressure losses in diffusers. In the long run, the best solution will be the development of reliable methods for predicting the viscous and turbulent flow in diffusers.

The objectives of the present thesis are: (i) To experimentally measure the total pressure loss across a conical diffuser. (ii) To study the performance of the conical diffuser more closely by determining the proportion of the effectiveness depreciation that is caused by total pressure loss and that by flow non-uniformity. (iii) To compare the experimental results with Pozzorini's experimental data.

It was not within the scope of this thesis to formulate predictions or predictive methods for the performance of conical diffusers.

To achieve the objectives, measurements were carried out in a 16.4 degrees included angle straight conical diffuser. The conical diffuser was designed and constructed during 1982-83 for use with the annular wind tunnel in the Hydraulics Laboratory at Carleton University. Velocity profiles along the flow of the conical diffuser were measured by traversing the boundary layers. The velocity profiles were then integrated to obtain the total pressure loss across the diffuser. Finally, comparisons with Pozzorini's data were made.

The thesis begins with a review of the current knowledge concerning the performance of diffusers, including the current procedure for calculating diffuser total pressure loss.

The misconception concerning total pressure loss is identified. This is then followed by the correct identification of the mass averaged total pressure loss and flow non-uniformity. The experimental apparatus is described in detail in chapter 3. In chapter 4, the experimental methods are described. In chapter 5, the experimental results are presented and discussed. Finally, chapter 6 presents the conclusions and recommendations for future work.

Chapter 2

Theory

2.1 Static Pressure Recovery

At present, diffuser performance is most often expressed in terms of static pressure recovery, either as a pressure recovery coefficient or as a static pressure recovery effectiveness. The pressure recovery coefficient is the actual pressure rise in the diffuser divided by the average inlet dynamic pressure, i.e.,

$$C_p = \frac{\Delta P}{q_1} = \frac{P_2 - P_1}{q_1} \quad (2.1)$$

where $q_1 = \frac{1}{2}\rho\bar{u}_1^2$, and $\bar{u}_1$ is the mass averaged inlet velocity, and mass averaged velocity is expressed as, $\bar{u} = \frac{1}{A} \int_A u dA$

The overall diffuser effectiveness relates the actual pressure rise to that achievable from the same geometry with ideal, one-dimensional flow at the same flow rate, i.e.

$$\eta = \frac{\Delta P_{actual}}{\Delta P_{ideal}} = \frac{(P_2 - P_1)_{actual}}{(P_2 - P_1)_{ideal}} = \frac{C_{p,a}}{C_{p,i}} \quad (2.2)$$

It must be noted that, when η is expressed as $\frac{C_{p,a}}{C_{p,i}}$, it implies that the inlet dynamic pressure, $\frac{1}{2}\rho\bar{u}_1^2$, is the same in the ideal and real diffusers. The ideal pressure-recovery coefficient, $C_{p,i}$, can be readily shown to be a function of only the geometric area ratio of the diffuser, i.e.

$$C_{p,i} = 1 - \left(\frac{A_1}{A_2} \right)^2 \quad (2.3)$$

2.2 Total Pressure Loss

Total pressure loss coefficient across the diffuser is defined as

$$\omega = \frac{\bar{P}_{01} - \bar{P}_{02}}{q_1} \quad (2.4)$$

where P_0 is the mass-averaged total pressure and is expressed as $P_0 = \frac{1}{m} \int P_0 dm$

The total pressure loss coefficient is often related to C_p or η in the form.

$$\omega = (C_{pt} - C_{pe})_{outlet} \quad (2.5)$$

or

$$C_{pt,outlet}^{\omega} = 1 - \eta \quad (2.6)$$

As will be shown in the section below, equation (2.5) and (2.6) are not quite correct and in fact, these simple relationships will apply only if the flow is one-dimensional throughout the diffuser.

2.3 Diffuser Design Process

In order to examine the characteristics of diffusers more closely, it is useful to focus on the design process.

In general, the design requirements will vary depending on the particular application and specification. For example, the requirement may be to obtain the shortest possible length of the diffuser by specifying the change of area, or it may be necessary to maximize the area change over an available length. Alternatively, the requirement may be aerodynamic so that maximizing the static pressure recovery or minimizing the total pressure losses is necessary. Generally, designing a diffuser that will meet the given requirement will involve three steps. First, a range of possible geometries which have a stable flow must be determined. Secondly, the static pressure recovery for the specified geometry must be

found. Finally, the total pressure loss must be estimated. The experimental data available to inform this process is examined in the following sections.

2.3.1 Flow Stability and Related Geometry

Flow stability in diffusers is as important as the velocity reduction or static pressure rise. The stability is related to the overall geometry of the diffuser, where the primary parameters defining diffuser geometry are two of the divergence angle 2ϕ , the length ratio (length to inlet radius ratio $\frac{L}{R_{i,n}}$ in conical diffusers) and the area ratio AR. Fig 2.1 shows the flow-regime chart (performance chart) for conical diffusers correlated by McDonald and Fox (1966) where the ordinate is the divergence angle, 2ϕ , and the abscissa is length ratio $\frac{L}{R_{i,n}}$. Three different flow regimes exist, two of which have a steady, or reasonably steady flow, the other having an unsteady flow. Another plot taken from the ESDU data sheets (Engineering Science Data Unit, 1975) is shown in Fig 2.2. Two optimum lines, very useful for design purposes, appear in the figure. The C_p^* line is the locus of geometries for which C_p is maximum for a given diffuser length. The C_p^{**} line is the locus of geometries for which C_p is maximum for a given area ratio. Usually, a designer will design the required diffuser well within the stable region to obtain a stable diffuser. Frequently, a designer will specify one of the diffuser dimensions, either the area ratio or length ratio, and then go to the appropriate optimum lines (C_p^* or C_p^{**} lines) to obtain the corresponding geometries and approximate static pressure recovery coefficient, C_p .

2.3.2 The Static Pressure Recovery

Since the actual pressure recovery achieved for a given optimum geometry depends on inlet conditions, the C_p value that is obtained from the performance chart is only an approximate value. A. Klein (1981) has demonstrated the effect of the inlet blockage factor on diffuser performance. In Klein's paper, the diffuser's performance is described in terms of the pressure rise coefficient, C_p , and the inlet blockage, $B_{i,n}$. The inlet blockage factor is defined as: $B_{i,n} = \frac{2\delta_{i,n}^*}{R_{i,n}}$ where $\delta_{i,n}^*$ is the axisymmetric inlet boundary layer displacement

Line a-a - line of onset
of unsteady flow
(transitory stall)

Line α - α - line indicating
divergence angle which
gives maximum pressure
recovery when length
is given.

Δ location of the present
diffuser

Fig. 2.1 Flow Regime Chart for Conical Diffusers
(correlated by McDonald and Fox)

a--a line of onset of unsteady flow. (from Fig. 2.1)

C_p^* locus of geometries for which C_p is maximum for a given diffuser length.

C_p^{**} locus of geometries for which C_p is maximum for a given area ratio.

Fig. 2.2 Flow Regime Boundaries for Conical Diffusers
(ESDU data sheet)

thickness and R_{in} is the inlet radius of the diffuser. Fig.2.3 which was taken from Klein's paper shows the performance of a conical diffuser with an area ratio $AR \approx 2.3$. A family of static pressure coefficient curves for varying length ratio, $\frac{L}{R_{in}}$, is plotted against inlet blockage factors. In Fig.2.3, all the C_p curves of optimum area ratio (C_p^* line) decrease with increasing B_{in} . Hence, to determine the C_p value, the inlet blockage factor must be known.

Very often, the diffuser geometry is chosen to give optimum pressure recovery (either C_p^* or C_p^{**}). Therefore, it is reasonable to assume that the values of $\eta = \frac{C_{p_{actual}}}{C_{p_{ideal}}}$ will be very similar for a given value of inlet blockage. Since both $C_{p_{actual}}$ and $C_{p_{ideal}}$ vary with AR, the effect of diffuser area ratio is built into η . Therefore, the static pressure recovery for all optimum diffusers can be obtained from a single curve of η vs B_{in} . This curve could also be used to give an approximate estimate of static pressure recovery for non-optimum diffuser geometries. This η vs B_{in} curve is clearly more convenient than using Klein's many performance graphs. Padilla (1982) extracted data from Klein's paper and replotted Klein's data in terms of η vs B_{in} in Fig.2.4. In the figure the various η vs B_{in} curves for the optimum diffuser geometry (only C_p^* line) fall in a fairly narrow band. Padilla concluded that diffuser performance can be given in terms of η vs B_{in} and as far as optimum diffusers are concerned η is more convenient to use than C_p . The η value can be found at the specified B_{in} and C_{p^*} is deduced by using $\eta = \frac{C_{p^*}}{C_{p^*_{ideal}}}$. In addition, various experimental data for η are shown in Fig. 2.5 (Sjolander, 1981). Also included in the figure are a correlation for η as a function of B_{in} .

2.3.3 The Total Pressure Loss

It is evident from the discussion above that geometries which produce a stable diffuser flow can be obtained from the performance chart and the corresponding static pressure recovery can be found from the η vs B_{in} plot or the C_p performance charts. The next concern is the total pressure loss that occurs across the diffuser. Total pressure loss is an important consideration in the design of most internal flow systems. The relationship between total pressure loss and static pressure recovery given by equation (2.5),

Results of Miller $AR = 2.28, Re_D = 5.5 \cdot 10^5$; flagged symbols $L, D = 60$; full symbols: Dolan and Runstadler $Re_D = 1.2 \cdot 10^5$; $\times$ IIT Madras, $Re_D = 8.3 \cdot 10^5$.

Results of Cockrell and Markland $AR = 2.25, Re_D = 1.9 \cdot 10^5$; full symbols: Dolan and Runstadler $Re_D = 6.6 \cdot 10^5$; $\times$ IIT Madras, $Re_D = 8.3 \cdot 10^5$.

Results of Peters $AR = 2.34, Re_D = 2.0 \cdot 10^5$; full symbols: Dolan and Runstadler $Re_D = 6.6 \cdot 10^5$.

Fig. 2.3 Effect of Inlet Blockage on the Performance of Diffusers with an Area Ratio ≈ 2.3 , from Klein(1981)

**Fig. 2.4 Conical Diffuser Static Recovery Effectiveness
Variation with Inlet Blockage, from Padilla(1982)**

Fig. 2.5 Conical Diffuser Static Recovery Effectiveness
Variation with Inlet Blockage, from Sjolander (1981)

$(\varpi = C_{p1} - C_{p2})$ has been widely used for many years by engineers and designers (eg. Miller, 1978). This total pressure loss equation implies that the shortfall in static pressure recovery, $(C_{p1} - C_{p2})$, is entirely due to total pressure loss. This would be true only if the flow remains one-dimensional throughout the diffuser (see Fig.2.6). However, real diffuser flow does not remain one-dimensional. Sovran & Klomp pursued this point further with a detailed analysis (Sovran & Klomp, 1967). The following analysis of pressure loss is adapted from the discussion by Sovran & Klomp.

The total pressure on any streamline is

$$\begin{aligned} P_0 &= P_s + \frac{1}{2} \rho u^2 \\ P_0 &= P_s + q \end{aligned} \quad (2.7)$$

where

$$q = \frac{1}{2} \rho u^2$$

If the velocity is integrated over the area of a non-uniform flow, a mass-averaged velocity $\bar{u}$ is obtained ($\bar{u} = \frac{1}{A} \int_A u dA$), which is the velocity of the one-dimensional flow with the same flux as the actual flow. When the velocity squared is integrated over the area to obtain the mass-averaged dynamic pressure, $q_{ma} = [\frac{1}{A} \int_A u^2 dA] \frac{1}{2} \rho$, it is found that $q_{ma} \neq q$ (except in one-dimensional flow), where

$$q = \frac{1}{2} \rho u^2$$

and

$$q_{ma} = \frac{1}{2} \rho \bar{u}^2$$

Therefore, the mass-averaged total pressure at any cross-section of an incompressible internal flow system can be expressed as

$$\bar{P}_0 = P_s + q_{ma} \quad (2.8)$$

or

Fig. 2.6 One-Dimensional Flow in Conical Diffuser

$$\bar{P}_0 = P_s + \alpha q \quad (2.9)$$

with

$$q_{ms} = \alpha q \quad (2.10)$$

and

$$\begin{aligned} \alpha &= \frac{1}{A} \int_A \left(\frac{u}{\bar{u}} \right)^3 dA \\ &= \frac{\overline{u^3}}{\bar{u}^3} \end{aligned} \quad (2.11)$$

where

$\bar{P}_0$ = mass-averaged total pressure.

P_s = static pressure (assumed constant over the flow, a condition that very nearly exists for flow in uncurved ducts).

α = kinetic-energy-flux parameter for the velocity profile.

Physically, α represents the ratio of the actual kinetic-energy flux at a given cross-section to the kinetic-energy-flux which could exist at the particular flow rate with one-dimensional flow. The effect of velocity non-uniformity is to make α greater than unity. As the flow non-uniformity becomes more severe, α becomes greater. Some typical α values are as follows:

For uniform flow,

$$\alpha_{in} = 1.0$$

For fully developed laminar flow (parabolic profile assumed),

$$\alpha_{in} = 1.116$$

For fully developed turbulent flow (power law profile with $n=7$ assumed),

$$\alpha_{in} = 1.0584$$

Using equation (2.9), the total pressure loss coefficient relating two cross-sections of the flow stream can be written:

$$\begin{aligned} w &= \frac{\overline{P_{0,1}} - \overline{P_{0,2}}}{\overline{q_1}} \\ w &= \alpha_1 - \alpha_2 \frac{\overline{q_2}}{\overline{q_1}} - \left(\frac{P_{s,2} - P_{s,1}}{\overline{q_1}} \right) \end{aligned} \quad (2.12)$$

Equation (2.12) indicates that total pressure loss is not simply equal to the shortfall in static pressure recovery, $(C_{p,1} - C_{p,2})$, but also depends on the growth of flow non-uniformity. Alternatively, it implies that the shortfall in static pressure recovery is due to the change of flow non-uniformity along the length of a diffuser as well as the total pressure loss which is the result of the viscous effect in the flow (see Fig.2.7). For further analysis, the total pressure loss coefficient is expressed in another manner as follow,

$$\frac{w}{1 - \left(\frac{A_1}{A_2}\right)^2} = \frac{\alpha_1 \left[1 - \frac{\alpha_2}{\alpha_1} \left(\frac{A_1}{A_2}\right)^2 \right]}{1 - \left(\frac{A_1}{A_2}\right)^2} - \eta \quad (2.13)$$

The first term in equation (2.13) represents the change of flow non-uniformity along the length of a diffuser. If one-dimensional flow is assumed, $\alpha_2 = \alpha_1 = 1$, equation (2.13) will become eq. (2.6) with $\frac{w}{1 - \left(\frac{A_1}{A_2}\right)^2} = 1 - \eta$. However, in actual flow, flow non-uniformity increases across a diffuser (i.e. $\frac{\alpha_2}{\alpha_1} > 1$). Therefore, the first term in equation (2.13), $\left(\frac{\alpha_1 \left[1 - \frac{\alpha_2}{\alpha_1} \left(\frac{A_1}{A_2}\right)^2 \right]}{1 - \left(\frac{A_1}{A_2}\right)^2} \right)$ will be less than unity and a total pressure loss less than the value predicted by the one-dimensional model will be obtained. This relationship is shown in Fig.2.7. However, it must be noted that in some special flow situation over estimation in total pressure loss can also happen by using equation (2.13). For example, if the diffuser is made very gradual (long diffuser) and at the same time with a highly non-uniformity inlet velocity profile, the flow non-uniformity may be reduced along the length of the diffuser (i.e. $\alpha_2/\alpha_1 < 1$). As a consequence, the first term of equation (2.13) will be greater than unity and total pressure loss coefficient greater than $(1 - \eta)$ will be obtained. The diffuser

Fig. 2.7 Actual Flow in Conical Diffuser

effectiveness, η is most often found to be around 0.7 to 0.9, whereas, the corresponding $\frac{w}{1 - \left(\frac{A_1}{A_2}\right)^2}$ will be equal to around 0.3 to 0.1. Therefore, neglecting flow non-uniformity effect can significantly change the total pressure loss. This point is illustrated in the example below, (the data presented below is extracted from Pozzorini (1976)).

Diffuser: $AR = 4$, $2\phi = 6^\circ$ (low-core turbulence)

At the outlet,

$$C_{p1} = 0.9308$$

$$C_{p2} = 0.7837$$

$$\alpha_1 = 1.034282$$

$$\alpha_2 = 2.020141$$

Therefore, $\eta = 0.842011$

Using equation (2.6),

$$\frac{w}{1 - \left(\frac{A_1}{A_2}\right)^2} = 0.15799$$

Using equation (2.13),

$$\frac{w}{1 - \left(\frac{A_1}{A_2}\right)^2} = 0.119062$$

Thus, the total pressure loss is overestimated by about 25%.

As mentioned above, the kinetic-energy-flux parameter, α is expressed in terms of

ratio of the actual mass-averaged dynamic pressure to the dynamic pressure of one-dimensional flow (equation (2.11)). However, α can also be expressed in terms of boundary layer parameters,

$$\alpha = \frac{R^2}{4} \left[\frac{1/2R - \delta^* - \delta^{**}}{(\frac{1}{2}R - \delta^*)^3} \right] \quad (2.14)$$

where

δ^* is the axisymmetric boundary layer displacement thickness

δ^{**} is the axisymmetric boundary layer energy thickness

$$\int_0^R \left[1 - \left(\frac{u}{u_\infty} \right)^2 \right] \left(\frac{u}{u_\infty} \right) \frac{r}{R} dr$$

R is the radius of the diffuser.

The derivation of equation (2.14) is contained in Appendix A.

Unfortunately, the kinetic-energy-flux parameter α is not known for most diffuser experiments. This is because in most experiments only the static pressure change across the diffuser was measured whereas, α has to be determined from velocity traverses at inlet and outlet of the diffuser. As a result, total pressure losses in diffusers are unavailable and the size of the error by using $w = C_{p_i} - C_{p_o}$ is unknown. One of the major objectives of the present study is to estimate the magnitude of this error, from the little data available in the literature (Pozzorini, 1976) and from additional measurements.

2.4 Inlet Condition of Ideal and Actual Diffusers

As discussed in the previous sections, the static pressure recovery and total pressure loss of an actual diffuser are often expressed in terms of the performance of a corresponding ideal diffuser. The comparison is based on the assumption that the actual and ideal diffusers have the same geometry, the same mass flow, and the same inlet static pressure and the same inlet mass-averaged total pressure. Although it does not appear to be discussed in the diffuser performance literature, not all of the inlet conditions can be matched simultaneously. For example, if the ideal and actual diffusers have the same mass flow rates and inlet static pressures, they will not have the same inlet mass-averaged total pressures. In this case, the commonly used assumption that the shortfall in static pressure recovery is due to total pressure loss ($\omega = C_{p_i} - C_{p_e}$) will clearly lead to an ambiguous estimate for the total pressure loss in the actual diffuser. The present section examines the effect of the mismatched inlet conditions on the performance estimates.

In incompressible flow, the basic prime quantities which identify the inlet conditions are: inlet static pressure, inlet mass flow, inlet density, inlet area and inlet mass-averaged total pressure. It can be assumed that the density and area are the same in the ideal and real diffusers. However, only two out of the three remaining prime quantities can be matched between the two diffusers, leaving the other one different. For example, as mentioned above, if the inlet static pressure and mass flow are assumed to be the same, the inlet mass-averaged total pressure will be different. This relationship is demonstrated below.

The total pressure equation is employed for the two flow situations at the inlet.

For ideal flow,

$$\overline{P_{0i}} = P_{s_i} + \frac{1}{2} \rho \overline{u_i}^2$$

For real flow,

$$\overline{P_{01}} = P_{s1} + \alpha_1 \frac{1}{2} \rho \overline{u_1}^2$$

Then,

$$(\overline{P_{01}} - \overline{P_{01}}) = (P_{s1} - P_{s1}) + \frac{1}{2} \rho \overline{u_1}^2 (\alpha_1 - 1)$$

Because the inlet static pressures are the same, that is $P_{s1} = P_{s1}$, and the inlet kinetic-energy-flux parameter, α_1 is greater than unity, the above relationship becomes

$$\Delta C_{P_{01, \text{inlet}}} = \frac{\overline{P_{01}} - \overline{P_{01}}}{\frac{1}{2} \rho \overline{u_1}^2} = \alpha_1 - 1 \quad (2.15)$$

That is, the inlet total pressure is larger in the actual than the ideal flow. This example is shown graphically in Fig.2.8.

Alternatively, if the ideal and actual diffusers have the same mass flows and inlet total pressures, then the inlet static pressures will not be matched. This relationship is shown in Fig.2.9 and is demonstrated below.

Again,

$$(\overline{P_{01}} - \overline{P_0}) = (P_{s1} - P_{s1}) + \frac{1}{2} \rho \overline{u_1}^2 (\alpha_1 - 1)$$

But now,

$$(\overline{P_{01}} - \overline{P_0}) = 0$$

And thus,

$$\Delta C_{P_{01, \text{inlet}}} = \frac{(P_{s1} - P_{s1})}{\frac{1}{2} \rho \overline{u_1}^2} = (\alpha_1 - 1) \quad (2.16)$$

In this case, the static pressure is larger in the ideal than the actual flow.

Inlet Conditions: Same inlet mass flows and
inlet static pressures.
Different inlet total pressures.

Fig. 2.8 Inlet Mass-Averaged Total Pressure Off-Set in Diffuser

Fig. 2.9 Inlet Static Pressure Off Set in Diffuser

7

From the above examples, it is clear that no matter which inlet matching conditions are used, there will be an ambiguity due to either inlet static pressure off-set, $\Delta C_{p, \text{inlet}}$, or inlet total pressure off-set, $\Delta C_{p_0, \text{inlet}}$, in the values of C_p or C_{p_0} predicted at the outlet. The relative importance of this ambiguity depends on the overall change in C_p or C_{p_0} and can be measured with the following parameters:

(1) Inlet static pressure off-set parameters

$$E_{oo} = \frac{\Delta C_{p, \text{inlet}}}{(C_{p_i} - C_{p_o})_{\text{outlet}}} \quad (2.17)$$

and,

$$I_{oo} = \frac{\Delta C_{p, \text{inlet}}}{C_{p_i, \text{out}} - C_{p_i, \text{in}}}$$

Since $C_{p_i, \text{in}} = 0$,

$$I_{oo} = \frac{\Delta C_{p, \text{inlet}}}{1 - \left(\frac{A_1}{A_2}\right)^2} \quad (2.18)$$

(2) Inlet total pressure off-set parameters

$$T_{oo} = \frac{\Delta C_{p_0, \text{inlet}}}{\omega} \quad (2.19)$$

E_{oo} and I_{oo} relate the inlet static pressure off-set to the effectiveness depreciation $(C_{p_i} - C_{p_o})_{\text{outlet}}$ and the ideal static pressure recovery. T_{oo} relates the inlet total pressure off-set to the total pressure loss coefficient. Typical magnitudes of these parameters will be examined in chapter 5.

Of course, the ambiguity is removed entirely if the performance of the actual diffuser is defined without reference to the "equivalent" ideal diffuser. However, as discussed in section 2.3, this results in a much larger number of performance curves being needed (a η vs B_{in} plot can replace the various C_{p_o} vs B_{in} plots as described by Padilla (1982)). Therefore, it is still convenient to include the ideal pressure recovery model into diffuser performance analysis.

Chapter 3

Apparatus

From the review of previous work on diffuser performance, discussed in chapter 2, it is evident that more experimental data are needed on the total pressure losses in diffusers. To obtain such data, boundary layer measurements were made in a conical diffuser test rig designed for use with the Carleton University Annular Wind Tunnel. The present chapter describes the apparatus used in the experiment.

3.1 The Annular Wind Tunnel

The annular wind tunnel is of the open-circuit type and is located in the Hydraulics Laboratory in the Department of Mechanical and Aeronautical Engineering of Carleton University. A cross-sectional drawing of the annular wind tunnel with all the major components indicated is shown in Fig. 3.1 (Sjolander, 1975). Air is drawn into the wind tunnel by a Budworth two-stage axial flow compressor driven by a variable speed DC motor (item 1, Fig. 3.1). The compressor can deliver flow rates of up to about 9 lbm/sec at a maximum total pressure rise of about 20-in. of water (508 mm of water). Behind the compressor is a diffuser which has an area ratio of 2.72 and a cone angle of 14-degree (item 4). This diffuser is used to diffuse the air from the compressor and also functions as a passage which leads air to the cylindrical settling chamber (item 2). At the diffuser outlet, there is a hexagonal honeycomb (item 5) of 3/8-inch cell width and 3 inches depth which is used to remove residual swirl from the compressor. In the settling chamber, there are three sets of screens (item 6) which are used to reduce the turbulence intensity of the flow and to improve the total pressure uniformity. Finally, at the outlet of the wind tunnel, the air flows through a contraction and leaves as an air jet measuring 16 inches in diameter, which then flows into the conical diffuser test rig (item 3).

Fig 3.1 Annular Wind Tunnel, adapted from Sjolander (1975)

The diffuser test rig was mated to the annular wind tunnel by four threaded metal rods which pass through the flanges and fasten onto a triangular bracket on the settling chamber. The connection was fitted together tightly to minimize air leakage. After passing through the diffuser, the flow was discharged into the laboratory room. Since the laboratory room is large, intake flow should not be affected by the diffuser discharge flow. A more detailed description of the conical diffuser is given below.

3.2 The Conical Diffuser

The diffuser test rig was designed by a fourth year student (Tsang,1982) as part of a fourth year project. Fig. 3.1 shows a sectional drawing of the conical diffuser test rig. The diffuser test rig was manufactured from maple wood and was sealed with polyurethane in order to minimize swelling or shrinking which might result from changes in atmospheric humidity. Unfortunately, this aspect of the design was not successful and, as discussed below, swelling and cracking of the wood were encountered. Apparently, moisture penetration was the source of these problems.

The conical diffuser test rig was comprised of two sections: a contraction section (item 1, Fig. 3.2), and the diffuser test section (item 2, Fig. 3.2). The front contraction section serves as a bell mouth directing air flow from the annular wind tunnel into the diffuser test section. The diffuser test section is a straight conical diffuser and the geometry of the diffuser is: $R_1=5.4$ in., $R_2=8$ in., $L=18$ in., the divergence angle $2\phi=16.4$ degrees, length ratio $L/R_1=3.34$ and the area ratio, $AR=2.22$. The geometry of the diffuser is marked with a triangle on the diffuser performance diagram of McDonald & Fox (1966), Fig.2.1: this diagram indicates that the flow should be steady. Also, in Fig.2.2, another flow regime chart from the ESDU data sheets(1973), the present diffuser lies below line a-a, the line of onset of unsteady flow. Therefore, the test diffuser is within the steady flow regime. The two sections were mounted together by bolted flanges. In addition, a straight tail pipe measuring approximate 16 inches long was mounted onto the diffuser exit by three angle-brackets in order to attain a more complete pressure recovery. Since most measurements of static pressure and velocity profile were taken in the conical diffuser test

Fig. 3.2 Conical Diffuser

section, the design of this test section is described in more detail below.

There were fourteen static tap stations made from brass tubing of 0.094 in.(2.45 mm) outside diameter, 0.065 in.(1.65 mm) inside diameter, located on the side walls of the diffuser, with seven static tap stations on each side of the diffuser. However, modification were made in order to obtain a more accurate measurement of the static pressure distribution. Thus, twelve more static taps were added to the diffuser wall (to give 13 on each side). These static taps were connected to the scanivalve system by plastic tubing. The co-ordinates of the static taps are given in Table 3.1. Also, seven 1/8 inches(0.125 in.) holes were drilled through the top wall of the diffuser test section to allow a probe to be inserted for traversing the boundary layers. Table 3.2 shows the location of the traversing stations.

3.3 Instrumentation of The Conical Diffuser

The following subsections describe the type and use of instruments used in the experiment.

3.3.1 Computer System

A Hewlett Packard model 3054A data acquisition system (see Fig. 4.1) was used in the experiment. The system is composed of a system main controller, the HP-3497A data acquisition unit and the HP-3456 digital voltmeter. They are interfaced via the 82937A HP- IB (HP Interface Bus) I/O card to the HP-85A system computer which includes 30.7 K bytes of RAM. (Refer to HP-3456A User Guide)

The HP-3497A main controller with the 44421A 20 channels guarded acquisition plug-in assembly offers switching and control of the input signals. In the experiment, two input analog signals from the pressure transducers were connected to the 20 channels acquisition plug-in assembly. Fig. 3.3 shows the schematic wiring diagram of the input channels. The input analog signals were processed by the HP-3456A digital voltmeter which is accurate

Static Tap Station of side 1	Distance x (inches)	Static Tap Station of side 2	Distance x (inches)
1-A	-1.69	2-A	-1.73
1-B	2.27	2-B	2.19
1-C	3.40	2-C	3.38
1-D	4.94	2-D	5.08
1-E	6.53	2-E	6.48
1-F	7.88	2-F	8.15
1-G	8.99	2-G	8.91
1-H	10.63	2-H	10.52
1-I	12.02	2-I	11.96
1-J	13.09	2-J	13.04
1-K	14.56	2-K	14.50
1-L	15.87	2-L	15.78
1-M	17.05	2-M	17.01
1-N	20.23	2-N	20.23

Side 1 is the left side of the diffuser looking upstream.

Side 2 is the right side of the diffuser looking upstream.

Also note that station N is in the tail pipe which is attached to the diffuser outlet.

Test Rig Geometry:

Area Ratio 2.22; Cone Angle 16.4° ; L/R_1 3.34.

Table 3.1: Static Tap Locations

to 10 PPM at 10 V range (or accuracy of 0.002 percent of the measured value) with six and a half digits resolution. The integrating analog-to-digital (A/D) conversion circuit included in the 3456A voltmeter provides a reading rate of 48 readings per second by using the Multi-Slope II conversion technique. The run-up integration time period for the A/D converter with selected integration setting of one power-line-cycle at 60 Hz operation was 16.67 milliseconds. The processed digital signals were transmitted to the system computer and were stored in array memory (refer to 3456A operation manual for detailed technical information).

3.3.1.1 Data Sampling Program

A Basic program was written to select input channels and control data sampling rate of the 3456A Digital Voltmeter. A print-out of the program are included at Appendix B.

3.3.2 Circular Pitot Probe

In order to design the pitot probe which was used to measure the velocity profiles in the diffuser, the following were taken into consideration.

3.3.2.1 Pitot Probe Diameter

In 1983, a fourth year engineering student (Velazquez, 1983) made preliminary measurements of the velocity profiles in the present diffuser. Velazquez found that at the inlet section, u is already .8385 of U_{∞} at 1/32 in. (.03125 in.) from the wall. The half diameter of Velazquez's pitot probe was 0.03125 in. and this is therefore the closest distance from the wall that he could make measurement. Thus, details of the velocity profile were lost. Moreover, from Fig. 3.4 (Velazquez, 1983), the displacement thickness and the momentum thickness were plotted against distance from the wall at the inlet section on the assumption that the velocity varied linearly from zero at the wall to a certain corrected velocity at .03125 in. from the wall. It can be seen from Fig. 3.4 that

=1 variable capacitance differential pressure transducer voltage

=2 variable capacitance differential pressure transducer voltage

Fig. 33 Wiring of Input Channels to the 3497A Controller

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Fig. 3.4 Distribution of Displacement and Momentum Thickness Functions (from wall to 0.03125 inches)

the major contribution to the two integral parameters comes from this .03125 in. portion nearest to the wall. Therefore, Velazquez recommended that the geometric center of the new pitot probe must be made smaller than .03125 in.. The present pitot probe has outside diameter, $D = .033$ in. and an inside diameter, $d = .017$ in. so that the geometric centre is well within the .03125 in. region.

3.3.2.2 Misalignment Effect

Fig. 3.5 (Macmillan, 1954) shows the variation of yaw sensitivity of the pitot probe of different d/D ratios. The d/D ratio of the required probe has to be large enough so that it is insensitive to yaw. The present probe has $d/D = .515$ (.017/.033) and from Fig. 3.5, the reduction in total head reading is less than 1% for 10 degrees of yaw angle. In the experiment, probe alignment was determined aerodynamically (described in Section 4), and yaw angle was kept within one to two degrees. Therefore, the total pressure measurement was quite accurate even with the maximum two degrees of yaw. Also, as seen in Fig. 3.6, as the pitot probe approaches near the wall, the pitch angle may reach a maximum equal to the wall inclined angle of 8.2 degrees. However, this is still well within the allowable 10 degrees of misalignment angle, and therefore, total pressure measurement was still quite accurate.

3.3.2.3 Pitot Probe Stem

The pitot probe stem should preferably be long enough to reach the center line of the diffuser. From Fig. 3.7, the suggested minimum length of the required probe stem is 11.3 inches. However, the probe was designed to be inserted from inside the diffuser, and so the length of the probe was restricted by the diffuser throat diameter of 10.8 inches. The length of the present probe stem is 10.7 inches which is shorter than the required 11.3 in.. Therefore the probe could not traverse the whole of the flow and a small unmeasured region exists near the center line region of the diffuser. But, this small unmeasured region is not important to the whole velocity profile measurement, since at the outlet section,

Fig. 3.5 Yaw Sensitivity of Pitot Probe

Fig. 3.6 Pitching Misalignment as Probe Approaches Wall

Fig. 3.7 Length of Pitot Probe Stem required to reach Centerline

the boundary layer thickness is about 2.5 in. which is well within the measurement range of the probe stem.

3.3.2.4 Length of Pitot Probe

Another minor consideration was the length of the .033 inches (outside diameter) pitot probe. The probe was designed to be long enough so that the stream line at the stagnation point would be very little affected by the probe stem. Appendix C contains the inviscid calculations (Velazquez, 1983) of the minimum length of the .033 inch (O.D) pitot probe. In Velazquez's calculation, the probe was assumed to have 5 degree of misalignment with respect to the flow and 10 degree of velocity misalignment at the stagnation point. His calculation found that the minimum length of the pitot probe is 0.2154 inches. The length of the present pitot probe is .75 in. which is well above the minimum length of the probe. The final configuration of the pitot probe is shown in Fig.3.8.

3.3.3 The Traversing Gear

The traversing gear was designed by Velazquez (1983) and was modified in minor way for the present work. The traversing gear was mounted on the top wall of the diffuser and the pitot probe was attached to it as shown in Fig. 3.7. By operating the traversing gear, the pitot probe could be advanced across the diffuser test section in step as small as .001 inches. Fig. 3.9 shows the required length of the traverse column and Figs. 3.10, 3.11 and 3.12 shows the schematic diagrams of the traversing gear. The major components of the traversing gear are shown and listed in Figs. 3.11 and 3.12. As shown in the figures, the stem of the pitot probe is inserted through the platform (item 2, Fig.3.12). By tightening the screw (item 4), the holder (item 3) is fixed. The platform and holder (items 2 and 3) are linked by a threaded rod (item 6, Fig.3.12). By turning the knob (item 1), the platform can be moved together with the pitot probe in small steps as read from the dial gauge (item 7). The dial gauge can read from one inch down to 0.001 inches, so that, by adjusting the turning knob (item 1) reading from the dial gauge, the pitot probe could be

Fig 3.8 Actual Pitot Probe

Fig. 3.9 Required Length of Traverse Column to allow Probe to reach Centerline

Fig. 310 Traverse Gear Details

(figure taken from Velasquez (1983))

Fig 3 11 Traverse Gear (a)

- (1) Knob
- (2) Platform
- (3) Holder
- (4) & (5) Screws
- (6) Threaded Bar
- (7) Chain Gauge

Fig. 3.12 Traverse Gear (b)

Fig 4-1 Arrangement of Instrumentation for Velocity Profile Measurements

Fig. 3.15 Pressure Transducer Calibration Curve (b)

Fig. 3.14 Pressure Transducer Calibration Curve (a)

Fig. 3.15 Pressure Transducer Calibration Curve (b)

experimental error, voltmeter inaccuracy and curve fitting inaccuracy all combine to produce this figure of 0.5%. Thus, this percentage can form the basis for a final estimation of the experimental error.

As mentioned above, a Rosemount pressure transducer was connected to a single scanivalve, model DSS-48C, and was used to measure pressure. A scanivalve interface controller, model ITF-488, was used to command the scanivalve to step from one port to another (or home). The complete scanivalve system is shown in Fig. 3.16. The scanivalve system is capable of scanning up to 48 differential pairs of analog pressure at a rate set by the interface controller. In the experiment, 26 connection ports were used and were connected to twenty-six static stations in the diffuser. (refer to DSS-48C Scanivalve Manual for detailed information)

3.3.5 Miscellaneous Apparatus

Two digital voltmeters (DISA model 55D31, inv. no. 652 and HP model 3440A serial no. 415-0088) were used in the experiment to display the voltages transmitted by the transducers. Both digital voltmeters were set to read between ± 1 volt and are accurate to ± 0.001 volts.

The temperature of the settling chamber was measured from a YSI model 42SF tele-thermometer, serial number 1443. According to previous study (Sjolander, 1975), the tele-thermometer was found to agree to within ± 0.5 degree F over the 75 degree to 100 degree F range of the measurements. The measured temperature is approximately equal to the fluid total temperature in the settling chamber and was used to obtain the viscosity of the air.

An HP-5221A electronic counter is used to measure the RPM of the compressor rotor.

- ① Scanivalve
- ② Scanivalve Controller
- ③ Tubings

Fig. 3.16 Scanivalve System

Chapter 4

Experimental Method

4.1 Scope of measurements

The objectives of the experimental part of the thesis were

1. The measurement of the velocity profile from the inlet to the outlet of the diffuser and
2. Static pressure recovery along the length of the diffuser.

Once the velocity profile data were collected, they were then integrated to obtain the boundary layer integral parameters (displacement thickness, momentum thickness and energy thickness) and the total pressure loss of the diffuser.

4.2 Experimental Set Up

The overall arrangement of the instrumentation for the experiments is shown in Fig. 4.4. The wooden conical diffuser (item 1) was connected to the annular wind tunnel (item 2). The traversing gear (item 3) with the pitot probe (item 4) was mounted on top of the diffuser. Tubing from the scanivalve system were connected to the diffuser static tap stations and the pitot probe. Two pressure transducers (item 5) were used for pressure measurement. Disa and HP digital voltmeters (item 6 and 7) were used to obtain transducer readings. The pressure signals from the transducers were also connected to the 3054A data acquisition system for data sampling (item 8).

4.3 Experimental Procedures

The experimental procedures are briefly outlined as follows:

Fig 4-1 Arrangement of Instrumentation for Velocity Profile Measurements

- a) The traversing gear and the pitot probe were mounted on the diffuser at the inlet section.
- b) Initial conditions of the transducers, room temperature and atmospheric pressure were recorded.
- c) The annular wind tunnel was turned on and allowed to run for about 30 minutes to allow the operating point to stabilize. The data acquisition program (software) was loaded into the HP-85A computer so that the 3054A automatic system was in the ready mode for data sampling.
- d) The wind tunnel was adjusted to run at the wind tunnel operating point.
- e) The scanivalve was adjusted to the inlet section of the diffuser to take dynamic pressure reading.
- f) The position datum for the pitot probe was determined.
- g) The pitot probe was aligned with the main flow direction (yaw angle adjustment).
- h) Boundary layer traverse was carried out at the inlet section by advancing the pitot probe across the flow passage. Data were sampled by the 3054A system.
- i) The above procedures were repeated at the remaining traverse stations.
- j) Static pressure measurements were made on each side of the diffuser.
- k) The temperature of the room, the wind tunnel reference pressure and the atmospheric pressure was monitored throughout the experiment. The wind tunnel operating point was readjusted if necessary during the course of the measurements.
- l) The final conditions of the experiment, that is, the transducers readings, room temperature, atmospheric pressure and tunnel temperature were recorded. These were compared with the initial conditions and if there were significant discrepancies, the run was discarded. Detailed explanations of the experimental method are given in the following sections.

4.4 Wind Tunnel Operating Point

Two static taps are located on the outer wall of the wind tunnel contraction, one near the start and the other near the end of the contraction as shown in Fig.4.2. The pressure difference between these taps was used to monitor the tunnel operating point because this pressure difference ($P_{e_1} - P_{e_2}$) is directly related to the diffuser test section dynamic pressure. The operating point was chosen to give a Reynolds Number of 3.58×10^5 , based on the diffuser inlet section radius and the diffuser inlet mass-averaged velocity (which was approximately 40 m/sec). Based on the variations in ambient pressure and settling chamber temperature, the dynamic pressure was checked roughly every half hour and adjusted if necessary to maintain constant Reynolds Number. The contraction pressure difference required to maintain constant Reynolds Number was found to vary by up to 5% during a typical test run of 3 to 4 hours duration.

4.5 Data Acquisition

4.5.1 The Operation of the 3054A System for Data Sampling

The 85A system computer controls the system operation through the use of instructions transmitted over the interface bus, HP-IB to each instrument. In the experiment, the sequence of instructions required to perform the task of data sampling came from the data acquisition program written for the experiment. Fig.4.3 shows the signal flow path of the 3054A system. The main controller 3497A, was set up to select and control the input multiplexing signals. The input channels were scanned sequentially by the 3456A digital voltmeter. Fig.4.4 shows the real time scanning process of the two input analog signals from the pressure transducers. The A to D converter inside the 3456A converted the input analog signal to a digital signal. The processed digital signal was then transmitted to the 85A system computer and was stored in array memory. At the termination of the scanning process, the data were retrieved from the array memory for hard copy reproduction.

Fig. 4.2 Arrangement of Wind Tunnel Reference Static Taps

Fig. 43 Signal Flow Path of the 3054A System during Experiment

t' is the total time required to take reading from channel 1 which measures the dynamic pressure from transducer #1

t'' is the total time required to take reading from channel 1 which measures the wind tunnel reference pressure from transducer #2.

T is the time interval that allow measurement to be completely performed and data to be stored before another scan.

$T-(t'+t'')$ is the wait period between each scan. No functions are being performed during this time.

Fig. 4.4 Real Time Scanning Process of Input Analog Signals

4.5.2 Measurement Rate and Averaging Time for Data Sampling

According to preliminary velocity profile measurements in the diffuser, it was found that the input analog DC voltage signals were highly varying both in time and space. Therefore, a large number of measurements were needed to give a reliable average value for the fluctuating signal. A fast measurement is also desirable to obtain the needed samples as quickly as possible. The accuracy or resolution was an equally important factor to be considered during scanning. As stated from the 3456A operation manual, the selection of integration time setting is the key to both measurement speed and measurement accuracy in the 3456A digital voltmeter. Integration times of 0.10, 1.0 and 10 power-line-cycles were tried and the 1 power-line-cycle as recommended by the manual was found to give a reasonable compromise between accuracy and data acquisition time, thereby, one power-line-cycle was selected as the system integration time setting (1 power-line-cycle has a time period of $1/60$ or 0.016667 seconds for 60 Hz operation). The corresponding reading rate was 48 readings/second with six digits of resolution. Having established the measurement rate which enabled measurement of the signals, the averaging time for data sampling was also determined. The averaging time is the measurement period required to obtain a reliable average value of the input varying voltage. In order to determine this averaging time, data were sampled at two different locations at the diffuser outlet section where the most severe disturbances were expected to occur. Voltage readings obtained from the two different locations were plotted against time and are shown in Fig 4.5 and Fig 4.6. Fig 4.5 shows the time-averaged voltages that were taken in the shear layer at $y = 0.03$ inches. The time-averaged voltages become stabilized within a small band of 0.01 after scanning sixty seconds of data. Therefore, sixty seconds was selected to be the averaging time for sampling a data point when traversing across the shear layer. Similarly, the averaging time of data sampling at the free stream is determined to be twenty seconds (Fig 4.6).

Fig. 4.5 Averaging Time for Scanning Inside Shear Layer

Fig. 4.6 Averaging Time for Scanning Free Stream Region

4.6 Velocity Profile Traversing

4.6.1 Pitot Probe Alignment with main Flow and Probe Zero Position

Before velocity profile measurements were carried out, the pitot probe yaw angle must be nulled and the probe zero position determined. The detailed explanations of the probe yaw angle and zero position are given below:

4.6.1.1 Probe Alignment

Since misalignment of the pitot probe with the main flow vector causes reduction in total head reading (as described in sect. 3.3.2), it was necessary to null the probe yaw angle before the measurements were taken. The total head reading was measured against the probe yaw angle ψ as shown in Fig.4.7. The probe position that gives maximum total head reading should be the zero yaw position and the probe was therefore set to this angle.

4.6.1.2 Probe Zero Position

The diffuser wall was used as the position reference at each traverse section. Therefore, before the velocity traverse was carried out, the probe was adjusted to touch the wall and this wall location was then the probe zero position. The location of the wall was determined aerodynamically as shown in Fig.4.8. The total head readings were measured against the traverse position and the probe position that gives minimum readings should be the wall location. After the zero position was determined, boundary layer measurements were made by traversing the pitot probe from the zero position to the free stream at the center core.

4.6.2 Traversing Step

Once the probe yaw angle was set and the probe position datum was determined, the

Fig. 4.10 Static Pressure Variation Along Diffuser

Fig. 48 Determination of the Wall Location

boundary layer traverse was carried out. The probe's movement was controlled manually by adjusting the traversing gear (as described in sect. 3.3.3) and the travelling distance of the probe was read on the dial gauge. In order to obtain a detailed velocity profile, the probe must be traversed in small steps. In the shear layer, close to the wall, where the velocity gradients were steep, steps of 0.002 inches were used. As velocity gradients declined, traverse steps larger than 0.002 inches were taken. For example, at the inlet section, steps of 0.002 in. were taken from $y=0.0165$ in. (geometric center of the probe) to $y=0.0305$ in. with 8 measurements; from $y=0.0305$ in. to $y=0.0935$ in., steps measuring 0.003 in. were taken with 21 measurements; and steps 0.03 in. were taken from $y=0.2735$ in. to $y=0.4835$ in. with 6 measurements. In total, 90 measurements were taken at the inlet section and the boundary layer thickness at the inlet section was approximately 0.12 inches. The boundary layer thickness at the outlet was approximately 2.4 inches and about 140 measurements were taken at this section.

4.6.3 Dynamic Pressure Measurement

At every point in the traverse, a pressure difference, ΔP_{pitot} was measured with a Rosemount pressure transducer (serial number 633). ΔP_{pitot} is the pressure difference between total pressure measured by the pitot probe and wall static pressure measured by the nearest wall static tap as shown in Fig. 4.9. However, this pressure difference ΔP_{pitot} was not the actual dynamic pressure, since the pitot probe and the static tap were not in the same plane. The static tap was 0.075 inches (length of probe) behind the probe plane. Therefore, to obtain the dynamic pressure, it was necessary to interpolate the static pressure at the pitot probe plane. As shown in Fig. 4.10, the static pressure variation along the length of the diffuser was measured. There is a pressure difference, ΔP_s , between the reference static pressure $P_{s,r}$ (static pressure that was measured from the nearest wall static tap) and the static pressure at the same plane as the pitot probe, P_s (see Fig. 4.9). This pressure difference ΔP_s was determined from the static pressure distribution curve (see Fig. 4.10). The static pressure measurements are described in sect. 4.6.4.

The dynamic pressure is expressed as follows:

Fig. 4.9 Dynamic Pressure Measurement

Fig. 4.10 Static Pressure Variation Along Diffuser

$$\frac{1/2\rho u^2}{P_{e1} - P_{e2}} = \frac{P_0}{P_{e1} - P_{e2}} - \frac{P_s}{P_{e1} - P_{e2}} \quad (4.1)$$

where $1/2\rho u^2$ is the dynamic pressure, P_0 is the total pressure measured by the pitot probe, P_s is the static pressure at the same plane of the probe and $(P_{e1} - P_{e2})$ is the wind tunnel reference pressure. This reference pressure was used to non-dimensionalize measured dynamic pressures as well as static pressures. Since a change in the supply dynamic pressure will cause a change in the measured pressure, so the ratio of measured pressure/ $(P_{e1} - P_{e2})$ will compensate for the change due to the fact that the two pressures are directly related.

From the measurement, we have

$$\frac{\Delta P_{\text{pitot}}}{P_{e1} - P_{e2}} = \frac{P_0 - P_{\text{ref}}}{P_{e1} - P_{e2}}$$

Therefore,

$$\frac{P_0}{P_{e1} - P_{e2}} = \frac{\Delta P_{\text{pitot}} + P_{\text{ref}}}{P_{e1} - P_{e2}} \quad (4.2)$$

And,

$$\frac{\Delta P_s}{P_{e1} - P_{e2}} = \frac{P_{\text{ref}} - P_s}{P_{e1} - P_{e2}}$$

Therefore,

$$\frac{P_s}{P_{e1} - P_{e2}} = \frac{P_{\text{ref}} - \Delta P_s}{P_{e1} - P_{e2}} \quad (4.3)$$

By substituting (4.2) and (4.3) into (4.1), we obtain

$$\frac{1/2\rho u^2}{P_{e1} - P_{e2}} = \frac{\Delta P_{\text{pitot}}}{P_{e1} - P_{e2}} + \frac{\Delta P_s}{P_{e1} - P_{e2}} \quad (4.4)$$

From equation (4.4), dynamic pressure is obtained at every point in the traverse.

4.6.4 Static Pressure Measurement

The static pressure variation along the length of the diffuser was measured with the scanivalve system (as described in sect. 3.3.5). In all cases, the pressure was measured rel-

ative to the static pressure at the diffuser inlet. The measured static pressure is expressed as $\frac{P_s - P_{s1}}{P_{e1} - P_{e2}}$.

where P_s is the measured static pressure, P_{s1} is the reference static pressure at the inlet and $(P_{e1} - P_{e2})$ is the wind tunnel reference pressure.

The static pressure sensed by a finite-sized static tap is inevitably different from the true static pressure because the hole distorts the flow. Therefore, static hole error at the static taps station along the wall of the diffuser was estimated. The data of Shaw (1960) for the static hole error of small holes was applied. The error was estimated to be 10 percent of the wall shear stress, or about 0.03 percent of the mainstream dynamic pressure based on the assumed value of $C_p = 0.003$. This is small compared with the experimental uncertainty in making the static pressure measurement, and, the static hole error was therefore neglected.

4.6.5 Effect of Velocity Gradient

When a pitot probe is used to measure shear flow, the effective measuring point is generally shifted from the centre of the tube towards the region of higher velocity (see Fig.4.11). For the present study, the displacement correction was based on the work of Young & Maas (1936). Young & Maas confined their experiments to plain cylindrical tubes with square ends like the probe used in the present experiment. They found that the displacement correction was,

$$\frac{z}{D} = 0.131 + 0.082 \frac{D}{d} \quad (4.5)$$

where z is the outward displacement correction, D is the outside diameter of the pitot probe and d the inside diameter. MacMillan (1954) suggested that the value of z given by equation (4.5) is a little too high. He used a tube in which $\frac{d}{D} = 0.6$ and obtained a value of $\frac{z}{D}$ between 0.14 and 0.16, whereas (4.5) gives 0.18. However, in the absence of better data, the correction equation (4.5) has been used.

For the probe used in the experiment, $d = 0.017$ inches, $D = 0.033$ inches. Therefore, by applying equation (4.5), $z = 0.005649$.

**Fig. 4.11 Effect of Velocity Gradient on Effective
Measuring Point of a Pitot Probe**

4.6.6 Effect of Wall Proximity and Viscosity

MacMillan(1954) found that in boundary layer measurement, wall proximity correction is necessary if the geometric centre of a probe for which $\frac{d}{D}=0.6$ is nearer than $2D$ to a solid boundary. The velocity measured has to be increased in accordance with curve A as shown in Fig.4.12 (MacMillan, 1954). The pitot probe used in the experiment has $\frac{d}{D} = \frac{0.017}{0.033} = 0.515$, which is close to 0.6 on MacMillan's curve. Thus, curve A on Fig.4.12 was used to correct the measured velocity.

Also, the pitot probe was subjected to error due to viscosity. The magnitude of the error has been established (see Fig.4.13 (MacMillan, 1954)) for small pitot probes. In the present experiment, the Reynolds Number based on the diameter of the probe and the minimum velocity measured at the wall location at the outlet section was greater than 100 and from Fig.4.13 the corresponding C_p value was approximately 1.005. Therefore, we may conclude that viscosity effect on pitot probe readings was negligible.

4.6.7 Effect of Turbulence

Goldstein(1936) made a theoretical investigation of turbulence effect and showed that the pressure measured by the pitot probe in incompressible flow is not $(P+1/2\rho V^2)$ but $(P+1/2\rho V^2) + 1/2\rho(\overline{v_x^2} + \overline{v_y^2} + \overline{v_z^2})$, where $\overline{v_x^2}$, etc. are the mean squares of the turbulent components v_x , v_y , and v_z . Turbulence measurement was carried out in the free stream flow at the outlet of the wind tunnel by Amrud (1985). The turbulence intensity in the axial direction, $\frac{\overline{v_x}}{V_\infty}$ was measured to be 0.4%. Sjolander(1975) measured a turbulence intensity of 0.5 to 0.7% (freestream) in the same wind tunnel but with a different test section. Since 0.7% is only a very small contribution to the main flow, the turbulence effect is likely to be negligible. On the other hand, the values of turbulent intensity are much higher within the shear layer close to the wall. However, since we did not measure the turbulent intensity in the shear layer in the present experiment, no attempt has been made to correct the measurements for the effects of turbulence.

Wall proximity correction for pitot tubes. Curve A: circular probe with $d/D = 0.6$ (Macmillan). $R_p = 2.4$ to 11.8×10^6 . Curves B and C: flattened tubes with $b/H = 0.6$ (Quarmby and Das⁽²³⁾). $R_p = 2.8 \times 10^6$ for curve B and 5.8×10^6 for curve C.

Fig. 4.12 Wall Proximity Correction for Pitot Probe

Fig. 4.13 Viscosity Errors of Small Pitot Probes

Chapter 5

Results and Discussion

5.1 Static Pressure Measurement

Static pressures were measured on both sides of the diffuser. Fig. 5.1 shows two static pressure variation curves which were measured on different dates: 17 April, 1984 and 16 Jan., 1984. As seen from the figure, the later static measurements gave a lower static recovery than the earlier ones. The differences between these two static curves were first thought to be measurement error. However, it was later discovered that the boundary layer was separating on the lower wall of the diffuser. The separation was probably triggered by an especially severe crack which had produced a forward-facing step on the wall. The lowered static pressure recovery was therefore mainly the result of the reduced diffuser flow area produced by the separated flow. During the course of the experiment, warping and cracking occurred gradually and caused an uneven surface curvature along the diffuser wall. In Fig. 5.2, many cracks along the length of the diffuser are seen, but the uneven surface is less obvious. This warping and cracking of the wood in the diffuser were believed to be the major cause of discrepancy in the later measurements. In order to regain the original static recovery of the diffuser, the diffuser surface was re-finished. Sandpaper was applied to the wood surface to remove the irregularities and wood chips were used to fill up the cracks. However, this did not entirely cure the separation problem and the original diffuser performance was not recovered completely. It was therefore decided to install vortex generators. The vortex generators were designed and made according to the paper by Senoo and Nishi (1974). The design of the vortex generators and their locations are described in Appendix D. The performance of the diffuser (static pressure rise) was improved after the vortex generators were installed, as is evident in Fig. 5.3. Fig. 5.3 compares the static pressure variation for the diffuser installed with the

Fig. 5.1 Static Pressure Variation Curves

Fig 5.2 Flow Surface in Conical Diffuser

2

Fig 5.3 Static Pressure Variation Curves after Installation of Vortex Generators

vortex generators to the earlier variation curve (no vortex generators) and it shows good agreement between the two curves. However, discrepancies still existed between two sides of the diffuser wall as shown in Fig 5.4. Side two gives a better static recovery at the first half of the diffuser length but a lower recovery near the end of the diffuser. The differences are thought to be due to the changing of the shape of the diffuser caused by the warping effect so that the diffuser did not maintain a uniform circular shape. No attempt was made to measure the out-of-roundness of the diffuser. A smooth static pressure curve was drawn using a french curve based on the results from the two sides, as shown in Fig 5.5. This curve was used as the static pressure variation curve for the rest of the calculations and evaluation of the results.

Fig 5.6 shows the diffuser performance as static pressure recovery coefficient (from the average static curve) vs area ratio. The pressure recovery data are compared to performance predicted by the ideal diffuser model, $C_{p,i}$. The actual static recovery was $C_{p,s} = 0.721$ while the ideal recovery was $C_{p,i} = 0.797$. Also shown in Fig 5.6 is the diffuser static pressure effectiveness data. These effectiveness values are almost constant and are not dependent on the area ratio of the diffuser. As noted in chapter 2, this is one of the useful properties of the effectiveness coefficient. The inlet η value is 0.8835 whereas the η at the outlet is 0.9049. The outlet η value was plotted with the other experimental data in Fig 5.7. The present η value seems to agree with the correlation derived by Sjölander(1981) where η is a function of B_{in} . In Table 5.1, the diffuser performance is compared with various data in the literature. As seen from the table, the static pressure recovery of the present diffuser is in consistent with the results obtained by others on the similar conditions.

5.2 Boundary Layer Traverse Data

Boundary layer traverses were made with the pitot probe at eight different stations along the length of the diffuser. The reduction of the velocity profile data will first be described. This will be followed by a presentation and discussion of the velocity profiles. Finally, the boundary layer integral length scales and various other data will be

Fig. 5.5 Final Static Pressure Variation Curve

Fig 5.5 Final Static Pressure Variation Curve

Fig. 5.6 Static Pressure Recovery Coefficient Distribution

Fig. 5.7 Conical Diffuser Static Pressure Recovery Variation
with Inlet Blockage, from Sjolander (1981)

Table 5.1 Comparisons with other Static Recovery Data

At $B_{in} = 0.008$,

Present Diffuser,

$$C_{p_s} = 0.722, \quad \eta = 0.9058, \quad L/R_{in} = 3.34, \quad AR = 2.22, \quad Re_D = 3.5 \times 10^5$$

Cockrell & Markland(1962),

$$C_{p_s} = 0.64, \quad \eta = 0.7975, \quad L/R_{in} = 3.8, \quad AR = 2.25, \quad Re_D = 1.8 \times 10^5$$

Miller(1971),

$$C_{p_s} = 0.74, \quad \eta = 0.9163, \quad L/R_{in} = 4.0, \quad AR = 2.28, \quad Re_D = 5.5 \times 10^5$$

ESDU Data Sheet,

$$C_{p_s} = 0.67$$

(data was extrapolated from Fig.6 for diffusers with tailpipe, $L_d/D_2 = 4-8$, and entry length ratio $L_e/D_{in} \geq 1$)

summarized for use in calculating the total pressure loss and flow non-uniformity of the diffuser.

5.2.1 Velocity Profile Data Reduction

The boundary layer traverse data were sampled by the 3054A data acquisition system and were reproduced in hard copy. Table 5.2 gives an example of the output from the data acquisition system. The traverse data were documented in y (inches) distance from the wall and the corresponding ΔP_{pitot} and wind tunnel reference pressure ($P_{e1} - P_{e2}$). ΔP_{pitot} is the pressure difference between total pressure measured by the pitot probe and wall static pressure measured by the nearest wall static tap (refer to Fig 4.9). ($P_{e1} - P_{e2}$) is the wind tunnel reference pressure. These traverse data were reduced with a Fortran program which was run on the Honeywell CP-6 computer system of Carleton University to obtain the velocity profile and the corresponding integral length scales. In the computer program, the traverse data were first corrected for the effects of velocity gradient and wall proximity. Static pressure offset ΔP_s was also taken into account in the reduction of ΔP_{pitot} values, where ΔP_s was estimated graphically from the static pressure distribution plot, Fig 5.5. The reduced velocity profile were then integrated to obtain the corresponding integral length scales. The output of the program was the velocity profile expressed in u/u_∞ and the corresponding integral length scales. The data reduction program is contained in Appendix E.

5.2.1.1 Near Wall Data

The geometric center of the present pitot probe is 0.0165 inches and the first available measurement is therefore at this distance from the wall. Particularly near the inlet, this represents a significant fraction of the boundary layer thickness. Therefore, additional points were interpolated between the wall and the first measurement. This was done as shown on Fig 5.8 which represents the data from station 3. The measured values of velocity nearest to the wall were plotted to a large scale and a smooth curve was drawn

	P(REF)	P(PITOT)			
.000000	.187000	.000000	.689500	.198303	.105550
.002000	.187000	.000300	.729500	.197795	.114712
.004000	.187000	.000500	.769500	.197621	.124008
.006500	.187000	.000750	.819500	.197560	.133973
.008000	.187000	.000940	.869500	.197616	.143580
.011000	.187000	.001220	.919500	.197628	.152999
.013200	.187000	.001400	.969500	.197801	.161865
.016300	.187964	.001690	1.019500	.198127	.169930
.018500	.188856	.001890	1.069500	.197868	.176676
.021500	.188958	.002150	1.119500	.188778	.173131
.024500	.189886	.002410	1.169500	.188511	.176857
.029500	.189449	.002921	1.219500	.188660	.180384
.034500	.190542	.003240	1.269500	.192139	.186912
.039500	.190629	.004100	1.319500	.192842	.189707
.044500	.190142	.004500	1.369500	.192997	.191345
.049500	.190701	.004697	1.419500	.192704	.192722
.059500	.191202	.005624	1.469500	.193387	.193289
.069500	.190744	.006326	1.519500	.193405	.193920
.079500	.190783	.007226	1.569500	.193010	.194483
.089500	.191261	.008318	1.619500	.193397	.194721
.099500	.191330	.009153	1.719500	.193926	.194709
.114500	.191316	.010335	1.819500	.192749	.194997
.129500	.191220	.011502	1.919500	.192893	.194741
.144500	.191777	.012646	2.119500	.193309	.194803
.159500	.191502	.013966	2.319500	.193025	.195557
.174500	.192223	.015080	2.519500	.193141	.195105
.189500	.192484	.016276	2.719500	.193817	.195458
.204500	.191961	.017500	2.919500	.194182	.195678
.219500	.192230	.018700	3.219500	.193326	.195521
.239500	.192640	.021349	3.519500	.193632	.195391
.259500	.192925	.023615	3.819500	.193402	.195399
.279500	.192039	.026897	4.119500	.195005	.195442
.299500	.191856	.030071	4.419500	.193404	.195199
.319500	.192197	.033540	4.719500	.193879	.194793
.339500	.192863	.035981	5.019500	.194516	.194567
.359500	.192777	.039703	5.319500	.193488	.193647
.379500	.192455	.042797	5.619500	.193740	.193377
.399500	.192447	.046397	5.919500	.192478	.193141
.419500	.192466	.049855	6.219500	.194145	.192373
.449500	.193736	.055599	6.519500	.192593	.192105
.479500	.197989	.064004	6.819500	.192963	.191286
.509500	.197808	.069282	7.119500	.193000	.190000
.539500	.197809	.076848	7.419500	.193000	.190000
.569500	.197380	.082031	7.861200	.193000	.190000
.609500	.197364	.088226			
.649500	.198186	.096964			

Table 5.2 Sample Output from the Data Acquisition System

Fig. 5.8 Interpolation of Near Wall Velocity Profile Data

them. Values between the wall and the first measurement were then read from this curve. These interpolated values were used later in the calculation of the integral length scales of the boundary layer.

5.2.2 Velocity Profiles and Boundary layer Parameters

The velocity profiles are presented as velocity ratio u/u_∞ against distance y where u is the local velocity, u_∞ is the free stream velocity in the center core and y is the distance from the wall measured in inches. The velocity profiles from station 1 (inlet) to station 7 are presented in Fig 5.9 (a), (b), (c), (d), (e), (f), (g). At the outlet of the diffuser velocity profile measurements were made at different angles around the circumference. These outlet velocity profiles are given in Fig 5.10 (a), (b), (c), (d), (e), (f), and (g). It must be noted that all the above profile measurements were made after the installation of the vortex generators.

The development of the velocity profiles along the diffuser as shown in Fig 5.9 and Fig 5.10 shows that the wall boundary layer grows very rapidly from a nearly uniform inlet flow to a highly non-uniform outlet flow. These results show that even for small area ratios the outlet boundary layers are relatively thick compared to the radius of the diffuser. Therefore, the boundary layers are probably beginning to interact and thus then creates problems in predicting their development using traditional boundary layer methods.

The boundary layer thickness δ at the inlet was 0.12 inches whereas the δ at the outlet was 2.4 inches. Note that these boundary layer thickness values were approximate value based on the height at which u/u_∞ reached 0.995.

As shown in Fig 5.10, there are different velocity distributions in the diffuser outlet section at different circumferential locations. This shows that the diffuser outlet flow was not axi-symmetric. This was probably due to the out-of-roundness of the diffuser and the influence of the vortex generators. As discussed in section 5.1, it was observed that a separated region developed on the bottom side of the diffuser near the outlet section. This problem was cured using vortex generators and the static recovery was

Fig. 5.9(a) Velocity Profile of Section 1 (Inlet Section)

Fig. 5.9(b) Velocity Profile of Section 2

Fig. 5.9(c) Velocity Profile of Section 3

Fig. 5.9(d) Velocity Profile of Section 4

Fig. 5.9(e) Velocity Profile of Section 5

Fig. 5.9(f) Velocity Profile of Section 6

Fig. 5.9(g) Velocity Profile of Section 7

Fig. 5.10(a) Velocity Profile at Outlet Section (zero deg.)

Fig. 5.10(b) Velocity Profile at Outlet Section (30 deg.)

Fig. 5.10(c) Velocity Profile at Outlet Section (60 deg.)

Fig. 5.10(d) Velocity Profile at Outlet Section (120 deg.)

Fig. 5.10(e) Velocity Profile at Outlet Section (-30 deg.)

Fig. 5.10(f) Velocity Profile at Outlet Section (-60 deg.)

Fig. 5.10(g) Velocity Profile at Outlet Section (-120 deg.)

largely regained. The vortex generators were located in the lower part of the diffuser; and as would be expected, the boundary layer development downstream of the vortex generators was altered. Fortunately, the outlet velocity profiles in Fig.5.10 show that the circumferential flow variation was not drastic. Therefore, the boundary layer development in the upper portion of the diffuser, which was outside the region of direct influence of the vortex generators, should experience nearly the "undisturbed" pressure gradient and should reasonably represent what would have occurred if the separation had not been present.

Table 5.3 and 5.4 present the boundary layer parameters from the inlet to the outlet: the axi-symmetric boundary layer displacement thickness (δ^*); axi-symmetric momentum thickness (θ); shape factor (H); kinetic energy-flux parameter (α); energy thickness (δ^{**}); mass averaged dynamic pressure (q); and dynamic pressure based on mass-averaged velocity (q). Also, the outlet boundary layer parameters obtained from various outlet velocity profiles are listed in Table 5.4. All these results were obtained after the installation of the vortex generators. The δ^* , θ , H , and α were plotted against area ratios as shown in Fig.5.11 (a), (b), and (c). The boundary layer parameters all show a normal trend of increase along the length of the diffuser. The inlet shape factor H was 1.4033. This value suggests that the inlet flow was turbulent. The inlet kinetic-energy-flux parameter α was 1.0178 indicating that the inlet flow was nearly uniform and the inlet blockage factor is 0.008. The α at station 7 is 1.1556 which reflects the non-uniformity of the flow. The corresponding blockage factor is 0.0957 which suggests that the flow is still not fully developed. The corresponding H is 2.3309 which indicates the strong adverse pressure gradient imposed in the flow. This shape factor value also suggests that the flow is close to separation.

Along the traverse, the velocity started with zero at the wall and increased to the edge of the boundary layer. Outside the boundary layer, the velocity became constant. It was expected that the velocity would remain constant to the center line. However, the velocity started to decrease slightly before the center line was reached. This suggested that the probe was not traversing along a line of constant static pressure. This is proba-

Station #	AR	θ (inches)	δ^* (inches)	H	δ^{**} (inches)	α
1	1.0	0.0155	0.0216	1.387	0.0279	1.0178
2	1.178	0.0418	0.0661	1.581	0.0711	1.0327
3	1.366	0.0710	0.1274	1.794	0.1163	1.0570
4	1.530	0.0754	0.1543	2.048	0.1139	1.0731
5	1.739	0.1012	0.2229	2.204	0.1486	1.1013
6	1.927	0.1506	0.3383	2.247	0.2270	1.1425
7	2.122	0.1614	0.3762	2.3309	0.2392	1.1556

Table 5.3: Boundary Layer Parameters of the Present Diffuser
(from station 1 to 7)

Degree	θ (inches)	δ^* (inches)	δ^{**} (inches)	α
zero(a)	0.3058	0.5065	0.5065	1.147
zero(b)	0.2964	0.5172	0.4771	1.153
zero(c)	0.2642	0.4761	0.4162	1.150
30	0.3519	0.6449	0.5602	1.200
60	0.3809	0.6290	0.6285	1.1600
120(a)	0.3184	0.6014	0.5095	1.1927
120(b)	0.2600	0.5509	0.3954	1.2053
-30(a)	0.3157	0.6690	0.4928	1.2455
-30(b)	0.3102	0.6316	0.4872	1.2218
-60	0.3332	0.7076	0.5170	1.2603
-120	0.2781	0.4135	0.4794	1.0910

Measurements (a), (b), and (c) represent profiles obtained at the same angular position at different times.

Table 5.4: Boundary Layer Parameters at the Outlet Section (around the circumference)

Fig. 5.11(a) Momentum and Displacement Thickness Distribution

Fig. 5.11(b) Shape Factor Distribution

Fig. 5.11(c) Kinetic-Energy-Flux Parameter Distribution

bly true since the isobar should always be perpendicular to the stream lines and as shown in Fig.5.12, traverses were made perpendicular to the centerline. As seen in Fig.5.12, a one-dimensional flow model suggests that the isobar is a circular arc with the diffuser wall convergence point as the center. An estimate of the effect of static pressure between the present assumed isobar and the one-dimensional-flow model isobar was made. Even though the actual flow in the diffuser was not one-dimensional, comparison with one-dimensional flow will allow rough estimation of the error that was involved in the experiment by using the present assumption of constant static pressure. It was found that the offset distance at the center line of the diffuser in the outlet section is 0.586 inches which corresponds to $\frac{\Delta P}{(P_{t,1} - P_{t,2})} = 0.01$. In the outlet, at $y = 2$ inches, which is approximately the boundary layer edge, the offset distance is 0.2 inches. The corresponding static pressure offset $\frac{\Delta P}{(P_{t,1} - P_{t,2})}$ is 0.002 and this value is small enough to ignore. At the inlet section, the offset distance at the center line is 0.394 inches which corresponds to $\frac{\Delta P}{(P_{t,1} - P_{t,2})} = 0.12$. The boundary layer edge in the inlet is at $y = 0.12$ inches and the corresponding offset distance is very small and can be ignored. Therefore, it can be concluded that this static offset effect is not important and probably can be neglected inside the boundary layer in the present experiment. However, the offset will reach a maximum at the center line especially at the inlet section, so for fully developed flow this offset effect is significant. In addition, the slightly decreased velocity in the center line region may also be due to non-uniform total pressure supplied by the wind tunnel. No attempt was made to correct this velocity drop. Instead, the region of constant velocity was assumed to predominate for the rest of the cross section outside the boundary layer.

The scatter in the velocity profile data caused by errors are discussed here. The equipment has been calibrated properly to eliminate some possible experimental errors. Also, it is assumed that instrumentation has adequate resolution so that fluctuations in reading are not excessive. Moreover, some known errors such as yaw angle misalignment, velocity gradient effect and wall proximity effect have either been nulled or corrected during the course of the experiment and data reduction. Some errors like probe geometry effect, viscosity on pitot probe, voltmeter A/D conversion are very small and are neglected. Then

Fig. 6.12 Constant Static Pressure across Diffuser Cross-Section

the other possible sources of error were probe pitching effect, static hole error, transducer calibration, time-averaged voltage reading inaccuracy and turbulence in the flow. As mentioned in sect. 3.3.2.2, as the pitot probe approached the wall, the probe's pitch angle will reach a maximum equal to the wall inclined angle of 8.2 degree. Consequently, the reduction in total head reading will reach a maximum of 1% at the wall location. Note that this 1% error only happens at the time when the probe is touching the wall and this 1% error will diminish as the probe moves away from the wall. The static hole error as mentioned in sect. 4.6.4 is estimated to be 0.03% of the mainstream dynamic pressure. The error resulting from the transducer calibration is estimated to be 0.5%, which is combined with the error resulting from drift in transducer calibration, voltmeter inaccuracy, curve fitting inaccuracy and finite number of data samplings. The time-averaged voltage reading inaccuracy as shown in Fig.4.5 and 4.6 is 0.0001 volts in 0.005 volts (i.e 2%) as the probe is touching the wall. Again, as the probe moves away from the wall, this 2% inaccuracy will decrease. The error resulting from flow turbulence is rather difficult to quantify, since, as mentioned in sect. 4.6.7, the source of error of the measured data comes mostly from the local turbulence in the shear layer close to the wall. However, no turbulence measurement was made in the shear layer; therefore, the main stream turbulence intensity of 0.7% is taken as rough estimation of the turbulence effect on the diffuser. From the above estimation, the overall maximum % error in the velocity profile data is $(1 + 0.03 + 0.5 + 2 + 0.7) \% = 4.23 \%$. This 4.23 % is the maximum value, occurring only when the probe is touching the wall; While the probe is traversing through the shear layer away from the wall, the percentage error will decrease. The reader should also be aware of the distortion effect of the diffuser caused by warping and cracking of wall surface, because, this problem caused inaccuracy in the measurements which cannot be quantified.

5.3 Total Pressure Loss Coefficient and Flow Non-uniformity Coefficient

The total pressure loss coefficient ω , was calculated from equation (2.12) and the flow non-uniformity coefficient γ , was calculated from the relationship, $\gamma = C_{p1} - C_{p2} - \omega$. Fig.5.13 shows the plots of total pressure loss coefficients and non-uniformity coefficients

against area ratio. As can be seen in Fig 5.13, the total pressure loss coefficient increases along the diffuser with the inlet ω equal to zero and the outlet ω is 0.0626. Also included in Fig 5.13 is the non-uniformity coefficient data curve. The γ coefficient increases gradually along the length of the diffuser and gives a maximum value of 0.0206 at AR = 1.927, and then γ decreases gradually towards the exit of the diffuser. As discussed in sect 2.4, the use of the ideal flow diffuser will lead to an ambiguous estimates for the ideal static pressure recovery and the ideal total pressure loss coefficient. Since the γ was calculated from the relationship of the ideal pressure recovery and the total pressure loss coefficient, that is $\gamma = (C_{p_i} - C_{p_e})_{ideal} - \omega_{ideal}$, so the apparent decrease in "non-uniformity" towards the outlet is probably not too meaningful. In Fig.5.14, the proportion of $(C_{p_i} - C_{p_e})_{ideal}$ due to total pressure loss is plotted against area ratio, $\frac{\omega}{(C_{p_i} - C_{p_e})_{ideal}}$ vs AR. It must be noted that in this calculation the inlet conditions between the ideal and real diffusers are assumed all matched. The ratio is reasonably constant along the length and shows that ω contributes approximately three-quarters of the effectiveness depreciation, $(C_{p_i} - C_{p_e})_{ideal}$. Thus, the proportion of the effectiveness depreciation that is caused by flow non-uniformity is approximately one-quarter.

5.3.1 Center Line Total Pressure Coefficient

Center line total pressure is expressed as

$$P_{0_c} = P_{s_c} + 1/2 \rho u_c^2 \quad (5.1)$$

where P_{0_c} , P_{s_c} , and u_c are the total pressure, static pressure and velocity at the center stream line of the diffuser

Center line total pressure coefficient is defined as,

$$\frac{P_{0_c} - P_{ref}}{q_1} = \frac{P_{s_c} - P_{ref}}{q_1} + \frac{q_c}{q_1}$$

Fig. 5.13 Total Pressure Loss Coefficient Distribution (Present Diffuser)

Fig. 5.14 $(C_{p1} - C_{p0})$ vs Area Ratio (Present Diffuser)

or

$$C_{p_{0.}} = C_{p_{.}} + \frac{q_0}{\bar{q}_1} \quad (5.2)$$

Where

P_{ref} = reference pressure (in this case the inlet static pressure P_{s1})

$C_{p_{0.}}$ = center line total pressure coefficient, $\frac{P_{0.} - P_{ref}}{\bar{q}_1}$

$C_{p_{.}}$ = static pressure recovery coefficient, $\frac{P_{s.} - P_{s1}}{\bar{q}_1}$

q_0 = center-line dynamic pressure, $\frac{1}{2} \rho u_0^2$

$\bar{q}_1$ = dynamic pressure based on mass-averaged velocity, $\frac{1}{2} \rho \bar{u}^2$

Since,

$$\frac{\bar{u}}{u_\infty} = 1 - \frac{2\delta^*}{R} \quad (\text{Sovran \& Klomp, 1967}) \quad (5.3)$$

Then,

$$\frac{q}{q_0} = \left(1 - \frac{2\delta^*}{R}\right)^2 \quad (5.4)$$

Using equation (5.4), equation (5.2) can be expressed as,

$$C_{p_{0.}} = C_{p_{.}} + \left(\frac{q}{\bar{q}_1}\right) \left(\frac{1}{1 - \frac{2\delta^*}{R}}\right)^2 \quad (5.5)$$

The center-line total pressure coefficients along the length of the diffuser are computed by equation (5.5) and the results are plotted in Fig.5.15. In the present diffuser, the boundary layers did not meet on the centerline and therefore the centerline total pressure should be constant. Thus, extracting the centerline total pressure coefficient from the wall static measurements, the traverse data becomes a check on the internal consistency of the data. The $C_{p_{0.}}$ data will be discussed further in the next section when comparison is made with Pozzorini's data.

5.4 Comparison with Pozzorini's Data

Pozzorini (1976) carried out an experiment in a conical diffuser with an area ratio

Fig. 5.15 Center-Line Total Pressure Coefficient Distribution
(Present Diffuser)

$AR=4$, and included angle $2\phi=6^\circ$. Boundary layer measurements were made at various locations in the inlet pipe and along the diffuser. The measurements were taken at four different inlet conditions, however, most of his test flows have highly turbulent free stream flow and when analysed were found to give internally inconsistent results. Therefore, only his low core turbulence case was considered here. In this case, the flow was characterized by a conventional velocity profile with a fully developed turbulent boundary layer and low core turbulence (0.3% at the diffuser inlet). Pozzorini's flow was chosen as a test case for the second Stanford Conference (1981) and his measurements are considered very reliable. In his original thesis, Pozzorini presented his velocity profile data in graphical form only, along with tabulated values of δ^+ and θ . From this information, it would not have been possible to obtain accurate estimates of the energy thickness and therefore the total pressure losses. Fortunately, while the present work was in progress, the Stanford Conference Data Tape containing tabulated velocity profile data became available. Pozzorini's experiment and the present one are the only sources known to the writer for direct data on total pressure losses in diffusers. Of the two sets of data, Pozzorini's must be considered the more accurate because of the problems with distortion of the wooden diffuser encountered in the present experiment.

The profile development along the length of the diffuser for this particular Pozzorini's test case is shown in Fig 5.16. As can be seen from the figure, Pozzorini's diffuser had a very strong increase in non-uniformity from the inlet to the outlet. Also, the boundary layer met on the center line when the flow approached the outlet of the diffuser. The corresponding boundary layer length scales etc. are shown in Table 5.5. Also included in Table 5.5 are the total pressure loss coefficients and flow non-uniformity coefficients calculated from the corresponding boundary layer parameters. Fig 5.16 and the summary table of Pozzorini's data are extracted from the second Stanford Conference (1981).

Pozzorini's diffuser was operated at a Reynolds Number of 2.54×10^5 while the present diffuser was operated at 3.58×10^5 . The turbulence intensity in Pozzorini's diffuser was about 0.31% whereas the present diffuser had a higher intensity level of 0.4%. Therefore, both experiments were conducted under similar conditions. The comparison for the two

Typische Entwicklung des Geschwindigkeitsprofils im Diffusor bei schwach turbulenter Kernströmung.
Vergleich von Pitotrohr- und Hitzdraht-Resultaten ohne Turbulenz-Korrekturen

Fig. 5.16 Velocity Profiles Development along the Length of Pozzorini's Diffuser

Distance, x (m)	AR	θ (m)	δ^* (m)	δ^{**} (m)	ω	α
-0.0549	1.0	0.00178	0.00249	0.00314	0	1.03428
0.0954	1.103	0.00244	0.00374	0.00415	0.01142	1.06062
0.1980	1.210	0.00322	0.00519	0.00541	0.02025	1.08684
0.2861	1.323	0.00399	0.00698	0.00652	0.02337	1.12832
0.3817	1.440	0.00470	0.00875	0.00750	0.03122	1.16991
0.5724	1.690	0.00632	0.01325	0.00976	0.04312	1.28018
0.7631	1.960	0.00819	0.01904	0.01239	0.04798	1.42810
1.049	2.403	0.01096	0.02788	0.01626	0.06639	1.64016
1.240	2.722	0.01280	0.03392	0.01888	0.07884	1.76315
1.5264	3.240	0.01543	0.04343	0.02243	0.09402	1.93598
1.8127	3.802	0.01784	0.05238	0.02560	0.11082	2.02014

Table 5.5: Boundary Layer Parameters of Pozzorini's Diffuser

diffusers is as follow.

As shown in Fig.5.17, Pozzorini's diffuser shows behaviour similar to that of the present diffuser. The total pressure loss coefficient curve increases along the diffuser, whereas the non-uniformity coefficient increases from the inlet and gives a maximum value at an area ratio of approximately two, and then decreases towards the outlet. As mentioned before, the flow non-uniformity coefficient is an ambiguous quantity, and probably not too much significance should be attached to its variation. In the following paragraphs, various other flow quantities for the present diffuser are compared with those in Pozzorini's diffuser.

The ω values for the two diffusers are compared in Fig.5.18. The two sets of data fall closely together showing the same trend of increase towards the exit. As can be seen in the figure, the present diffuser has higher total pressure loss than Pozzorini's diffuser. This is explained by the boundary layer of the diffusers. The present diffuser has a thinner inlet boundary layer ($B_{in}=0.0083$) than Pozzorini's diffuser ($B_{in} = 0.04976$), and, as thinner boundary layers have larger values of wall shear stress, the total pressure loss is greater in the present diffuser. This was confirmed by the wall shear stress calculations of the two diffusers. The wall shear stress (C_f) distribution of the present diffuser and Pozzorini's diffuser are shown in Fig.5.19 and 5.20 respectively. In the figures, C_f were calculated separately from the Clauser plot method and the Preston Tube method. The C_f values for the two diffusers are compared in Fig.5.21. It can be seen that the wall shear stress values of the present diffuser are slightly larger than Pozzorini's.

The proportion of effectiveness depreciation that is caused by total pressure loss for Pozzorini's diffuser is shown in Fig.5.22. As shown in the figure, the $\frac{\omega}{(C_{pf}-C_{pa})_{total}}$ ratios vary between 0.35 and 0.45 from AR=1 to AR=2.0. For larger area ratios, the ratios start to rise and give the maximum value of 0.75 at the outlet, that is, the flow non-uniformity coefficients contribute a bigger proportion to the effectiveness depreciation than the total pressure loss coefficients in the first half of the diffuser. In the later half of the diffuser, the total pressure loss contribution becomes bigger and increases along the diffuser towards the exit. This characteristic is quite different from the present diffuser

Fig. 6.17 Total Pressure Loss Coefficient and Non Uniformity Coefficient Distributions
(Pozzorini's Diffuser)

Fig. 5.18 Comparison of Total Pressure Loss Coefficient between the Present Diffuser and Pozzorini's Diffuser

Fig. 5.19 Wall Shear Stress Coefficient Distribution (Present Diffuser)

Fig. 5.20 Wall Shear Stress Coefficient Distribution (Pozzorini's Diffuser)

Fig 5.21 Comparison of Wall Shear Stress Coefficient between the Present Diffuser and Pozzorini's Diffuser

Fig. 5.22 $\left(\frac{C_{n1} - C_{n2}}{C_{n2}}\right)$ Vs Area Ratio (Pozzorini's Diffuser)

where the total pressure loss ratios were about 75% throughout the diffuser (Fig 5.14). As a comparison, at $AR=2.218$ (the outlet of the present diffuser), the $\frac{C_{p,i} - C_{p,e}}{C_{p,i}}$ ratio of the present diffuser was 0.785 whereas Pozzorini's diffuser was 0.43. These results indicate that total pressure losses are the principal cause of the effectiveness depreciation in the present diffuser, but not in Pozzorini's case. Therefore, from Pozzorini's and the present experiment it is clear that total pressure loss can account for as little as half the shortfall in static pressure recovery in the real diffuser. The rest of the shortfall is due to the growth of non-uniformity. Thus, taking the difference between the actual and ideal static pressure recovery as being due entirely to total pressure loss, as is often suggested in the literature, will lead to considerably over-estimated values of the total pressure loss. Also, the fraction of the shortfall accounted for by the total pressure loss appears to vary from diffuser to diffuser and along the length of any particular diffuser. Thus until further data are available, it would appear that reliable estimates of the total pressure loss cannot be obtained from the shortfall in static pressure recovery. A more satisfactory approach would seem to be to use Fig 5.18 which suggests that the total pressure loss is primarily a function of the area ratio and only weakly a function of the inlet boundary layer thickness. This approach has the further advantage that since no reference is made to the ideal diffuser, the ambiguities concerning matching of inlet conditions (discussed in section 2.4), do not arise.

In Fig 5.23, the static pressure recovery of the two diffusers are compared. Also included in the figure are the ideal pressure recovery, $C_{p,i}$. It can be seen that the present diffuser gives better static pressure recovery performance than Pozzorini's diffuser. This is because the present diffuser has a thinner inlet boundary layer. As described before, static pressure recovery increases with decreasing inlet blockage factor.

The locations of the diffusers on the flow regime chart are examined next. As shown in Fig 5.24, Pozzorini's diffuser lies very close to the $C_{p,i}^*$ line, the optimum geometry line, whereas, the present diffuser lies closer to the $\alpha - \alpha$ line, the line of onset of unsteady flow. This probably explains why separation occurred when the diffuser began to develop cracks and small steps on the surface exposed to the flow.

Fig. 5.23. Comparison of Static Pressure Recovery

Present Diffuser

Pozzoni's Diffuser

a--a line of onset of unsteady flow. (from Fig. 2.1)

 C_p^* locus of geometries for which C_p is maximum for a given diffuser length.

 C_p^{**} locus of geometries for which C_p is maximum for a given area ratio.

Fig. 5.24 Location of the Two Diffusers on the Flow Regime Chart, ESDU(1973)

The center line total pressure coefficient, C_{p0} , in Pozzorini's diffuser is plotted in Fig 5 25. As seen from Fig 5 25, the C_{p0} of Pozzorini's diffuser varies within a range of ± 0.04 while the present diffuser from, Fig 5 15, gave a larger range of ± 0.07 . A larger range of C_{p0} simply implies that the present data had a larger uncertainty than Pozzorini's data. However, this difference ($0.07 - 0.04 = 0.03$) is small compared with the C_{p0} values in the two diffusers, thereby, the present data were still acceptable.

The comparison between the two diffusers for the same area change are summarized in Table 5 6.

Fig. 5 25 Center-Line Total Pressure Coefficient (Pozzorini's Diffuser)

	Pozzorini's Diffuser	Present Diffuser
AR	2.218	2.218
B_{in}	.0498	0.0083
$C_{p,}$	0.657	0.7215
ω	0.057	0.0591
$\frac{\omega}{C_{p,} - C_{p,}}$	0.43	0.785
flow regime	close to optimum line, $C_{p,}^*$	non-optimum diffuser
$C_{p,}$ Range	0.04	0.07
Re_D		
(based on R_{in})	2.54×10^5	3.58×10^5
Freestream Turbulence		
Intensity	0.31%	0.4%

Table 5.6: Comparisons between Pozzorini's Diffuser and the Present Diffuser for Same Area Change

5.5 Inlet static Pressure Off-set and Inlet Total Pressure Off-set

As discussed in section 2.4, it is not possible for the actual and ideal diffusers to have simultaneously the same geometry, the same mass flow, the same inlet static pressure and the same inlet mass averaged total pressure. One of these quantities will always be mismatched. As demonstrated in section 2.4, if the inlet static pressures, the mass flows and the other prime quantities such as inlet density and inlet area are assumed to be the same, the mass-averaged inlet total pressures will be different. On the other hand, if mass-averaged inlet total pressures and mass flows are assumed the same, then the inlet static pressures will not be matched. Therefore, no matter which inlet matching conditions are used, some aspect of the performance of the diffuser will be ambiguously defined. The effects of inlet static pressure off-set and inlet total pressure off-set are examined here.

The inlet static pressure off-set parameters (I_{os} and E_{os}) and the inlet total pressure off-set parameters were calculated from equations (2.17), (2.18) and (2.19) for the present diffuser and Pozzorini's. In Fig 5.26, I_{os} parameters were plotted against area ratios. The I_{os} relates the inlet static pressure off-set, $(C_{pI} - C_{p\infty})_{inlet}$ to the ideal pressure recovery, C_{pI} , (i.e. $I_{os} = \frac{\Delta C_{p_{inlet}}}{C_{pI}}$). Also included in the figure are the data curves calculated for assumed power law inlet velocity profiles. The values are therefore presented for a large range of inlet blockages. The data curve corresponding to a fully developed laminar pipe flow at the diffuser inlet obtained by assuming a parabola profile is also included. The value of I_{os} is a measure of the relative importance of the inlet static offset when estimating the static pressure recovery performance of a diffuser. Strictly speaking, the offset should be expressed in terms of the actual static pressure recovery but the ideal recovery was used because of its convenience. As seen from the figure, the inlet offset corresponds to about 4% and 2.5% of the static recovery for Pozzorini's and the present diffuser respectively, which is probably small enough to ignore. However, for a fully developed turbulent flow at the inlet ($B \approx 0.15 - 0.20$), with $I_{os} \approx 0.06 - 0.10$ for typical area ratios, the offset would start to become significant, particularly since it would be an larger fraction of the actual static recovery. Fig. 5.26 can thus be used by a designer to determine whether inlet static pressure offset needs to be considered in a particular application. Fig 5.27 shows the E_{os}

Fig 5.26 $I_{0.5}$ Vs Area Ratio

Fig 5.27 E_{00} Vs Area Ratio

curves where E_{oo} is defined as the inlet static pressure offset as a ratio of the effectiveness depreciation, $\frac{\Delta C_{p,ideal}}{(C_{p,i} - C_{p,e})_{ideal}}$. E_{oo} is a measure of the importance of the inlet static offset when, for example, the effectiveness depreciation is used to estimate the total pressure loss in the diffuser. The E_{oo} parameters calculated from power law profiles are also given in Fig 5.27. In these calculations, the correlation for the static pressure recovery factor given by Sjolander (1981), $\eta = 0.68 + 11.111(B - 0.15)^2$, was used to estimate the actual static pressure recovery $C_{p,e}$. Since Sjolander's η correlation does not have a value of η for fully developed laminar flow, the E_{oo} curve for $n=2$ is not given. As seen in Fig 5.27, the curves for E_{oo} are of course similar to those for I_{oo} , except that the magnitudes are larger. As also seen from Fig 5.27, the present diffuser and Pozzorini's diffuser give higher values of E_{oo} than diffusers with higher values of inlet blockage calculated from power law profiles. This is the result of the fact that the η predicted from Sjolander's correlation between $B_1 = 0.16$ to $B_1 = 0.18$ are the lowest values in the correlation curve (as seen in Fig 5.7). Thus, the effectiveness depreciation $(C_{p,i} - C_{p,e})$ increases for smaller η values and give smaller offset parameters. The inlet total pressure offset parameters, T_{oo} , are shown in Fig 5.28, $T_{oo} = \frac{\Delta C_{p0,ideal}}{(\overline{P}_{0,ideal} - \overline{P}_{0,actual})}$. The T_{oo} is defined as the inlet total pressure offset, $(\overline{P}_{0,ideal} - \overline{P}_{0,actual})$, as a ratio of the total pressure loss coefficient, ω . As shown earlier, the inlet total pressure offset has the same magnitude as the inlet static offset. However, since ω is smaller than $(C_{p,i} - C_{p,e})$, T_{oo} is larger than E_{oo} , as indicated in Fig 5.28. Great care must therefore be taken in applying any method for estimating total pressure loss which is based on a comparison of the ideal and actual diffuser performance. This is further reason for favouring an approach which makes no reference to the ideal diffuser such as using the empirical correlation given in Fig 5.18.

From the above results, it is clear that since not all the inlet conditions can be matched at the same time, the ambiguity that arises from the particular mismatched inlet condition must be carefully considered when estimating the diffuser performance. The relative importance of this ambiguity is measured by the offset parameters which depend on the area ratio and the inlet boundary layer thickness. The advantage of these offset parameters is that they give relevant magnitudes of the mismatch ambiguities and from

Fig 5.28 T_o , V_o Area Ratio

the plots the designer can decide whether these ambiguities are important in his particular application.

Chapter 6

Conclusions and Suggestion for Further Study

6.1 Conclusions

As far as hardware is concerned, the performance of the diffuser test section was found to be not very satisfactory. This was mainly due to the gradually developing cracks and small steps on the flow surface. As mentioned before, separation was triggered by a forward facing step on the wall. Moreover, different static pressure distributions occurred on the two sides of the diffuser probably due to out-of-roundness of the diffuser. These problems are partly attributed to the choice of diffuser material and partly to the design of the present diffuser. The diffuser test rig was manufactured from maple wood which unfortunately was penetrated by moisture, causing swelling and cracking of the wood. Also, the location of the present diffuser on the diffuser performance diagram (Fig.2.1) indicates that the design is close to the region of transitory stall. This probably explains why separation occurred so easily once surface imperfections began to appear. It is therefore recommended that any future experimental studies of diffuser performance be conducted in a test section made of a more stable material.

In the experiment, vortex generators were applied in an attempt to regain the original static pressure recovery of the diffuser. On the whole, the performance of the vortex generators were found to be satisfactory and the original static pressure recovery was largely regained. On the other hand, with the vortex generators in place the development of the diffuser boundary layer was no longer axisymmetric. Fortunately, traverses made at the diffuser outlet showed that the circumferential flow variation was not drastic. Therefore, the boundary layer development at the top of the diffuser, which was outside the region of direct influence of the vortex generators and which experienced nearly the "undisturbed" pressure variation, should be reasonably representative of what would have occurred had

the separation problem not been present. In short, while the present experimental results are clearly not as satisfactory as those of Pozzorini, it should nevertheless be possible to draw from them some general conclusions about axisymmetric diffuser performance.

Turning now to the present experimental results, they were successful in shedding some new light on the performance of diffusers. In particular, they clearly demonstrate that total pressure loss can account for as little as half the short-fall in static pressure recovery in a real diffuser. The rest of the shortfall is due to the growth of non-uniformity. Thus, the conventional way of estimating total pressure loss as being due entirely to the difference between the actual and ideal static pressure recovery will considerably overestimate values of the total pressure loss. Also, the fraction of the shortfall that is caused by total pressure loss appears to vary from diffuser to diffuser and along the length of any particular diffuser. The growth of total pressure loss with area change along the diffuser was found to be essentially the same in Pozzorini's and the present diffuser (Fig. 5.21), even though the relative inlet boundary layer blockage, $(\frac{\delta^*}{R_{in}})$ was about six times as large in Pozzorini's. This suggests that diffuser total pressure loss is primarily a function of the diffuser geometry and only weakly a function of the inlet boundary layer thickness. It is therefore suggested that further experiments be conducted with substantially thicker inlet boundary layers in order to test this observation.

The mismatching of inlet conditions between ideal and actual diffusers was thoroughly examined. The relative importance of the mismatching to the diffuser performance can be determined by examining the newly defined parameters I_{oo} , E_{oo} and T_{oo} . It was demonstrated that all inlet offset parameters are primarily a function of area ratio and inlet blockage. When estimating the static pressure recovery performance, the inlet offset is probably small enough to ignore for diffusers with small inlet blockages such as Pozzorini's diffuser and the present diffuser (.0498 and .008 respectively) at typical area ratios. However, as the flow becomes fully developed ($B_{in} \approx 0.15-0.20$) the offset would start to become significant. When the effectiveness depreciation is used to estimate the total pressure loss, the offset is significant even for small inlet blockages. Thus, particularly when trying to estimate diffuser total pressure loss, it is desirable to use an approach

which makes no reference to the ideal diffuser. Then, the ambiguities concerning matching of inlet conditions will not arise.

6.2 Suggestions for Future Work

A few suggestions concerning the hardware are made first. As already noted, any future test section should be manufactured from a material more stable than wood. Also, the diffuser should be carried out for different length and area ratios in an easy accessible way. Since the boundary layer traverses are made using a pitot probe, it is essential to have accurate values of the static pressure at each traverse plane in order to obtain accurate velocity profiles. To allow values of wall static pressure to be interpolated with more confidence at any point along the diffuser, it is strongly recommended that a much larger number of static taps be used than in the present case. The taps should be closely spaced longitudinally, at several circumferential locations, and the procedure for manufacturing the diffuser should allow the "as built" co-ordinates of the taps to be determined accurately. In addition, in order that the boundary layer measurements be made along a line of constant static pressure, as nearly as possible, the pitot probe should be traversed at right angles to the wall rather than at right angles to the diffuser centerline as was done in the present case.

In the present experiment, there are eight traverse stations along the top wall of the diffuser. It is felt that more traverse stations are desirable, and also that the velocity traverse should be done at different angles around the circumference of the diffuser at each traverse section. Also, a pitot probe smaller than the present one (less than 0.033 inches outside diameter) would be useful. This would allow more precise values of the integral length scales to be obtained when the boundary layer is as thin as it was at the diffuser inlet in the present experiment.

As mentioned in the discussion section of this report, further studies should be undertaken to verify whether the total pressure loss is in fact only weakly dependent on the inlet boundary layer thickness and the wall shear stress distribution in the diffuser, as

suggested by Fig. 5.21. This would involve thickening the inlet boundary layer. In the long run, it would probably be worthwhile to investigate the effect of non-uniform inlet flow conditions on the total pressure loss of diffuser. Specifically, we should look at wake flow, swirling flow and flow with small local vorticities, since these flows are often observed in the flow downstream of a large wind tunnel and in the flow downstream of the gas turbine or of certain types of combustor chambers. It is also interesting to investigate the interacting shear layer in the center core area, since its flow phenomena is still not clearly understood. Obviously, the best long term solution would be the development of reliable methods for calculating the wall boundary layer development. Numerical methods are more cost effective than experimental work, however, due to the flow complexity including the adverse pressure gradient and the interaction of the boundary layers, the flow is difficult to predict. Therefore, until calculation methods become more reliable, there will still be a need of measurement to provide design information.

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APPENDIX - A

Derivation of Kinetic-Energy-Flux Parameter Expressed in Terms of Boundary Layer Parameters

Mass Averaged Velocity

$$\begin{aligned} u &= \frac{1}{A} \int^A u dA \\ u &= \frac{1}{A} \int_0^R u 2\pi r dr \\ u &= \frac{2\pi}{A} \int_0^R ur dr \end{aligned} \quad (1)$$

Axi Symmetric Energy Thickness,

$$\begin{aligned} \delta^{**} &= \int_0^R \left(1 - \left(\frac{u}{U_\infty} \right)^2 \right) \left(\frac{u}{U_\infty} \right) \frac{r}{R} dr \\ &= \int_0^R \frac{u}{U_\infty} \frac{r}{R} dr - \int_0^R \left(\frac{u}{U_\infty} \right)^3 \frac{r}{R} dr \end{aligned}$$

therefore

$$\int_0^R \left(\frac{u}{U_\infty} \right)^3 \frac{r}{R} dr = \int_0^R \frac{u}{U_\infty} \frac{r}{R} dr - \delta^{**} \quad (2)$$

Axi Symmetric Displacement Thickness,

$$\begin{aligned} \delta^* &= \int_0^R \left(1 - \frac{u}{U_\infty} \right) \frac{r}{R} dr \\ &= \int_0^R \left(\frac{r}{R} - \frac{u}{U_\infty} \frac{r}{R} \right) dr \\ &= \int_0^R \frac{r}{R} dr - \int_0^R \frac{u}{U_\infty} \frac{r}{R} dr \end{aligned}$$

therefore,

$$\int_0^R \frac{u}{U_\infty} \frac{r}{R} dr = \frac{1}{2} R - \delta^* \quad (3)$$

Kinetic - Energy - Flux Parameter

$$\alpha = \frac{1}{A} \int^A \left(\frac{u}{u} \right)^3 dA$$

$$\alpha = \frac{\frac{1}{A} \int_0^R u^3 2\pi r dr}{\bar{u}^3}$$

from (1),

$$\alpha = \frac{\frac{2\pi}{A} \int_0^R u^3 r dr}{\left(\frac{2\pi}{A} \int_0^R u r dr \right)^3}$$

$$\alpha = \frac{\int_0^R u^3 r dr}{\left(\frac{2\pi}{A} \right)^2 \left(\int_0^R u r dr \right)^3}$$

$$\alpha = \frac{R \int_0^R \left(\frac{u}{U_\infty} \right)^3 \frac{r}{R} dr}{\left(\frac{2\pi}{A} \right)^2 R^3 \left(\int_0^R \frac{u}{U_\infty} \frac{r}{R} dr \right)^3}$$

from (2),

$$\alpha = \frac{R^2}{4} \left(\frac{\int_0^R \frac{u}{U_\infty} \frac{r}{R} dr - \delta^{**}}{\left(\int_0^R \frac{u}{U_\infty} \frac{r}{R} dr \right)^3} \right)$$

from (3),

$$\alpha = \frac{R^2}{4} \left(\frac{\frac{1}{2} R - \delta^* - \delta^{**}}{\left(\frac{1}{2} R - \delta^* \right)^3} \right)$$

APPENDIX - B

Data Sampling Program

The data sampling program comprised of three segments

- i) A user written main program for defining system parameters, selecting channel, averaging readings and output the solution.
- ii) The system subprogram, `Init`, which initializes HP-IB and assigns device names to select codes, and lists the instrument connected to the HP-IB with their address. The input variables `P1` which specifies the system voltmeter is 3456 (i.e. $P1 = 3456$). This represents that 3456A voltmeter is used in the system.
- iii) The subprogram `Avdcv` which sets up the 3456A voltmeter to take an average DC voltage reading from a selected channel. The average DC voltage reading will be the result of taking 1 DC voltage reading over a period of 10 power line cycles. This subprogram is used twice in the experiment, when dynamic pressure is measured from the pitot probe, the input channel is 1, that is $P1 = 1$. When wind tunnel reference pressure is measured, $P1 = 2$, the input channel is 2.

(refer to 3054A system manual for more detailed information)

Input variables:

$P1 = 3456$, (set up HP-IB and specify 3456A voltmeter)

$P1 = 1$, (set up channel 1 to measure dynamic pressure from pitot probe)

$P2 = 2$, (set up channel 2 to measure wind tunnel reference pressure)

Output variables:

Z — Averaged wind tunnel reference pressure readings

V — Averaged dynamic pressure readings.

X — (dynamic pressure) / (wind tunnel reference pressure)

Flow Chart

Data Sampling Program

```

10 OPTION BASE 1
20 DIM C0(500), C1(500), D(500), E(500), B(500)
21 B=0
22 D=0
23 E=0
24 P1=3456
25 GOSUB 230
30 FOR I=1 TO 60
40 P1=1
50 GOSUB 1040
60 C0(I)=P
70 P1=2
80 GOSUB 1381
90 C1(I)=P
100 E=E+C0(I)+C1(I)
110 D=D+C0(I)
120 B=B+C1(I)
121 Z(I)=B/I
122 V(I)=D/I
123 X(I)=E/I
130 C=I
140 NEXT I
150 PRINT USING 201 : Z(1), V(1), X(1)
201 IMAGE 30 60, X, 30 60, X, 30 60
220 END
230 | SUBPROGRAM Init hp85
240 | QA 7/00/80 GAC
250 | P1=DvMeter
260 DIM 07$(23) | DEVICE NAMES
270 |
280 | INITIALIZE DEVICE ADDRES
290 |
300 R0=709
310 R1=722
320 R2=724
330 R3=0
340 R4=0
350 03=R0 DIV 100
360 04=R1
370 P1$="0000000000000000"
380 ON ERROR GOTO 810
390 IF P1=3497 THEN R1=R0
400 IF P1<3456 AND P1<3497 THEN
410 N 590 | Abort
410 OFF ERROR
420 |
430 |
440 | VERIFY THAT INTERFACE IS HP-IB
450 |
460 ON ERROR GOTO 530
470 STATUS 03, 0, 06
480 OFF ERROR
490 |
500 | PRINT ERROR MESSAGE TO CRT
510 | IF NO INTERFACE OR NOT HP-IB INTERFACE

```

```

520 IF 06=1 THEN 630
530 OFF EPROR
540 CLEAR
550 DISP USING "X.K" "CAUTION
HP-IB INTERFACE IS NOT PRESE
NT"
560 DISP USING "X.K" "PROGRAM
EXECUTION TERMINATED"
570 BEEP
580 STOP
590
600 INITIALIZE 82937A HP-IB IN
TERFACE, RESET INTERFACE
610
620
630 ABORTIO 03
640 RESET 03
650
660
670 CHECK FOR EQUIPMENT ON BUS
AT ALL ADDRESSES AND PRINT
DEVICE NAMES
680
690
700 CLEAR & DISP USING "X.K.D
O" "EQUIPMENT PRESENT
ON BUS"
710 FOR 02=0 TO 30
720 OUTPUT 03*100+02 USING "*"
ADDRESS DEVICE TO LISTEN
730 RESUME 03
740 STATUS 03,2 05
750 IF BINAND(05,3)=0 THEN 790
760 GOSUB 870
770 DISP USING 790 , 07$,02
780 NEXT 02
790 IMAGE 37A,"at address".2Z
800 GOTO 850 EXIT
810 OFF ERROR
820 R3=2
830 R$="Init"
840 CALL Warn
850 RETURN
860 SUBEND
870 SUB DEV_NAME
880 Q7$=DEVICE NAME
890 Q7$=""
900 IF 02<>04 MOD 320 THEN 920
910 Q7$="3456A DIGITAL VOLTMETER"

920 IF 02<>R2 MOD 320 THEN 940
930 Q7$="3437A System Voltmeter"
940 IF 02<>21 THEN 960
950 Q7$="hp85A System Computer"
960 IF 02<>R0 MOD 320 THEN 990
970 Q7$="3497A Scanner, Timer"
980 IF R1=R0 THEN Q7$=Q7$&" DVM"
990 IF Q7$="" THEN 1010
1000 Q7$="Device Unknown" UNKN
OMN DEVICE=ANY DEVICE WITH
NO LABEL

```

```

1010 |
1020 RETURN
1030 | SUBEND
1040 | SUBPROGRAM Avdcv hp85
1050 | QA 7/11/80 GAC
1060 | P1=Channel
1070 A=0
1190 FOR K=1 TO 6
1200 IF P1<>-1 THEN OUTPUT R0 , "
      AC",INT(P1)
1220 OUTPUT R1 , "VR3VA0VF1VD3VC0
      VS0VM0S01VN10VT3"
1230 ENTER R1 , P
1231 A=A+P
1233 NEXT K
1234 P=A/6
1240 GOTO 1370 | RETURN
1250 OUTPUT R1 , "VR5VA1VF1VD5VC0
      VS0VM0S01VN10VT3"
1260 P=0
1270 FOR O4=1 TO 10
1280 ENTER R1 USING "*,K" , O5
1290 P=P+O5
1300 NEXT O4
1310 OUTPUT R1 , "S00"
1320 P=P/10
1330 GOTO 1370
1370 RETURN
1380 | SUBEND
1381 | SUBPROGRAM Avdcv hp85
1382 | P1=CHANNEL
1383 IF P1<>-1 THEN OUTPUT R0 , "
      AC",INT(P1)
1384 OUTPUT R1 , "VR3VA0VF1VD3VC0
      VS0VM0S01VN10VT3"
1385 ENTER R1 , P
1386 RETURN
1387 | SUBEND

```

APPENDIX -C

Inviscid Calculation of the Minimum Length of the Pitot Probe

The probe was assumed to have 5° of misalignment with respect to the flow and 10° of velocity misalignment at point p. See Figure.

Inviscid flow calculation

At point p

At point p,

$$\sin 10^\circ = \frac{-v_\theta}{u} \quad (1)$$

$$\cos 10^\circ = \frac{-v_r}{u} \quad (2)$$

$$-v_r = -\frac{1}{r} \frac{\partial \phi}{\partial \theta}$$

$$-v_r = -u \left(1 - \frac{a^2}{r^2} \right) \cos \theta \quad (3)$$

$$-v_\theta = +\frac{\partial \phi}{\partial \theta}$$

$$-v_\theta = u \left(1 + \frac{a^2}{r^2} \right) \sin \theta \quad (4)$$

substituting (4) into (1), we get

$$\sin 10^\circ = \frac{u \left(1 + \frac{a^2}{r^2} \right) \sin \theta}{u} \quad (5)$$

substituting (3) into (2)

$$\cos 10^\circ = \frac{-u \left(1 - \frac{a^2}{r^2} \right) \cos \theta}{u} \quad (6)$$

rearranging (5) and (6)

$$\frac{\sin 10^\circ}{\cos 10^\circ} = - \left(\frac{1 + \frac{a^2}{r^2}}{1 - \frac{a^2}{r^2}} \right) \tan 175^\circ$$

$$-2.0154 = - \left(\frac{r^2 + a^2}{r^2 - a^2} \right)$$

$$2.0154 = \left(\frac{r^2 + 0.125^2}{r^2 - 0.125^2} \right)$$

$$2.0154r^2 - 0.0315 = r^2 + 0.0156$$

$$1.0154r^2 = 0.0156 + 0.0315$$

$$r^2 = \frac{0.0471}{1.0154}$$

$$r = 0.2154 \text{ in.}$$

Therefore, r , has to be greater than 0.2154 in.

DIST = y co-ordinate.

OPDYN = wind tunnel reference pressure, $(P_{e1} - P_{e2})$.

DYNP = dynamic pressure measured by pitot probe, ΔP_{pitot} .

RADIUS = radius of the cross section.

SP = static pressure correction value $\frac{\Delta P_s}{P_{e1} - P_{e2}}$.

INDYNP, INOPDYN = initial transducers' readings.

DATA = number of data in the input data file.

Output variables:

$$U/U_{\text{INF}} = \frac{u}{U_{\infty}}$$

$$\text{DELSTR} = \delta^{\circ}$$

$$\text{THETA} = \theta$$

$$H = \text{shape factor}, \frac{\delta^*}{\theta}$$

$$\text{ENTH} = \delta^*$$

$$\text{ALPHA} = \alpha$$

$$Q = \text{mass-averaged dynamic pressure}, q = \frac{\frac{1}{2} \rho \bar{u}^2}{P_{e1} - P_{e2}}$$

$$\text{QBAR} = \text{dynamic pressure based on mass-averaged velocity}, \bar{q} = \frac{\frac{1}{2} \rho \bar{U}^2}{P_{e1} - P_{e2}}$$

The derivation of formulas used in the program is described below.

(1) Displacement Thickness

by definition,

$$\delta_{\infty}^* = \int_0^R \left(1 - \frac{u}{U_{\infty}}\right) \frac{r}{R} dr$$

in terms of experimental data,

DIST = y co-ordinate

OPDYN = wind tunnel reference pressure $(P_{c1} - P_{c2})$

DYNP = dynamic pressure measured by pitot probe ΔP_{pitot}

RADIUS = radius of the cross section.

SP = static pressure correction value $\frac{\Delta P_s}{P_{c1} - P_{c2}}$

INDYNP INOPDYN = initial transducers' readings

DATA = number of data in the input data file

Output variables:

$$U/U_{\infty} = \frac{u}{U_{\infty}}$$

$$\text{DELSTR} = \delta^*$$

$$\text{THETA} = \theta$$

$$H = \text{shape factor} \cdot \frac{\delta^*}{\theta}$$

$$\text{ENTH} = \delta^*$$

$$\text{ALPHA} = \alpha$$

$$Q = \text{mass-averaged dynamic pressure} \quad q = \frac{\frac{1}{2} \rho \bar{u}^2}{P_{c1} - P_{c2}}$$

$$\text{QBAR} = \text{dynamic pressure based on mass-averaged velocity} \quad \bar{q} = \frac{\frac{1}{2} \rho \bar{u}^2}{P_{c1} - P_{c2}}$$

The derivation of formulas used in the program is described below

(1) Displacement Thickness

by definition,

$$\delta_{\text{dis}}^* = \int_0^R \left(1 - \frac{u}{U_{\infty}} \right) \frac{r}{R} \partial r$$

in terms of experimental data

APPENDIX -E

Data Reduction Program

The data is normally run through the program twice. On the first pass, the measured data is reduced to obtain the velocity ratios across the diffuser section. Then the computed values of velocity ratio nearest to the wall are plotted to a large scale and the near wall data are interpolated as described in sect. 5.2.1.1. Having interpolated the near wall data, the whole velocity profile (including the interpolated values) is re-run to obtain the corresponding integral length scales of the boundary layer.

The data reduction program comprised of three segments:

- i) A user written main program, responsible for defining system parameters and initial conditions. It would also control the integration and output the solution.
- ii) The integration function SIMP, which when called would advance the solution. Simpson method is used in this integration routine.
- iii) The IMSL library routines ICSEVU and ICSCCU which are used for evaluation of a cubic spline and cubic spline interpolation.

The experimental data are first read and re-arranged in reducible fashion. Then, following by the correction of wall proximity and shear flow, the boundary layer integral parameters are defined. Integration of the data is performed to obtain the corresponding integral parameters.

The integration in the program is performed in step of four data points. The library routine ICSEVU is used to fit a cubic polynomial (cubic spline) through the points. The fitted curve is then divided into 200 equal steps by using the interpolating routine ICSCCU. The area under the curve is obtained by calling the integration function SIMP. The results after integration are passed back to the main program for summing up. Finally the integral parameters and velocity ratios are printed out.

Input variables:

DIST = y co-ordinate

OPDYN = wind tunnel reference pressure $(P_{e1} - P_{e2})$

DYNP = dynamic pressure measured by pitot probe ΔP_{pitot}

RADIUS = radius of the cross section.

SP = static pressure correction value $\frac{\Delta P_s}{P_{e1} - P_{e2}}$

INDYNP INOPDYN = initial transducers' readings

DATA = number of data in the input data file

Output variables:

$$U/U_{\infty} = \frac{u}{U_{\infty}}$$

$$\text{DELSTR} = \delta^*$$

$$\text{THETA} = \theta$$

$$H = \text{shape factor} \cdot \frac{\delta^*}{\theta}$$

$$\text{ENTH} = \delta^*$$

$$\text{ALPHA} = \alpha$$

$$Q = \text{mass-averaged dynamic pressure} \quad q = \frac{\frac{1}{2} \rho \bar{u}^2}{P_{e1} - P_{e2}}$$

$$\text{QBAR} = \text{dynamic pressure based on mass-averaged velocity} \quad \bar{q} = \frac{\frac{1}{2} \rho \bar{u}^2}{P_{e1} - P_{e2}}$$

The derivation of formulas used in the program is described below

(1) Displacement Thickness

by definition,

$$\delta_{\text{dis}}^* = \int_0^R \left(1 - \frac{u}{U_{\infty}} \right) \frac{r}{R} \partial r$$

in terms of experimental data

$$\left(\frac{u}{U_\infty}\right)^2 = \frac{\frac{1}{2}\rho u^2}{P_{e_1} - P_{e_2}} / \frac{\frac{1}{2}\rho U_\infty^2}{P_{e_1} - P_{e_2}}$$

expressed with the notations in the program ,

$$\left(\frac{u}{U_\infty}\right)^2 = \left(\frac{U(J)}{UINF}\right)$$

and ,

$$\begin{aligned}\frac{u}{U_\infty} &= \sqrt{\frac{U(J)}{UINF}} \\ &= UR(J)\end{aligned}$$

therefore , in terms of the notations in the program ,

$$\begin{aligned}\delta_{as}^* &= \int_0^R \left(1 - \sqrt{\frac{U(J)}{UINF}}\right) \frac{r}{R} \partial r \\ \delta_{as}^* &= \int_0^R DTHICK \partial r\end{aligned}$$

(2) Momentum Thickness

by definition ,

$$\theta = \int_0^R \left(1 - \frac{u}{U_\infty}\right) \frac{u}{U_\infty} \frac{r}{R} \partial r$$

in terms of the notations in the program ,

$$\begin{aligned}\theta &= \int_0^R \left(1 - \sqrt{\frac{U(J)}{UINF}}\right) \sqrt{\frac{U(J)}{UINF}} \frac{r}{R} \partial r \\ \theta &= \int_0^R MTHICK \partial r \\ &= THETA\end{aligned}$$

(3) Kinetic Energy-Flux Parameter

by definition ,

$$\alpha = \frac{1}{A} \int^A \left(\frac{u}{u}\right)^3 \partial A$$

α can also be expressed as

$$\alpha = \frac{R^2 \int_0^R \left(\frac{u}{U_\infty}\right)^3 \frac{r}{R} \partial r}{4 \left(\int_0^R \frac{u}{U_\infty} \frac{r}{R} \partial r\right)^3}$$

in terms of the notations in the program ,

$$\alpha = \frac{R^4 \int_0^R U(J)^{3/2} \frac{r}{R} \partial r}{4 \left(\int_0^R U(J)^{1/2} \frac{r}{R} \partial r\right)^3}$$

$$= ALPHA$$

(4) Mass-Averaged Dynamic Pressure

$$q = \frac{1}{2} \rho \bar{u}^2$$

it can be expressed as ,

$$q = \frac{1}{2} \rho \frac{\int_0^R u^3 r \partial r}{\int_0^R u r \partial r}$$

in terms of the notations in the program , the dimensionless mass-averaged dynamic pressure is obtained ,

$$\frac{q}{P_{e1} - P_{e2}} = \frac{\int_0^R U(J)^{3/2} r \partial r}{\int_0^R U(J)^{1/2} r \partial r} = Q$$

(5) Dynamic Pressure based on Mass-Averaged Velocity

$$\bar{q} = \frac{1}{2} \rho \bar{u}^2$$

in terms of the notations in the program ,

$$\frac{\frac{1}{2} \rho \bar{u}^2}{P_{e1} - P_{e2}} = \frac{4}{R^4} \left[\int_0^R U(J)^{1/2} r \partial r \right]^2 = QBAR$$

(6) Energy Thickness

$$\delta^{**} = \int_0^R \left(1 - \left(\frac{u}{U_\infty} \right)^2 \right) \left(\frac{u}{U_\infty} \right) \frac{r}{R} \partial r$$

in terms of the notations in the program ,

$$\delta^{**} = \int_0^R \left(1 - \frac{U(J)}{UINF} \right) \sqrt{\frac{U(J)}{UINF}} \frac{r}{R} \partial r$$

$$\delta^{**} = \int_0^R ETHICK \partial r = ENTH$$

Notations of the above formulas used in the program are listed below ,

Notation in the Program	Parameter in the Formulas
----------------------------	------------------------------

ALPHA	α
-------	----------

DELSTR	δ^*
--------	------------

Flow Chart

Note: In the second pass, the input variables will include
the near wall data from interpolation.

Flow Chart

Note: In the second pass, the input variables will include the near wall data from interpolation.

1.000 C
2.000 C
3.000 C
4.000 C
5.000 C
6.000 C
7.000 C
8.000 C
9.000 C
10.000 C
11.000 C
12.000 C
13.000 C
14.000 C
15.000 C
16.000 C
17.000 C
18.000 C
19.000 C
20.000 C
21.000 C
22.000 C
23.000 C
24.000 C
25.000 C
26.000 C
27.000 C
28.000 C
29.000 C
30.000 C
31.000 C
32.000 C
33.000 C
34.000 C
35.000 C
36.000 C
37.000 C
38.000 C
39.000 C
40.000 C
41.000 C
42.000 C
43.000 C
44.000 C
45.000 C
46.000 C
47.000 C
48.000 C
49.000 C
50.000 C
51.000 C
52.000 C
53.000 C
54.000 C
55.000 C
56.000 C
57.000 C
58.000 C

DATA REDUCTION PROGRAM

```
REAL DIST(250),U(250),R(250),RADIUS,UINF,UR(250),DYNP(250),
REAL ETHICK(250),DYN(250),MASSF(250),USORT,ALPHA,ALPHATL
REAL ETHICKI(4),DYNI(4),MASSI(4),ENTH,SDYN,SMASSF,VELINT
REAL BTHICK(250),MTHICK(250),DISTCI(4),BTHICKI(4),MTHICKI(4)
REAL DELSTR,THETA,INC,SPACE,C(3,3),S(250),VAL(250),OPDYN(250)
REAL A(9,3),X(10),Y(10),CORR(100),PERCOR(100),H,U,QBAR,SP
REAL INDYNP,INOPDYN
INTEGER LAST,LASTC,FIN,FIRST,I,J,A,ERR,IC,M,END,L
INTEGER SI,NUM,Z,DATA
```

DEFINITIONS -

ARGUMENTS :-

ALPHA - KINETIC-ENERGY-FLUX PARAMETER
DATA - NUMBER OF INPUT DATA
DELSTR - DISPLACEMENT THICKNESS
DIST - DISTANCE MEASURED FROM THE WALL, Y CO-ORDINATE
DYNP - DYNAMIC PRESSURE MEASURED BY PITOT PROBE
DYN,DYNI,SDYN - WORK VECTORS FOR DYNAMIC PRESSURE
BTHICK,BTHICKI - WORK VECTORS FOR DISPLACEMENT THICKNESS
ENTH - ENERGY THICKNESS
ETHICK,ETHICKI - WORK VECTORS FOR ENERGY THICKNESS
H - SHAPE FACTOR
INC - SPACE INCREASEMENT IN INTEGRATION
INDYNP - INITIAL VOLTMETER READING FOR PITOT PROBE
INOPDYN - INITIAL VOLTMETER READING FOR REFERENCE PRESSURE
MASSF,MASSI,SMASSF - WORK VECTORS FOR MASS FLOW
MTHICK,MTHICKI - WORK VECTORS FOR MOMENTUM THICKNESS
OPDYN - WIND TUNNEL REFERENCE PRESSURE
Q - MASS AVERAGE DYNAMIC PRESSURE
QBAR - DYNAMIC PRESSURE BASED ON MASS-AVERAGED VELOCITY
R - RADIUS CO-ORDINATE
RADIUS - RADIUS OF DIFFUSER CROSS-SECTION
SP - STATIC PRESSURE CORRECTION VALUE
SPACE - INTEGRATION STEP SPACE
THETA - MOMENTUM THICKNESS
U,USORT - WORK VECTORS FOR VELOCITY RATIO
UR - VELOCITY RATIO, U/UINF
UINF - FREE STREAM VELOCITY
VAL - WORK VECTOR FOR SPACE INCREASEMENT IN INTEGRATION
X,Y - VECTOR OF DATA PAIR FOR MACHILLAN CORRECTION CURVE
FOR WALL PROXIMITY
NUM,A,SI,ERR - WORK VECTOR FOR SUBROUTINE ICSCCN
PERCOR,Z,CORR - WORK VECTOR FOR SUBROUTINE ICSEW

59.000 C
 60.000 C
 61.000 C
 62.000 C
 63.000 C
 64.000 C
 65.000 C
 66.000 C
 67.000 C
 68.000 C
 69.000 C
 70.000 C
 71.000 C
 72.000 C
 73.000 C
 74.000 C
 75.000 C
 76.000 C
 77.000 C
 78.000 C
 79.000 C
 80.000 C
 81.000 C
 82.000 100
 83.000 C
 84.000 C
 85.000 200
 86.000 C
 87.000 C
 88.000 C
 89.000 C
 90.000 C
 91.000 C
 92.000 C
 93.000 C
 94.000 C
 95.000 C
 96.000 C
 97.000 C
 98.000 C
 99.000 C
 100.000 C
 101.000 C
 102.000 C
 103.000 C
 104.000 C
 105.000 C
 106.000 C
 107.000 C
 108.000 C
 109.000 C
 110.000 C
 111.000 C
 112.000 C
 113.000 C
 114.000 C
 115.000 220
 116.000 C
 117.000 C
 118.000 C

LOCAL VARIABLES -

I, J, K, L, Z - DO LOOP INDICES
 LAST - INDICE OF LAST DATA POINT
 IC, FIRST, LASTC, FIN - COUNTER FOR INTEGRATION IN STEP OF
 FOUR DATA POINTS

PRINT*,
 PRINT*, INPUT THE NUMBER OF DATA IN THE INPUT DATA FILE.
 READ (1,1), DATA
 PRINT*,
 PRINT*,
 PRINT*,
 DO 100 I=1, DATA
 READ (5,1), DIST(I), OPDYN(I), DYNP(I)
 CONTINUE
 PRINT*,
 PRINT*,
 PRINT*, PLEASE INPUT RADIUS OF DIFFUSER.
 READ (1,1), RADIUS
 PRINT*,
 PRINT*, PLEASE INPUT PRESSURE DIFFERENCE SP.
 READ (1,1), SP
 PRINT*,
 PRINT*, PLEASE INPUT INITIAL VOLTMETER READINGS.
 PRINT*, INPUT INDYNP AND INOPDYN IN ORDER.
 READ (1,1), INDYNP, INOPDYN
 PRINT*,
 PRINT*, PLEASE INPUT FREESTREAM VELOCITY
 PRINT*,
 LAST=I-1

CALCULATE DYNAMIC PRESSURE RATIO

DO 220 L=1, LAST
 IF (DYNP(L) .EQ. 0.0) THEN
 U(L)=0.0
 ELSE
 U(L)=((DYNP(L)+INDYNP)/(OPDYN(L)+INOPDYN)+SP)*.16613/.16721
 ENDIF
 CONTINUE

```

119.000 C *****
120.000 C
121.000 C   MACHILLAN CORRECTION FOR WALL PROXIMITY
122.000 C
123.000 C   READ IN VALUES FROM THE CORRECTION CURVE
124.000 C
125.000 C *****
126.000 C
127.000 C
128.000 C
129.000 C   UINF=U(LAST)
130.000 C   DO 250 K=1,10
131.000 C     READ(5,*,X(K),Y,K)
132.000 C 250 CONTINUE
133.000 C   NUM=K-1
134.000 C   SI=0
135.000 C
136.000 C
137.000 C
138.000 C *****
139.000 C
140.000 C   FIT CURVE THROUGH POINTS
141.000 C
142.000 C *****
143.000 C
144.000 C
145.000 C
146.000 C   CALL ICSCCU(X,Y,NUM,A,SI,ERR)
147.000 C   DO 270 I=1,100
148.000 C     CORR(I)=DIST(I+7)/.033
149.000 C     IF (CORR(I) .GT. 2.0) GOTO 280
150.000 C 270 CONTINUE
151.000 C 280 CONTINUE
152.000 C   Z=I-1
153.000 C
154.000 C
155.000 C
156.000 C *****
157.000 C
158.000 C   GET PERCENTAGE CORRECTION IN VELOCITY DATA BY INTERPOLATION
159.000 C
160.000 C *****
161.000 C
162.000 C
163.000 C
164.000 C   CALL ICSEVU(X,Y,NUM,A,SI,CORR,PERCOR,Z,ERR)
165.000 C   DO 292 L=8,Z
166.000 C     U(L)=U(L)*(1+(PERCOR(L-7)/100)*.2)
167.000 C 292 CONTINUE
168.000 C   Z=Z-1
169.000 C
170.000 C
171.000 C
172.000 C *****
173.000 C
174.000 C   YOUNG & MASS CORRECTION FOR SHEAR FLOW
175.000 C
176.000 C *****
177.000 C
178.000 C

```

```

179.000 C
180.000 DO 283 L=Z,250
181.000 IF(DIST(L).EQ. 0.0) GOTO 283
182.000 IF(U(L).EQ. U(L-1)) GOTO 284
183.000 DIST(L)=DIST(L)+.005649
184.000 283 CONTINUE
185.000 284 CONTINUE
186.000 PRINT*,
187.000 PRINT*,
188.000 C
189.000 C
190.000 C
191.000 C *****
192.000 C BOUNDARY LAYER PARAMETER CALCULATION
193.000 C *****
194.000 C
195.000 C
196.000 C
197.000 C
198.000 C
199.000 DO 300 J=1, LAST
200.000 IF(U(L).EQ. 0.0) THEN
201.000 UR(J)=0.0
202.000 ELSE
203.000 UR(J)=SQRT(U(J)/UINF)
204.000 ENDIF
205.000 286 R(J)=(RADIUS-DIST(J))/RADIUS
206.000 DTHICK(J)=(1-UR(J))*R(J)
207.000 MTHICK(J)=(1-UR(J))*UR(J)*R(J)
208.000 ETHICK(J)=(1-(UR(J)**2))*UR(J)*R(J)
209.000 USORT=SQRT(U(J))
210.000 BYN(J)=(USORT**3)*(RADIUS-DIST(J))
211.000 MASSF(J)=USORT*(RADIUS-DIST(J))
212.000 300 CONTINUE
213.000 C
214.000 C
215.000 C *****
216.000 C INITIALIZATION
217.000 C *****
218.000 C
219.000 C
220.000 C
221.000 C
222.000 C
223.000 C
224.000 DELSTR=0.0
225.000 THETA=0.0
226.000 ENTH=0.0
227.000 SDYN=0.0
228.000 SMASSF=0.0
229.000 END = LAST
230.000 FIRST=1
231.000 LASTC=4
232.000 M=200
233.000 DO 460 I=1,200
234.000 K=1
235.000 DO 400 J=FIRST, LASTC
236.000 DISTC(K)=DIST(J)
237.000 DTHICKI(K)=DTHICK(J)
238.000 MTHICKI(K)=MTHICK(J)

```

```

239.000      ETHICKI(K)=ETHICK(J)
240.000      DYNI(K)=DYN(J)
241.000      MASSFI(K)=MASSF(J)
242.000      K=K+1
243.000 400  CONTINUE
244.000      SPACE=(DISTCI(K-1)-DISTCI(1))/200.0
245.000      INC=DISTCI(1)
246.000      DO 450 J=1,200
247.000          VAL(J)=INC
248.000          INC=INC+SPACE
249.000 150  CONTINUE
250.000 C
251.000      FIN=LASTC-FIRST+1
252.000      IC=LASTC-FIRST
253.000      CALL ICSCCU(DISTCI,ETHICKI,FIN,C,IC,ERR)
254.000      CALL ICSEVU(DISTCI,ETHICKI,FIN,C,IC,VAL,S,M,ERR)
255.000 C
256.000 C
257.000 C
258.000 C *****
259.000 C      INTEGRATION BY CALLING FUNCTION SIMP
260.000 C *****
261.000 C
262.000 C
263.000 C
264.000 C
265.000      DELSTR=DELSTR+SIMP(1,200,SPACE,S)
266.000      CALL ICSCCU(DISTCI,ETHICKI,FIN,C,IC,ERR)
267.000      CALL ICSEVU(DISTCI,ETHICKI,FIN,C,IC,VAL,S,M,ERR)
268.000      THETA=THETA+SIMP(1,200,SPACE,S)
269.000 C
270.000      CALL ICSCCU(DISTCI,ETHICKI,FIN,C,IC,ERR)
271.000 C
272.000      CALL ICSEVU(DISTCI,ETHICKI,FIN,C,IC,VAL,S,M,ERR)
273.000      ENTH=ENTH+SIMP(1,200,SPACE,S)
274.000      FIN=LASTC-FIRST+1
275.000      CALL ICSCCU(DISTCI,DYNI,FIN,C,IC,ERR)
276.000      FIN=LASTC-FIRST+1
277.000      CALL ICSEVU(DISTCI,DYNI,FIN,C,IC,VAL,S,M,ERR)
278.000      SDYN=SDYN+SIMP(1,200,SPACE,S)
279.000      FIN=LASTC-FIRST+1
280.000      CALL ICSCCU(DISTCI,MASSF,FIN,C,IC,ERR)
281.000      FIN=LASTC-FIRST+1
282.000      CALL ICSEVU(DISTCI,MASSF,FIN,C,IC,VAL,S,M,ERR)
283.000      SMASSF=SMASSF+SIMP(1,200,SPACE,S)
284.000      IF(LASTC.EQ.'END') GO TO 470
285.000      FIRST=LASTC
286.000      LASTC=LASTC+3
287.000      IF(LASTC.GE.'END') LASTC=END
288.000 460  CONTINUE
289.000 170  CONTINUE
290.000      H=DELSTR/THETA
291.000      PRINT*, 'DISTANCE'
292.000      PRINT*, 'FROM WALL'      U/UINF
293.000      PRINT*, '
294.000      DO 500 K=1,LAST
295.000          PRINT ' (2(F12.3,4X))',DIST(K),UR(K)
296.000 500  CONTINUE
297.000      PRINT*, '
298.000      PRINT*, '

```

```

294.000 Q=SDYN/SMASSF
300.000 QBAR=((SMASSF**2)**4)/(RADIUS**4)
301.000 ALPHA=((RADIUS**4)*SDYN)/(4*(SMASSF**3))
302.000 VELINT=(.5*RADIUS)-DELSTR
303.000 ALPHATL=((RADIUS**2)*(VELINT-ENTH))/(4*(VELINT**3))
304.000 PRINT*, 'SMASSF=', SMASSF
305.000 PRINT*, 'SDYN=', SDYN
306.000 PRINT*(1(A,F9.6)), ' THETA= ', THETA
307.000 PRINT*(1(A,F9.6)), ' DELSTR= ', DELSTR
308.000 PRINT*(1(A,F9.6)), ' H= ', H
309.000 PRINT*(1(A,F9.6)), ' ENTH= ', ENTH
310.000 PRINT*, 'ALPHA=', ALPHA
311.000 PRINT*, 'Q=', Q
312.000 PRINT*, 'QBAR=', QBAR
313.000 PRINT*, 'ALPHA(ALT)=', ALPHATL
314.000 STOP
315.000 END

316.000 C
317.000 C
318.000 C
319.000 C *****
320.000 C
321.000 C INTEGRATION FUNCTION SIMP
322.000 C
323.000 C
324.000 C THIS INTEGRATION SCHEME USES SIMPSON METHOD
325.000 C *****
326.000 C
327.000 C
328.000 C
329.000 C
330.000 REAL FUNCTION SIMP(FIRST, LAST, STEP, FNCTN)
331.000 INTEGER FIRST, LAST, I
332.000 REAL STEP, FNCTN(200), SUM
333.000 C
334.000 C
335.000 C *****
336.000 C
337.000 C
338.000 C DEFINITION
339.000 C
340.000 C ARGUMENT :-
341.000 C
342.000 C FIRST - STARTING POINT
343.000 C LAST - ENDING POINT
344.000 C STEP - X CO-ORDINATE
345.000 C FNCTN - Y CO-ORDINATE
346.000 C SUM - WORK VECTOR
347.000 C
348.000 C *****
349.000 C
350.000 C
351.000 C
352.000 SUM=0.0
353.000 SUM=FNCTN(FIRST)
354.000 DO 50 I=(FIRST+1), (LAST-1)
355.000 IF((I/2)*2).EQ.I) THEN
356.000 SUM=SUM+(4*FNCTN(I))
357.000 ELSE
358.000 SUM=SUM+(2*FNCTN(I))

```

```
359.000      ENDIF
360.000 50    CONTINUE
361.000      SIMP=(STEP/3)*(SUM+FNCTH(LAST))
362.000      RETURN
363.000      END
```

Data Sheet (at inlet section)

16, April, 1984

Initial Condition (at start)

Transducer #1 (from H-P voltmeter) = -0.008 volts

Transducer #2 (from Disa voltmeter) = 0.001 volts

Room temperature = 21°C

Barometric pressure = 28.43 in. Hg

Wind tunnel total temperature = 78°F

At operating point, transducer #1 = 0.196 volts (after starting)

At operating point, transducer #1 = 0.207 volts (before shut down)

Final Condition (at shut down)

Transducer #1 (H-P voltmeter) = -0.008 volts

Transducer #2 (Disa voltmeter) = 0.001 volts

Room temperature = 23°C

Barometric pressure = 28.16 in. Hg

Wind tunnel total temperature = 83°F

INPUT RAW DATA

SET 5 INLET-1
RL

INPUT THE NUMBER OF DATA IN THE INPUT DATA FILE.
390

	P(REF)	P(PITOT)
.000000	.196000	.000000
.003000	.196000	.117600
.004000	.196000	.156800
.006000	.196000	.196000
.008000	.196000	.235200
.012000	.196000	.274400
.015000	.196000	.313600
.016500	.197290	.325528
.018500	.196425	.339815
.020500	.196403	.355489
.022500	.195145	.366873
.024500	.195514	.383207
.026500	.194893	.394684
.028500	.194813	.407159
.030500	.193931	.416952
.033500	.195078	.435024
.036500	.194207	.448618
.039500	.194348	.464492
.042500	.193926	.478769
.045500	.194202	.490814
.048500	.195733	.507609
.051500	.198147	.532213
.054500	.197962	.545383
.057500	.198656	.562551
.060500	.198731	.577111
.063500	.198224	.590180
.066500	.198346	.600084
.069500	.199648	.610477
.072500	.197701	.620836
.075500	.197975	.628412
.078500	.197683	.635501
.081500	.199818	.645000
.084500	.199789	.650804
.087500	.199606	.656049
.090500	.200654	.660171
.093500	.199128	.662824
.098500	.199341	.667670
.103500	.198310	.668742
.108500	.198274	.672439
.113500	.198271	.675220
.123500	.197590	.679108
.133500	.198959	.686409
.143500	.206369	.713886
.153500	.205826	.713309
.163500	.205865	.713293
.173500	.205978	.714803

.183500	.205929	.718044
.198500	.205776	.715537
.213500	.205838	.716110
.233500	.205255	.714287
.253500	.205197	.715048
.273500	.204703	.713595
.303500	.204933	.714601
.333500	.207675	.724370
.363500	.207045	.722587
.393500	.206348	.720199
.423500	.206055	.719255
.453500	.206133	.718899
.483500	.205572	.718532
.533500	.205216	.717708
.563500	.204342	.718823
.633500	.206009	.722932
.673500	.207000	.730000
.833500	.207000	.730000
.933500	.207000	.730000
1.033500	.207000	.730000
1.133500	.207000	.730000
1.233500	.207000	.730000
1.333500	.207000	.730000
1.433500	.207000	.730000
1.533500	.207000	.730000
1.633500	.207000	.730000
1.733500	.207000	.730000
1.833500	.207000	.730000
1.933500	.207000	.730000
2.033500	.207000	.730000
2.233500	.207000	.730000
2.533500	.207000	.730000
2.733500	.207000	.730000
3.033500	.207000	.730000
3.233500	.207000	.730000
3.533500	.207000	.730000
3.733500	.207000	.730000
4.033500	.207000	.730000
4.233500	.207000	.730000
4.533500	.207000	.730000
4.733500	.207000	.730000
5.033500	.207000	.730000
5.233500	.207000	.730000
5.396000	.207000	.730000

PLEASE INPUT RADIUS OF DIFFUSER.
75.396

PLEASE INPUT PRESSURE DIFFERENCE SP.
70

PLEASE INPUT INITIAL VOLTMETER READINGS.
INPUT INDYNP AND INOPDYN IN ORDER.
7.001,-.008

DU-PU

DISTANCE
FROM WALL

U/UNE

.000000	.000000	.739149	1.000000
.003000	.414411	.833500	1.000000
.004000	.478016	.933500	1.000000
.006000	.531099	1.033500	1.000000
.008000	.584829	1.133500	1.000000
.012000	.631496	1.233500	1.000000
.015000	.674945	1.333500	1.000000
.016500	.694868	1.433500	1.000000
.018500	.709763	1.533500	1.000000
.020500	.724359	1.633500	1.000000
.022500	.736976	1.733500	1.000000
.024500	.751407	1.833500	1.000000
.026500	.762112	1.933500	1.000000
.028500	.774610	2.033500	1.000000
.030500	.785192	2.133500	1.000000
.033500	.798842	2.233500	1.000000
.036500	.812621	2.333500	1.000000
.045149	.825967	3.033500	1.000000
.048149	.838959	3.133500	1.000000
.051149	.847961	3.233500	1.000000
.054149	.858795	3.333500	1.000000
.057149	.873722	3.433500	1.000000
.060149	.884877	4.033500	1.000000
.063149	.897035	4.133500	1.000000
.066149	.908370	4.233500	1.000000
.069149	.919804	4.333500	1.000000
.072149	.927179	5.033500	1.000000
.075149	.931978	5.133500	1.000000
.078149	.944650	5.233500	1.000000
.081149	.949702	5.396000	1.000000
.084149	.955770		
.087149	.961866		
.090149	.966189		
.093149	.972371		
.096149	.975371		
.099149	.978793		
.104149	.981584		
.109149	.983616		
.114149	.988210		
.119149	.989932		
.129149	.990488		
.139149	.991446		
.149149	.991338		
.159149	.992171		
.169149	.991965		
.179149	.993117		
.189149	.993358		
.204149	.993560		
.219149	.994234		
.239149	.994471		
.259149	.994590		
.279149	.994457		
.309149	.994804		
.339149	.994905		
.369149	.994989		
.399149	.994547		
.429149	.995704		
.459149	.996031		
.489149	.999020		
.539149	.997641		

THETA= .015541
 DELSTR= .021564
 H= 1.387554
 ENTH= .027938
 ALPHA= 1.017820
 J= 3.611309
 QBAR= 3.548082

STOP

Appendix F : Velocity Profiles Data

Station—1

DISTANCE FROM WALL	U/UINF		
.000000	.000000	.739149	1.000000
.003000	.414411	.833500	1.000000
.004000	.478016	.933500	1.000000
.006000	.534099	1.033500	1.000000
.008000	.584829	1.133500	1.000000
.012000	.631496	1.233500	1.000000
.015000	.674945	1.333500	1.000000
.016500	.694868	1.433500	1.000000
.018500	.709763	1.533500	1.000000
.020500	.724359	1.633500	1.000000
.022500	.736976	1.733500	1.000000
.024500	.751407	1.833500	1.000000
.026500	.762112	1.933500	1.000000
.028500	.774610	2.033500	1.000000
.030500	.785192	2.233500	1.000000
.033500	.798842	2.533500	1.000000
.036500	.812621	2.733500	1.000000
.045149	.825967	3.033500	1.000000
.048149	.838959	3.233500	1.000000
.051149	.847961	3.533500	1.000000
.054149	.858795	3.733500	1.000000
.057149	.873722	4.033500	1.000000
.060149	.884877	4.233500	1.000000
		4.533500	1.000000
.063149	.897035	4.733500	1.000000
.066149	.908370	5.033500	1.000000
.069149	.919804	5.233500	1.000000
.072149	.927179	5.396000	1.000000
.075149	.931978		
.078149	.941650		
.081149	.949702		
.084149	.955770		
.087149	.957501		
.090149	.961866		
.093149	.966189		
.096149	.966573		
.099149	.972371		
.104149	.975371		
.109149	.978793		
.114149	.981584		
.119149	.983616		
.129149	.988210		
.139149	.989932		
.149149	.990488		
.159149	.991446		
.169149	.991338		
.179149	.992171		
.189149	.991965		
.204149	.993117		
.219149	.993358		
.239149	.993560		
.259149	.994234		
.279149	.994471		
.309149	.994590		
.339149	.994457		
.369149	.994804		
.399149	.994805		
.429149	.994989		
.459149	.994547		
.489149	.995704		
.539149	.996031		
.589149	.999020		
.639149	.997641		

Station-2DISTANCE
FROM WALL

U/UINF

.000000	.000000		
.001000	.099999	.267149	.978584
.002500	.199997	.277149	.979217
.004500	.300001	.292149	.983535
.007500	.375002	.307149	.985208
.011250	.425001	.327149	.986505
.014500	.450000	.347149	.987698
.016500	.466546	.367149	.987952
.018500	.481046	.387149	.988582
.020500	.487930	.407149	.990538
.022500	.493819	.427149	.989611
.024500	.500515	.447149	.988618
.026500	.505427	.467149	.989097
.028500	.510433	.487149	.989383
.030500	.517272	.507149	.991599
.032500	.522242	.537149	.991911
.034500	.528526	.567249	.993060
.043149	.535411	.597149	.994178
.046149	.545102	.627149	.994051
.049149	.555569	.657149	.995149
.052149	.563978	.707149	.995459
.055149	.625131	.757149	.997756
.058149	.581688	.807149	.997048
.061149	.590353	.857149	.998464
.064149	.598281	.907149	.997583
.067149	.607290	.957149	.999185
.072149	.621964	1.007149	.996708
.077149	.639185	1.057149	.998542
.082149	.656048	1.107149	1.000097
.087149	.675135	1.157149	.999906
.092149	.694965	1.207149	1.000000
.097149	.713028	1.301500	1.000000
.102149	.730600	1.401500	1.000000
.107149	.746844	1.501500	1.000000
.112149	.760356	1.601500	1.000000
.117149	.772327	1.701500	1.000000
.122149	.787578	1.801500	1.000000
.127149	.802338	2.001500	1.000000
.132149	.817068	2.201500	1.000000
.137149	.831418	2.401500	1.000000
.142149	.841929	2.601500	1.000000
.147149	.851752	2.801500	1.000000
.152149	.865637	3.001500	1.000000
.157149	.874143	3.501500	1.000000
.162149	.891392	4.001500	1.000000
.172149	.907878	4.501500	1.000000
.187149	.924356	5.001500	1.000000
.197149	.935648	5.855600	1.000000
.207149	.944910		
.217149	.953507		
.227149	.961899		
.237149	.969343		
.247149	.972758		
.257149	.977028		

3 3

OF / DE

Station-3DISTANCE
FROM WALL

U/UINF

.000000	.000000	.530149	.989787
.002000	.049999	.560149	.989632
.004000	.124999	.610149	.991777
.005500	.159999	.660149	.992339
.007000	.195000	.710149	.999197
.011000	.250000	.760149	.995743
.014000	.285000	.810149	.999426
.016500	.307398	.860149	.999431
.018500	.326220	.910149	.998625
.020500	.340463	1.010149	.999766
.023500	.360647	1.110149	1.002640
.032149	.392767	1.210149	.999449
.035149	.403596	1.310149	1.000700
.040149	.412268	1.410149	1.000371
.045149	.426557	1.510149	1.001180
.050149	.435009	1.610149	1.000000
.055149	.448555	1.704500	1.000000
.060149	.457028	2.204500	1.000000
.070149	.472428	2.504500	1.000000
.080149	.486226	2.804500	1.000000
.090149	.499979	3.104500	1.000000
.100149	.521278	3.404500	1.000000
.110149	.538896	3.704500	1.000000
.120149	.560789	4.004500	1.000000
.130149	.576535	4.304500	1.000000
.145149	.604295	4.604500	1.000000
.160149	.633407	4.904500	1.000000
.175149	.657842	5.204500	1.000000
.190149	.684498	5.504500	1.000000
.205149	.716675	5.804500	1.000000
.220149	.743729	6.305800	1.000000
.230149	.768830		
.250149	.793727		
.265149	.817624		
.280149	.844954		
.295149	.865333		
.310149	.887528		
.325149	.904794		
.340149	.921695		
.355149	.932825		
.370149	.942184		
.390149	.957231		
.410149	.964870		
.430149	.974998		
.450149	.980749		
.470149	.982435		
.500149	.986304		

Station—4

DISTANCE FROM WALL	U/UINF		
.000000	.000000	.7/2149	1.0007/8
.001000	.049996	.8/2149	1.002960
.001500	.099993	.8/2149	1.003016
.002000	.150009	.8/2149	1.004835
.004000	.200000	.9/2149	1.005657
.007000	.250005	1.0/2149	1.004942
.013000	.299999	1.1/2149	1.009106
.016500	.323055	1.2/2149	1.000949
.018500	.332220	1.2/2149	1.010614
.021500	.334909	1.3/2149	1.008300
.024500	.346236	1.4/2149	1.007428
.033149	.349066	1.5/2149	1.009183
.036149	.354578	1.6/2149	1.007005
.039149	.359297	1.7/2149	1.008664
.042149	.366062	1.8/2149	1.011275
.047149	.376261	2.0/2149	1.008330
.052149	.381599	2.2/2149	1.009181
.057149	.389995	2.4/2149	1.006794
.062149	.396949	3.0/2149	1.009884
.067149	.402759	3.2/2149	1.010254
.072149	.411733	3.3/2149	1.007503
.082149	.424525	3.5/2149	1.006577
.092149	.440479	3.8/2149	1.004968
.102149	.451151	4.2/2149	1.006591
.112149	.460259	4.5/2149	1.000420
.122149	.468125	4.8/2149	1.003968
.132149	.493844	5.1/2149	.79/690
.142149	.507527	5.4/2149	1.000000
.152149	.517541	5.6/2149	1.000000
.162149	.533360	6.0/16500	1.000000
.172149	.549749	6.3/5200	1.000000
.182149	.564637		
.197149	.583131		
.212149	.601459		
.227149	.635272		
.242149	.662731		
.257149	.692324		
.272149	.693789		
.287149	.714580		
.302149	.738020		
.317149	.762045		
.332149	.775074		
.347149	.792896		
.362149	.817278		
.377149	.832492		
.392149	.851314		
.407149	.867166		
.422149	.887970		
.442149	.901356		
.462149	.918195		
.482149	.934096		
.502149	.945068		
.522149	.951531		
.542149	.963590		
.562149	.967450		
.582149	.978547		
.612149	.983303		
.642149	.990267		
.672149	.995044		
.702149	.996691		

Station-5DISTANCE
FROM WALL

U/UINF

.000000	.000000	.927149	1.001526
.001000	.049969	.977149	1.004367
.002000	.100009	1.027149	1.006822
.004000	.150002	1.077149	1.005814
.006000	.200001	1.127149	1.007937
.009000	.224995	1.177149	1.010786
.012000	.250002	1.227149	1.012706
.016500	.278295	1.377149	1.017215
.019500	.284136	1.477149	1.012865
.020500	.288244	1.577149	1.011106
.023500	.294119	1.677149	1.012814
.026500	.299475	1.877149	1.009082
.035149	.304827	2.077149	1.012640
.038149	.308797	2.277149	1.014346
.041149	.312315	2.577149	1.011842
.044149	.317999	2.877149	1.011423
.047149	.322174	3.177149	1.017517
.052149	.328655	3.477149	1.012627
.057149	.334905	3.777149	1.008536
.062149	.340482	4.077149	1.008303
.067149	.345430	4.377149	1.008213
.072149	.350121	4.677149	1.007209
.077149	.354062	4.977149	1.006474
.082149	.358200	5.277149	1.005816
.087149	.362412	5.577149	1.003586
.097149	.367176	5.877149	1.003695
.107149	.380705	6.177149	1.000000
.117149	.388995	6.471500	1.000000
.127149	.400348	6.771500	1.000000
.137149	.411157	7.115100	1.000000
.152149	.427919		
.167149	.443014		
.182149	.459447		
.197149	.474340		
.217149	.493513		
.237149	.518535		
.257149	.544330		
.277149	.566500		
.297149	.585725		
.317149	.614144		
.337149	.631634		
.357149	.654302		
.377149	.668982		
.397149	.698653		
.417149	.719689		
.447149	.748218		
.477149	.774811		
.507149	.808904		
.537149	.839456		
.557149	.858232		
.597149	.885932		
.627149	.905123		
.657149	.923485		
.697149	.943774		
.717149	.958298		
.747149	.960777		
.777149	.973057		
.807149	.983273		
.847149	.992487		
.887149	.997410		

Station-6DISTANCE
FROM WALL

U/UINF

.000000	.000000
.001000	.050009
.002000	.075003
.003000	.099985
.005000	.124989
.007500	.150005
.011500	.175009
.015500	.203801
.019500	.207274
.023500	.210732
.027500	.214979
.031500	.219294
.035149	.223624
.039149	.227878
.041149	.230614
.044149	.234036
.047149	.237389
.052149	.243185
.057149	.248551
.062149	.253613
.067149	.258541
.072149	.266540
.082149	.273244
.092149	.289328
.102149	.299427
.112149	.309810
.122149	.317718
.132149	.331959
.142149	.336501
.162149	.340665
.177149	.365286
.192149	.375805
.212149	.390221
.232149	.408598
.252149	.427122
.272149	.437782
.292149	.457444
.312149	.485102
.332149	.512497
.352149	.541260
.372149	.566957
.392149	.591805
.412149	.619264
.432149	.646479
.452149	.672854
.472149	.699986
.492149	.724530
.512149	.758540
.532149	.775278
.552149	.803984
.572149	.835140
.592149	.864202

.812149	.889147
.832149	.912684
.852149	.928645
.872149	.944467
.892149	.959002
.912149	.970684
.932149	.982804
.952149	.991160
.972149	.998055
.992149	1.000720
1.012149	1.003819
1.032149	1.006905
1.052149	1.008305
1.072149	1.007767
1.092149	1.009512
1.112149	1.008267
1.132149	1.010650
1.152149	1.011683
1.172149	1.009127
1.192149	1.010427
1.212149	1.008929
1.232149	1.005647
1.252149	1.003424
1.272149	1.005114
1.292149	1.001991
1.312149	1.007352
1.332149	1.001506
1.352149	1.006065
1.372149	1.000000
1.392149	1.000000
1.412149	1.000000
1.432149	1.000000
1.452149	1.000000
1.472149	1.000000

Station-7DISTANCE
FROM WALL

U/UINF

.000000	.000000
.001000	.124995
.002000	.137507
.003000	.149993
.004000	.162513
.005000	.175009
.006000	.187484
.007000	.204921
.008000	.206892
.009000	.209545
.010000	.210895
.011000	.217177
.012000	.220722
.013000	.230546
.014000	.235123
.015000	.237117
.016000	.246833
.017000	.254218
.018000	.263179
.019000	.273459
.020000	.281173
.021000	.291792
.022000	.301958
.023000	.311221
.024000	.322094
.025000	.330377
.026000	.339330
.027000	.348810
.028000	.357310
.029000	.375460
.030000	.390311
.031000	.412030
.032000	.431499
.033000	.451270
.034000	.464152
.035000	.484268
.036000	.500701
.037000	.518759
.038000	.535497
.039000	.550409
.040000	.590786
.041000	.612796
.042000	.642677
.043000	.663104
.044000	.683958
.045000	.715385
.046000	.744259
.047000	.775133
.048000	.801690
.049000	.834994
.050000	.862958
.051000	.889607
.052000	.913594
.053000	.934400
.054000	.952761
.055000	.967399
.056000	.978141
.057000	.987107
.058000	.994472
.059000	.999690

1.375149	1.003429
1.425149	1.007736
1.475149	1.007266
1.525149	1.008907
1.575149	1.011329
1.625149	1.010945
1.675149	1.009341
1.725149	1.013354
1.775149	1.012305
1.825149	1.011297
1.875149	1.013987
1.925149	1.012526
1.975149	1.011524
2.025149	1.011059
2.075149	1.013053
2.125149	1.011872
2.175149	1.012534
2.225149	1.008190
2.275149	1.012026
2.325149	1.009683
2.375149	1.007350
2.425149	1.007888
2.475149	1.004507
2.525149	1.009429
2.575149	1.002955
2.625149	1.006482
2.675149	1.003373
2.725149	1.000000
2.775149	1.000000
2.825149	1.000000

Outlet (a)DISTANCE
FROM WALL

U/UIM

.000000	.000000
.002000	.102545
.004000	.202117
.007000	.220272
.010000	.241988
.014000	.266246
.018500	.277033
.024149	.294210
.030149	.303635
.035149	.312408
.040149	.321373
.045149	.329306
.050149	.334959
.055149	.339836
.060149	.343962
.065149	.347771
.072149	.352742
.082149	.358209
.092149	.363051
.102149	.368724
.112149	.373408
.122149	.378162
.132149	.382891
.142149	.387370
.152149	.393034
.172149	.398737
.182149	.404008
.202149	.409995
.222149	.415697
.242149	.421224
.262149	.425503
.282149	.440428
.302149	.444748
.322149	.459562
.342149	.477596
.362149	.491295
.382149	.506162
.402149	.518444
.422149	.52874
.442149	.533932
.462149	.544653
.482149	.557682
.502149	.579618
.522149	.614964
.542149	.627342
.562149	.648710
.582149	.664426
.602149	.671353
.622149	.701393
.642149	.718935
.662149	.734816
.682149	.753542
.702149	.774675

1.002149	.796505
1.052149	.818506
1.102149	.840631
1.152149	.858250
1.202149	.881001
1.252149	.898451
1.302149	.905895
1.402149	.928760
1.502149	.948962
1.602149	.959066
1.702149	.966726
1.802149	.971976
1.902149	.973934
2.002149	.975060
2.102149	.976007
2.202149	.976820
2.302149	.977509
2.402149	.977588
2.502149	.977588
2.602149	.977588
2.702149	.977588
2.802149	.977588
2.902149	.977588
3.002149	.977588
3.102149	.977588
3.202149	.977588
3.302149	.977588
3.402149	.977588
3.502149	.977588
3.602149	.977588
3.702149	.977588
3.802149	.977588
3.902149	.977588
4.002149	.977588
4.102149	.977588
4.202149	.977588
4.302149	.977588
4.402149	.977588
4.502149	.977588
4.602149	.977588
4.702149	.977588
4.802149	.977588
4.902149	.977588
5.002149	.977588
5.102149	.977588
5.202149	.977588
5.302149	.977588
5.402149	.977588
5.502149	.977588
5.602149	.977588
5.702149	.977588
5.802149	.977588
5.902149	.977588
6.002149	.977588
6.102149	.977588
6.202149	.977588
6.302149	.977588
6.402149	.977588
6.502149	.977588
6.602149	.977588
6.702149	.977588
6.802149	.977588
6.902149	.977588
7.002149	.977588
7.102149	.977588
7.202149	.977588
7.302149	.977588
7.402149	.977588
7.502149	.977588
7.602149	.977588
7.702149	.977588
7.802149	.977588
7.902149	.977588
8.002149	.977588
8.102149	.977588
8.202149	.977588
8.302149	.977588
8.402149	.977588
8.502149	.977588
8.602149	.977588
8.702149	.977588
8.802149	.977588
8.902149	.977588
9.002149	.977588
9.102149	.977588
9.202149	.977588
9.302149	.977588
9.402149	.977588
9.502149	.977588
9.602149	.977588
9.702149	.977588
9.802149	.977588
9.902149	.977588
10.002149	.977588

Outlet (a)DISTANCE
FROM WALL

U/W/IN

.000000	.000000
.002000	.102565
.004000	.202117
.006000	.298272
.008000	.391988
.010000	.484246
.012000	.575033
.014000	.664210
.016000	.751835
.018000	.837959
.020000	.923635
.022000	.100000
.024000	.187249
.026000	.274498
.028000	.361747
.030000	.448996
.032000	.536245
.034000	.623494
.036000	.710743
.038000	.797992
.040000	.885241
.042000	.972490
.044000	.100000
.046000	.187249
.048000	.274498
.050000	.361747
.052000	.448996
.054000	.536245
.056000	.623494
.058000	.710743
.060000	.797992
.062000	.885241
.064000	.972490
.066000	.100000
.068000	.187249
.070000	.274498
.072000	.361747
.074000	.448996
.076000	.536245
.078000	.623494
.080000	.710743
.082000	.797992
.084000	.885241
.086000	.972490
.088000	.100000
.090000	.187249
.092000	.274498
.094000	.361747
.096000	.448996
.098000	.536245
.100000	.623494
.102000	.710743
.104000	.797992
.106000	.885241
.108000	.972490
.110000	.100000
.112000	.187249
.114000	.274498
.116000	.361747
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.120000	.536245
.122000	.623494
.124000	.710743
.126000	.797992
.128000	.885241
.130000	.972490
.132000	.100000
.134000	.187249
.136000	.274498
.138000	.361747
.140000	.448996
.142000	.536245
.144000	.623494
.146000	.710743
.148000	.797992
.150000	.885241
.152000	.972490
.154000	.100000
.156000	.187249
.158000	.274498
.160000	.361747
.162000	.448996
.164000	.536245
.166000	.623494
.168000	.710743
.170000	.797992
.172000	.885241
.174000	.972490
.176000	.100000
.178000	.187249
.180000	.274498
.182000	.361747
.184000	.448996
.186000	.536245
.188000	.623494
.190000	.710743
.192000	.797992
.194000	.885241
.196000	.972490
.198000	.100000
.200000	.187249
.202000	.274498
.204000	.361747
.206000	.448996
.208000	.536245
.210000	.623494
.212000	.710743
.214000	.797992
.216000	.885241
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.220000	.100000
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.226000	.361747
.228000	.448996
.230000	.536245
.232000	.623494
.234000	.710743
.236000	.797992
.238000	.885241
.240000	.972490
.242000	.100000
.244000	.187249
.246000	.274498
.248000	.361747
.250000	.448996
.252000	.536245
.254000	.623494
.256000	.710743
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.260000	.885241
.262000	.972490
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.268000	.274498
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.274000	.536245
.276000	.623494
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.296000	.536245
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.314000	.361747
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.318000	.536245
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.352000	.100000
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.362000	.536245
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.384000	.536245
.386000	.623494
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.428000	.536245
.430000	.623494
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.438000	.972490
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.448000	.448996
.450000	.536245
.452000	.623494
.454000	.710743
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.458000	.885241
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.462000	.100000
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.472000	.536245
.474000	.623494
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.480000	.885241
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.484000	.100000
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.488000	.274498
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.492000	.448996
.494000	.536245
.496000	.623494
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.502000	.885241
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.516000	.536245
.518000	.623494
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.528000	.100000
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.536000	.448996
.538000	.536245
.540000	.623494
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.550000	.100000
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.582000	.536245
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.594000	.100000
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.604000	.536245
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.616000	.100000
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.624000	.448996
.626000	.536245
.628000	.623494
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.636000	.972490
.638000	.100000
.640000	.187249
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.648000	.536245
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.652000	.710743
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.728000	.187249
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.736000	.536245
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.758000	.536245
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.768000	.972490
.770000	.100000
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.780000	.536245
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.786000	.797992
.788000	.885241
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.796000	.274498
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.802000	.536245
.804000	.623494
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.824000	.536245
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.828000	.710743
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.832000	.885241
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.836000	.100000
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.854000	.885241
.856000	.972490
.858000	.100000
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.862000	.274498
.864000	.361747
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.868000	.536245
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.876000	.885241
.878000	.972490
.880000	.100000
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.884000	.274498
.886000	.361747
.888000	.448996
.890000	.536245
.892000	.623494
.894000	.710743
.896000	.797992
.898000	.885241
.900000	.972490
.902000	.100000

Output (c)DISTANCE
FROM WALL

OUTPUT

.000000	.000000	.588147	.513126
.004500	.207711	.588147	.530236
.009000	.216780	.618149	.545434
.013500	.225555	.648149	.567487
.018000	.234178	.678149	.581122
.022500	.242751	.708149	.601816
.027000	.248720	.738149	.610075
.031500	.251500	.768147	.630453
.036000	.257593	.798149	.657899
.040500	.263176	.828149	.685353
.045000	.267375	.858149	.705292
.049500	.271755	.888149	.701577
.054000	.275447	.918149	.721667
.058500	.281417	.948149	.736712
.063000	.287185	.978149	.751824
.067500	.291945	1.008149	.762575
.072000	.294261	1.038149	.792749
.076500	.300000	1.068149	.808743
.081000	.303356	1.098149	.814667
.085500	.307553	1.128149	.835302
.090000	.311473	1.158149	.849582
.094500	.316492	1.188149	.864093
.103149	.320456	1.218149	.876314
.111314	.324751	1.248149	.887425
.123149	.328741	1.278149	.900316
.133149	.331917	1.308149	.912652
.143149	.335215	1.338149	.921895
.153149	.338527	1.368149	.928727
.163149	.342584	1.398149	.947475
.183149	.347025	1.418149	.945814
.193149	.350668	1.448149	.954573
.213149	.354952	1.478149	.963857
.223149	.360233	1.508149	.965960
.243149	.367502	1.538149	.975783
.253149	.372770	1.568149	.983015
.273149	.377795	1.598149	.983833
.283149	.385726	1.628149	.988670
.303149	.390770	1.658149	.992839
.323149	.400145	1.708149	.997548
.343149	.410192	1.758149	1.003984
.363149	.420663	1.808149	1.008978
.383149	.427704	1.858149	1.009477
.403149	.428867	1.908149	.015115
.423149	.438446	2.058149	1.014356
.443149	.447142	2.138149	1.014800
.463149	.462185	2.358149	1.015085
.483149	.475910	2.558149	1.015732
.523149	.494744	2.758149	1.017629
		3.058149	1.015958
		3.358149	1.019146
		3.658149	1.015875
		3.958149	1.017432
		4.258149	1.014080
		4.558149	1.015715
		5.058149	1.013207
		5.558149	1.012350
		6.058149	1.012055
		6.558149	1.008803
		7.058149	1.006816
		7.558149	1.001127
		8.042643	1.000000

END

1 5 H 0 4 1 8 6 1

FIN