

VELOCITY AND TEMPERATURE DISTRIBUTIONS

FOR MERCURY IN TURBULENT FLOW

by

ROBERT ALEXANDER LOUW

The copyright of this thesis is held by the
University of Cape Town.

Reproduction of the whole or any part
may be made for study purposes only, and
not for publication.

Submitted

in fulfilment of the requirements
for the degree of
Master of Science in Engineering

University of Cape Town
September, 1971.

The copyright of this thesis vests in the author. No quotation from it or information derived from it is to be published without full acknowledgement of the source. The thesis is to be used for private study or non-commercial research purposes only.

Published by the University of Cape Town (UCT) in terms of the non-exclusive license granted to UCT by the author.

ABSTRACT

Velocity and temperature profiles in mercury are reported for vertical flow in a pipe at Reynolds numbers of approximately 3.3×10^4 and 5.4×10^4 with variation in heat flux. At a Reynolds number $\approx 3.3 \times 10^4$ profiles are reported for thermal calming lengths of approximately 17, 36, 61 and 84.

The velocity profiles, temperature profiles and Nusselt numbers are shown to be strongly influenced by free convection effects. Correlations are presented whereby the amount of distortion of the velocity profile from the isothermal profile under given conditions may be estimated, and the value of the Nusselt number under given conditions may be predicted.

ACKNOWLEDGEMENTS

The author wishes to express his sincere appreciation and gratitude to Professor A.D. Carr and Dr. H.O. Buhr for their encouragement and assistance during the course of this work.

He also wishes to thank Mr. K. Wheeler for constructing various modifications made to the equipment.

The author is grateful to the S.A. Atomic Energy Board for the loan of the mercury, and to the Council for Scientific and Industrial Research and the Industrial Development Corporation for their generous financial assistance.

Finally, the author wishes to express his most sincere gratitude to his parents for their encouragement and assistance during his undergraduate studies and to his wife and parents for their further encouragement during the course of this work.

TABLE OF CONTENTS

ABSTRACT		11
ACKNOWLEDGEMENTS		111
TABLE OF FIGURES		vii
<u>CHAPTER 1</u>	: <u>COMBINED FREE AND FORCED CONVECTION IN TURBULENT PIPE FLOW</u>	
1.1	INTRODUCTION	1
1.2	THE EQUATIONS OF MOMENTUM AND ENERGY	2
<u>CHAPTER 2</u>	: <u>EXPERIMENTAL EQUIPMENT</u>	
2.1	THE TEST LOOP	6
2.2	THE TEST SECTION	9
2.3	TEST SECTION HEATING	10
2.4	THE PROBE	10
2.5	PRESSURE MEASUREMENT	14
2.6	THERMOCOUPLES AND TEMPERATURE MEASUREMENT	14
2.7	COOLING WATER	16
2.8	OPERATION	16
	2.8.1 Cleaning and Filling	16
	2.8.2 Probe Installation and Positioning	16
	2.8.3 Start Up	17
	2.8.4 Operating Procedure	17
<u>CHAPTER 3</u>	: <u>EXPERIMENTAL RESULTS</u>	
3.1	INTRODUCTION	20
3.2	VELOCITY AND TEMPERATURE PROFILES	21
3.3	ENTRANCE LENGTH EFFECTS	21
3.4	VELOCITY AND TEMPERATURE PROFILE TRENDS	27

<u>CHAPTER 4</u>	: <u>DISCUSSION OF RESULTS CONCLUSIONS AND RECOMENDATIONS</u>	
4.1	EDDY DIFFUSIVITIES OF MOMENTUM	33
4.2	EDDY DIFFUSIVITIES OF HEAT	33
4.3	THE RATIO OF EDDY DIFFUSIVITIES	38
4.4	CORRELATION OF NON-ISOTHERMAL VELOCITY PROFILES	38
4.5	NUSSELT NUMBERS	41
	4.5.1 Velocity and Temperature Profile Effects on the Nusselt Number	41
	4.5.2 Nusselt Number Correlation	46
4.6	CONCLUSIONS	49
4.7	RECOMENDATIONS	50
	NOMENCLATURE	51
	LIST OF REFERENCES	54
	APPENDICES	55
<u>APPENDIX A</u>	: <u>CALCULATION PROCEDURE</u>	A - 1
A.1	OVERALL MEASUREMENTS	A - 1
	A.1.1 Heat Balance	A - 1
	A.1.2 Mean Velocity	A - 3
A.2	VELOCITY PROFILE	A - 3
A.3	TEMPERATURE PROFILE	A - 5
	A.3.1 Wall Temperature	A - 6
	A.3.2 Mean Temperature	A - 6
A.4	DIMENSIONLESS PARAMETERS	A - 7
A.5	NUSSELT NUMBERS	A - 9
	A.5.1 Nusselt Number Correlation	A -11
<u>APPENDIX B</u>	: <u>CALIBRATION</u>	B - 1
B.1	ORIFICE METER	B - 1
B.2	THERMOCOUPLES	B - 2
B.3	KILOWATT - HOUR METER	B - 3
B.4	THE PRESSURE MEASURING SYSTEM	B - 4
B.5	THE PT10T - STATIC TUBE	B - 6

<u>APPENDIX C</u>	: <u>PHYSICAL PROPERTIES</u>	C - 1
<u>APPENDIX D</u>	: <u>EDDY DIFFUSIVITIES</u>	D - 1
D.1	FITTING OF EQUATIONS TO VELOCITY AND TEMPERATURE PROFILES	D - 1
D.2	CALCULATION PROCEDURE	D - 3
	EDDY DIFFUSIVITIES OF HEAT AND MOMENTUM	D - 7
<u>APPENDIX E</u>	: <u>EXPERIMENTAL RESULTS</u>	E - 1
	VELOCITY AND TEMPERATURE PROFILE MEASUREMENTS	E - 2

TABLE OF FIGURES

<u>Figure No.</u>		<u>Page</u>
2.1	Schematic drawing of the test loop	7
2.2	Top portion of the loop	8
2.3	Details of the probe	11
2.4	The probe tip	12
2.5	The probe assembled in the test section (fibre-glass lagging removed)	12
2.6	Differential pressure measuring system	15
3.1	Developing velocity profiles at $Re \approx 3.3 \times 10^4$; $Ra \approx 1.4 \times 10^5$	23
3.2	Developing velocity profiles at $Re \approx 3.3 \times 10^4$; $Ra \approx 6.0 \times 10^4$	24
3.3	Developing velocity profiles at $Re \approx 3.3 \times 10^4$; $Ra \approx 2.5 \times 10^4$	25
3.4	Developing temperature profiles at $Re \approx 3.3 \times 10^4$; $Ra \approx 2.5 \times 10^4$	26
3.5	Velocity profiles at $Re \approx 5.4 \times 10^4$; $L/D = 83.6$	28
3.6	Velocity profiles at $Re \approx 3.3 \times 10^4$; $L/D = 83.6$	29
3.7	Temperature profiles at $Re \approx 5.4 \times 10^4$; $L/D = 83.6$	30
3.8	Temperature profiles at $Re \approx 3.3 \times 10^4$; $L/D = 83.6$	31
4.1	ϵ_M/v values at $Re \approx 5.4 \times 10^4$; $L/D = 83.6$	34
4.2	ϵ_M/v values at $Re \approx 3.3 \times 10^4$	35
4.3	ϵ_H/α values at $Re \approx 5.4 \times 10^4$; $L/D = 83.6$	36
4.4	ϵ_H/α values at $Re \approx 3.3 \times 10^4$	37
4.5	ϵ_H/ϵ_M values at $Re \approx 5.4 \times 10^4$	39
4.6	ϵ_H/ϵ_M values at $Re \approx 3.3 \times 10^4$	40
4.7	Correlation of velocity profiles	42
4.8	Velocity profiles from fig 4.7	43
4.9	Effect of velocity profile on Nusselt number	45
4.10	Nusselt number correlation	47
4.11	Predicted Nusselt numbers	48
B.4	Differential pressure transducer calibration for run 7	B-5

CHAPTER 1

COMBINED FREE AND FORCED CONVECTION IN TURBULENT PIPE FLOW

1.1 INTRODUCTION

The effect of free convection on the velocity and temperature profile in turbulent forced convection has either been neglected or regarded as insignificant by the majority of investigators in this field of research to date. A numerical study of the problem by Ojalvo and Grosh [1] in 1962 showed, however, that free convection effects could influence velocity and temperature profiles to a marked extent.

More recently Horsten [2] carried out an experimental study of this problem in turbulent pipe flow of mercury under conditions of constant wall heat flux. His results confirm that even at low heat fluxes the velocity and temperature profiles distort significantly. The resulting eddy diffusivities of heat and momentum and heat transfer coefficients are also shown to be affected by free convection effects. A problem that arises, however, is whether the measured profiles were fully developed, or whether the observed effects were due to profile development.

The effect of thermal entry length on the Nusselt number in turbulent flow of liquid metals was reviewed by Kays [3] in 1966. The survey shows that the greater the Reynolds number the longer it takes the Nusselt number to reach its final value. Typically for a Reynolds number of 50 000 the Nusselt number only assumes its final value after an $L/D \approx 35$ and at a Reynolds number of 100 000 the final value of the Nusselt number is only assumed after an $L/D \approx 45$.

More recently Azer [4] analysed the problem of thermal entry length and suggested the interpolation formula

$$L/D = \frac{0.701 Pe^{0.827}}{7.0 + 0.025 Pr^{0.15} Pe^{0.83}} \quad (1.1)$$

(where L is the thermal entrance length) be used to establish when flow is fully developed. L/D values obtained using this equation are low compared to the data reported by Kays. Typically for a Reynolds number of 50 000 with Pe = 1300 and Pr = 0.024 an L/D ratio of 21.1 is obtained.

Since none of the work on thermal entrance lengths has been based on a knowledge of both the actual velocity and temperature profiles an experimental determination of these profiles would be desirable.

Briefly, the objectives of this thesis were :

- (i) To extend and confirm the work done by Horsten i.e. measure non-isothermal velocity and temperature profiles using the same loop as he did.
- (ii) To attempt a correlation of the effect of free convection on velocity and temperature profiles, eddy diffusivities and Nusselt numbers.
- (iii) To examine the effect of thermal entry length on the velocity and temperature profile with a view to establishing whether fully developed flow was reached in the experimental equipment used.

Experiments were carried out to measure velocity and temperature profiles at Re ≈ 54 000 for L/D = 84 and at Re ≈ 33 000 for various L/D ratios and a variety of heat fluxes. The basis for the determination of eddy diffusivities of heat and momentum from such measured profiles is set out in the following section.

1.2 THE EQUATIONS OF MOMENTUM AND ENERGY

The equation of motion in cylindrical coordinates for a fluid flowing in a pipe is [5]

$$\frac{\rho}{g_c} \left(\frac{\partial u_x}{\partial t} + u_r \frac{\partial u_x}{\partial r} + \frac{u_\psi}{r} \frac{\partial u_x}{\partial \psi} + u_x \frac{\partial u_x}{\partial x} \right) = - \frac{\partial p}{\partial x} - \left(\frac{1}{r} \frac{\partial}{\partial r} (r \tau_{rx}) + \frac{1}{r} \frac{\partial \tau_{\psi x}}{\partial \psi} + \frac{\partial \tau_{xx}}{\partial x} \right) + \rho \frac{g_x}{g_c} \quad (1.2)$$

The corresponding equation of energy is [5]

$$\rho C_p \left(\frac{\partial T}{\partial t} + u_r \frac{\partial T}{\partial r} + \frac{u_\psi}{r} \frac{\partial T}{\partial \psi} + u_x \frac{\partial T}{\partial x} \right) = - \left(\frac{1}{r} \frac{\partial}{\partial r} (r q_r) + \frac{1}{r} \frac{\partial q_\psi}{\partial \psi} + \frac{\partial q_x}{\partial x} \right) - T \left(\frac{\partial p}{\partial T} \right) \left(\frac{1}{r} \frac{\partial}{\partial r} (r u_r) + \frac{1}{r} \frac{\partial u_\psi}{\partial \psi} + \frac{\partial u_x}{\partial x} \right) + \text{viscous dissipation terms.} \quad (1.3)$$

The following assumptions are made :

- (i) Flow is fully developed.
- (ii) Wall heat flux is uniform i.e. $\partial T/\partial x = \text{const.}$, A [1].
- (iii) Flow is vertically upward in the positive x-direction i.e. $u_r = \bar{u}_\psi = 0$.
- (iv) Viscous dissipation is negligible.
- (v) Axial heat conduction is negligible.
- (vi) The fluid is essentially incompressible and the overall increase in velocity due to heating is negligible. The continuity equation may thus be expressed as $\partial u_x/\partial x = 0$.
- (vii) Static pressure is constant across any cross-section i.e. $\partial p/\partial r = \partial p/\partial \psi = 0$.
- (viii) All fluid properties (except the density) in the driving force term are constant and evaluated at the mean cup temperature.
- (ix) The flow is single phase (i.e. liquid phase)
- (x) There is no slip at the wall i.e. the velocity at the wall = 0.
- (xi) $\tau_{\psi x} = \tau_{xx} = 0$.

For turbulent flow the shear stress is expressed as [6]

$$g_c \tau_{rx} = -\mu \frac{\partial u_x}{\partial r} + \rho \overline{u'_x u'_r} \quad (1.4)$$

where $-\mu \frac{\partial u_x}{\partial r}$ is the laminar contribution and $\rho \overline{u'_x u'_r}$ is the turbulent contribution to the shear stress.

The heat flux is analogously expressed as

$$-q_r = k \frac{\partial T}{\partial r} + \rho C_p \overline{u'_r T'} \quad (1.5)$$

Where $k \frac{\partial T}{\partial r}$ is the laminar and $\rho C_p \overline{u'_r T'}$ the turbulent component of the heat flux.

The eddy viscosity (or eddy diffusivity of momentum, ϵ_M , first suggested by Boussinesq (see Brodkey [6]), is defined as

$$\overline{u'_x u'_r} = -\epsilon_M \frac{\partial u_x}{\partial r} \quad (1.6)$$

and similarly the eddy diffusivity of heat is defined as

$$\overline{u'_r T'} = \epsilon_H \frac{\partial T}{\partial r} \quad (1.7)$$

and hence the momentum equation becomes

$$\frac{dp}{dx} - \rho \frac{g}{g_c} = \frac{1}{r} \frac{d}{dr} \left[\frac{\mu}{g_c} r (1 + \epsilon_M/\nu) \frac{du_x}{dr} \right] \quad (1.8)$$

and the energy equation becomes

$$\rho C_p u_x \frac{dT}{dx} = \frac{1}{r} \frac{d}{dr} \left[kr(1 + \epsilon_H/\alpha) \frac{dT}{dr} \right] \quad (1.9)$$

where $\nu = \mu/\rho$, the kinematic viscosity and
 $\alpha = k/\rho C_p$, the thermal diffusivity.

The density variation in the body force term on the left-hand side of equation (1.8) may be expressed as

$$\rho = \rho_{av} [1 - \beta(T - T_{av})]. \quad (1.10)$$

$\frac{dp}{dx}$ may be evaluated from the friction factor relationship [7]

$$\frac{dp}{dx} + \rho_{av} \frac{g}{g_c} = - \frac{2u_m \mu}{D^2 g_c} f Re \quad (1.11)$$

where ρ_{av} is the mean fluid density and by definition is

$$\rho_{av} = 2 \int_0^1 \rho n dn \quad (1.12)$$

ρ_{av} must thus be evaluated at T_{av} where

$$T_{av} = 2 \int_0^1 T n dn \quad (1.13)$$

and not at the mean cup temperature,

$$T_m = 2 \int_0^1 \frac{u}{u_m} T n dn \quad (1.14)$$

Using the dimensionless parameters

$$\eta = r/R$$

$$U = u_x/u_m$$

$$\theta = T - T_{av}$$

$$\phi = \frac{2k\theta}{\rho_{av} u_m C_p AD^2}$$

$$\text{and } Ra = \frac{\rho_{av}^2 \beta g C_p AD^4}{\mu k}$$

equation (1.8) combined with (1.10) and (1.11) becomes

$$\frac{1}{\eta} \frac{d}{d\eta} \left[\eta \left(1 + \epsilon_M/\nu \right) \frac{dU}{d\eta} \right] = - \frac{\phi Ra}{8} - 0.5 f Re \quad (1.15)$$

and equation (1.9) becomes

$$\frac{1}{\eta} \frac{d}{d\eta} \left[\eta (1 + \epsilon_H/\alpha) \frac{d\phi}{d\eta} \right] = \frac{U}{2} \quad (1.16)$$

Equations (1.15) and (1.16) can be rearranged to give the eddy diffusivities of momentum and heat :

$$\epsilon_M/\nu = \frac{\left[\frac{Ra \int_0^\eta \phi \eta d\eta}{8\eta} - 0.25 f Re \eta \right]}{\frac{dU}{d\eta}} - 1 \quad (1.17)$$

and

$$\epsilon_H/\alpha = \frac{0.5 \int_0^\eta U \eta d\eta}{\eta \frac{d\phi}{d\eta}} - 1 \quad (1.18)$$

Experimental determination of the velocity and temperature distribution will now allow calculation of the eddy diffusivities of heat and momentum.

CHAPTER 2

EXPERIMENTAL EQUIPMENT

2.1 THE TEST LOOP.

The mercury test loop which had previously been used by Horsten [2] is shown schematically in fig. 2.1. All the sections were constructed from type 316 seamless stainless steel tubing. Mercury flowed vertically upward through an 18 ft 7 in. length of tubing with an I.D. of 1.968 in. and O.D. of 2.047 in.

The top portion of the loop is shown in fig. 2.2. It was constructed out of 1.624 in. I.D. tubing and contained a Saunders diaphragm valve, an orifice meter (incorporating flange taps) and an expansion chamber. A 12 in. centrifugal pump was used to pump the mercury around the loop. It was mounted at the top of the loop so as to minimize static pressure on the pump glanding. The pump was belt driven by a 3 h.p. motor through a sliding-pulley variable speed drive and a 10 to 1 reduction gearbox. Speeds could be varied from 70 to 300 r.p.m. Monitoring of the pump speed with a tachometer gave less than a 1% fluctuation over many hours of running time [2]. The motor, variable speed drive and reduction gearbox were attached to a steel frame supported on rubber pads on a concrete platform to minimize the transmission of vibrations to the flow loop.

The inner pump casing was made of cast iron and was epoxy painted to prevent rusting and contamination of the mercury. The pump shaft was glanded with an asbestos impregnated teflon bush. The latter material was rigid and had the lubricating properties of teflon but did not "flow" as teflon does.

Control of the mercury flow rate was achieved by varying the pump speed and utilizing a Saunders diaphragm valve on the pump outlet. A mercury manometer, connected to the orifice meter flange taps, indicated the flow rate.

The vertical and bottom horizontal return pipes (0.788 in. I.D.) were fitted with 1.25 in. diameter stainless steel water jackets, the water flowing counter - currently to the mercury. Two 6 ft. metal

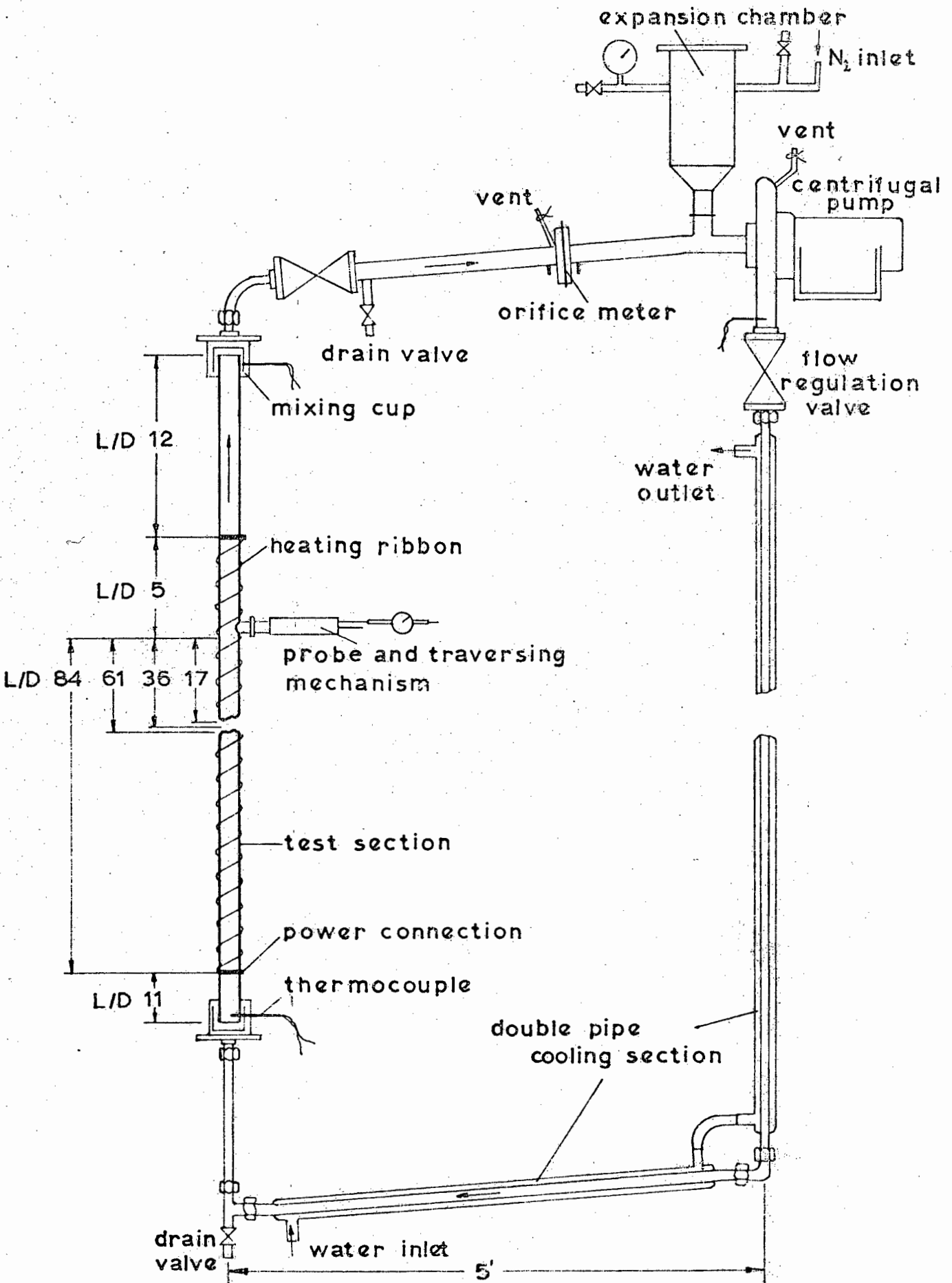


FIGURE 2.1 SCHEMATIC DRAWING OF THE TEST LOOP

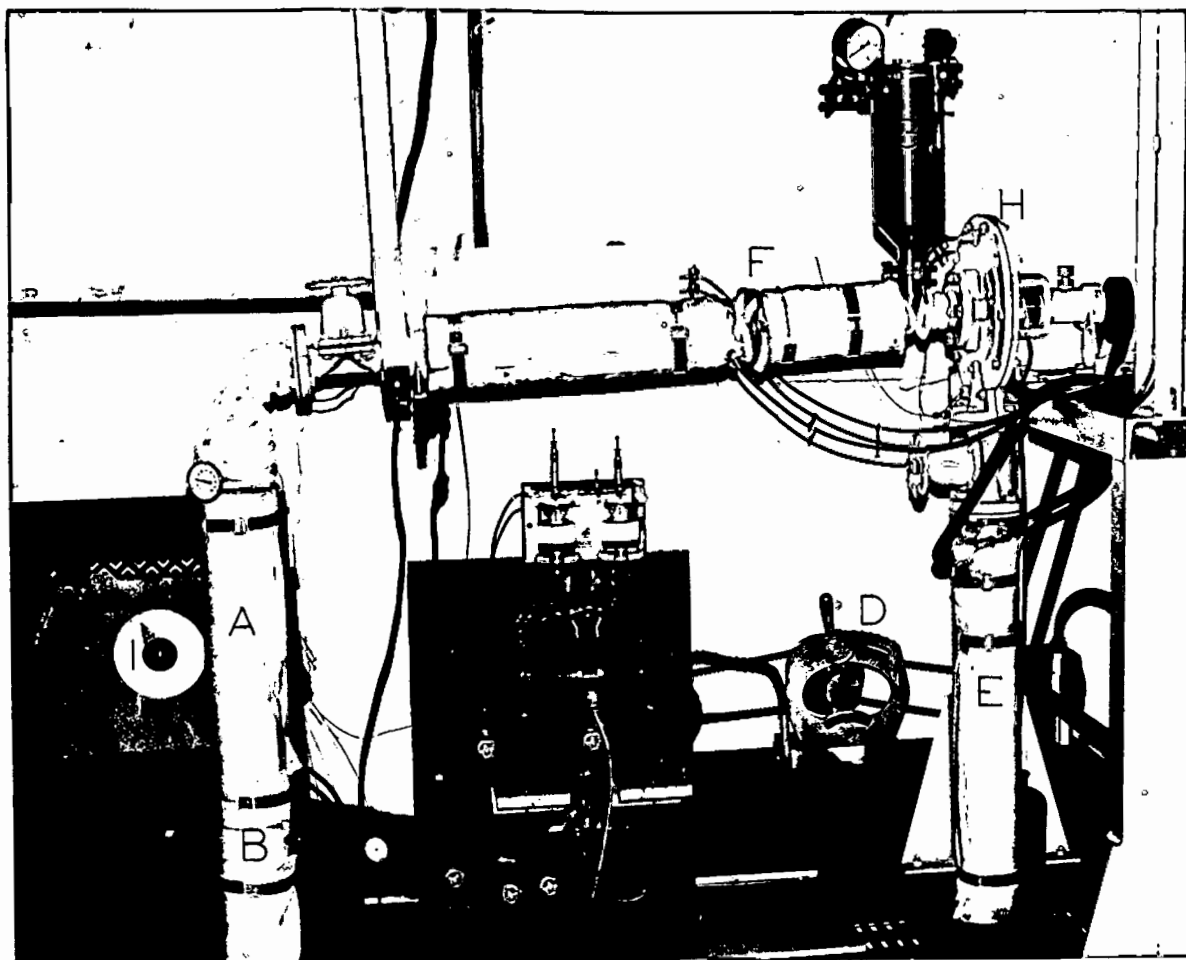


FIGURE 2.2 TOP PORTION OF THE LOOP

A. Insulated test section B. Probing station C. Differential pressure measuring system D. Variable speed control of pump drive E. Vertical return pipe F. Orifice meter G. Expansion Chamber H. Pump I. Thermocouple switching panel

pillars, situated immediately under each vertical leg of the test loop and bolted to the ground floor, supported the loop. Wooden clamps, situated at the level of two laboratory landings and attached to the outside of the asbestos rope insulation (see section 2.2), held the loop vertically.

The loop was filled through the expansion chamber. The top and bottom cross sections were at a slight angle to the horizontal and gas vents were provided at the orifice plate and the pump so that gas trapped in the loop during filling could be released. A drain valve was provided at the bottom of the loop. In case of emergency the mercury could be drained into a stainless steel tank but under normal conditions the mercury was drained into polythene storage bottles when necessary.

2.2 THE TEST SECTION

As mentioned in the previous section, the test section was made from an 18 ft 7 in. length of seamless stainless steel tubing with an I.D. of 1.968 in. and an O.D. of 2.047 in.

Two mixing cups were welded onto each end of the test section. The design of the mixing cups ensured complete mixing of the mercury and hence accurate inlet and outlet temperatures could be measured.

A 5/16 in. diameter hole, through which the probe was inserted was drilled into the tube 2 ft 7 in. from the top end and a nozzle to which the probe traversing mechanism could be attached was silver soldered about this hole. Silver solder was used to prevent distortion of the tube but had to be carefully covered with an epoxy cement to prevent contamination of the mercury.

The test section was evenly wound with 1 in. wide and 0.032 in. thick chromel C heating tape. The length of heated test section to the probe tip was 13 ft 8.5 in. and the distance between the top and bottom lugs was 14 ft 7 in. There were 11 diameters of unheated pipe before the start of the test section and 17 diameters of pipe above the probe tip, 5 of which were heated and 12 unheated.

To obtain different heating lengths, steel hose clips, provided with power cable connections, were clamped around the heating ribbon at distances of 33 in., 72 in. and 119.25 in. below the probe tip. Non-isothermal velocity and temperature profiles could thus be measured at thermal calming lengths of 16.8, 35.6, 60.6 and 83.6.

2.3 TEST SECTION HEATING

The supply voltage was passed through a 74 amp, 220 volt Foster voltage stabilizer and then through a variable transformer capable of providing 100 amps at 160 volts. The minimum output voltage of the transformer was 60 volts. For high heat input runs the transformer was connected directly to the heating ribbon, but for low heat input runs an additional resistance was inserted into the circuit to give the required power output. Power consumed was measured by timing the revolutions on a calibrated domestic KWH meter rated to take 80 amps at 220 volts. An ammeter and a voltmeter were also included in the circuit. During all non-isothermal experimental runs one of the power cables remained connected to the top of the heating ribbon while the other power cable was connected to either of the four other power connections provided.

The heating ribbon was electrically insulated from the pipe by means of asbestos paper glued to the pipe with sodium silicate and covered with a 2 in. woven fibre-glass ribbon. Successive windings of the heating tape were spaced by 1/16 in. diameter asbestos string. Hose clamps, provided at regular intervals, held the heating ribbon in position. The clamps were also insulated from the heating tape by means of asbestos paper and fibre-glass ribbon. Provision for the probe nozzle was made by cutting a semi-circle out of each of two successive heating tape windings. Heating tape-to-tube resistance was approximately 4×10^4 ohms when the insulation was dry.

The test section was thermally insulated by two layers of 3/4 in. asbestos rope wound fairly loosely to give maximum insulation. Preformed fibre-glass steam pipe lagging (1 1/4 in. thick) was finally placed around the asbestos rope, cutting heat losses to less than 2%.

2.4 THE PROBE

To enable simultaneous measurement of velocity and temperature profiles, a probe was constructed to serve as a combined pitot-static tube and Iron-constantan thermocouple. Figure 2.3 is a dimensioned drawing of the probe and fig. 2.4 is a photograph of the probe tip.

The outer tube was 10 gauge (0.077 in. I.D. and 0.128 in. O.D.) and the inner tube 18 gauge (0.032 in I.D. and 0.048 in. O.D.) stainless steel tubing. The goose-neck impact tube was 25 gauge (0.010 in. I.D. and

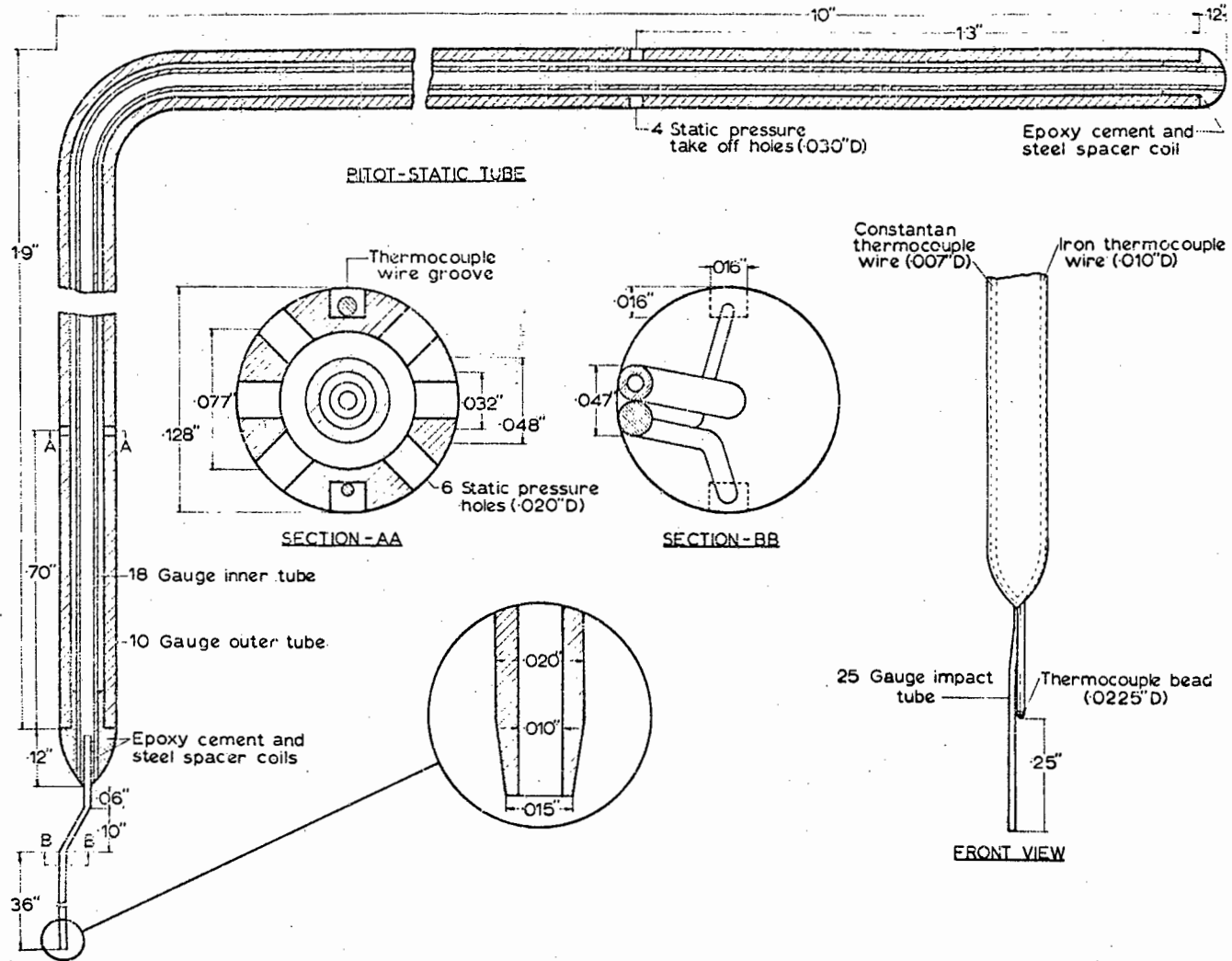


FIGURE 2.3 DETAILS OF THE PROBE

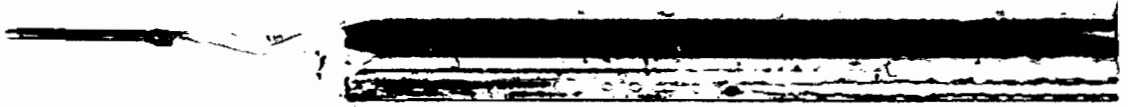


FIGURE 2.4 THE PROBE TIP

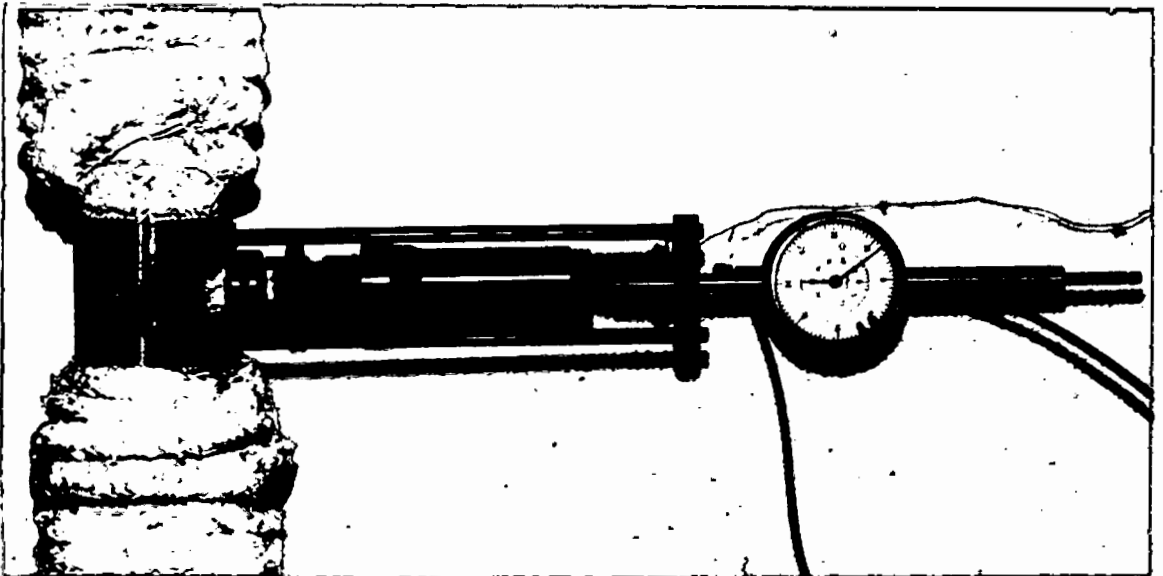


FIGURE 2.5 THE PROBE ASSEMBLED IN THE TEST SECTION

(Fibre-glass lagging removed)

0.020 in. O.D.) stainless steel hypodermic tubing, tapered to 0.015 in. at the probe tip.

Two grooves, 0.016 in. wide and 0.016 in. deep, were made down the sides of the outer tube to accommodate the thermocouple wires. Six 0.020 in. diameter static holes were drilled into the outer tube 1.3 in. downstream from the probe tip. The static holes and thermocouple wire were equally spaced at 45° to each other as shown in fig. 2.3.

At the probe tip tightly fitting wire coils were placed around the impact and inner tubes keeping them concentric to one another and to the outer tube. The tubes and springs were firmly held together by means of an epoxy cement.

The thermocouple was made of 30 gauge (0.010 in. O.D.) iron wire and 34 gauge (0.0067 in. O.D.) constantan wire. The bead had an average O.D. of 0.0225 in. To minimize interference in the flow around the probe tip the thermocouple bead was placed 0.25 in. downstream from the tip. The wires were carefully placed into the grooves provided and cemented in with an epoxy cement. After drying, the epoxy was machined flush with the outer tube. Epoxy cement was also used to streamline the impact tube, thermocouple bead and wires to the outer tube. The exposed bead was covered with a very thin layer of epoxy lacquer to avoid direct contact of the bead with the mercury. Fig. 2.3 shows how the thermocouple bead was positioned on the side of the impact tube. The overall width of the bead plus the impact tube was 0.047 in.

The impact tube was goose-necked, thus enabling the probe tip to touch the test section tube wall before the rest of the probe. This also enabled readings near to the wall to be taken and facilitated probe positioning.

At the rear of the probe the inner and outer tubes were again concentrically positioned by means of a steel coil placed around the inner tube. An epoxy cement was used to hold the tubes together and form a seal.

Four holes (0.030 in. I.D.) drilled into the outer tube and surrounded by a manifold provided a take-off point for static pressure measurement. A pressure tube fitting at the end of the inner tube enabled the impact pressure to be measured.

A Tufnol terminal block provided with small brass electrical connectors was positioned next to the manifold and served to join the thermo-

couple extension leads to the thermocouple wires.

Details of the probe traversing mechanism are given by Horsten [2].

2.5 PRESSURE MEASUREMENT

Fig. 2.6 is a photograph of the pressure measuring and transducing system. Only a brief description of the system will follow and further details may be found in Horsten's Ph.D thesis [2].

An inverted Dwyer hook gauge situated at the top of the system was used for calibration whereas the rest of the system measured pressure signals and transduced them to d.c. voltages.

Static and impact pressures were transmitted from the probe, by means of nylon pressure tubing, to two reservoirs half filled with mercury and half filled with water. These reservoirs had large cross-sectional areas, thus minimizing any offset pressures which could be caused by flow of mercury in the pressure tubes. Two water lines transmitted the pressures from the reservoirs to the ports of a Whittaker Corp. model Pace P 0 9 D differential pressure transducer, having a range of 0 to 1 in. water, and activated by a model C D 10 carrier demodulator giving an output range of 0 - 10 volts d.c. The transduced pressure signals (in the form of d.c. voltages) were electrically filtered to remove high frequency fluctuations and recorded on a 10 in. Beckman pen recorder.

The pressure measuring system was under a static pressure of approximately 30 p.s.i.

2.6. THERMOCOUPLES AND TEMPERATURE MEASUREMENT

Mixing cup, pump outlet, inside and outside insulation temperatures were obtained from Iron-constantan thermocouples. The thermocouples were epoxy cemented into 4 in. lengths of 1/8 in. stainless steel tubing with the bead protruding slightly. The thermocouple sheaths were ^{held} in position by Conax fittings and sealed with teflon bushes.

All thermocouples (including the probe thermocouple) were connected to leads of the same material and taken to a multiway switch from which their individual e.m.f.'s could be monitored. E.m.f.'s were measured relative to an Iron-constantan thermocouple placed in a double walled PVC container, filled with crushed ice. A model 887 AB Fluke

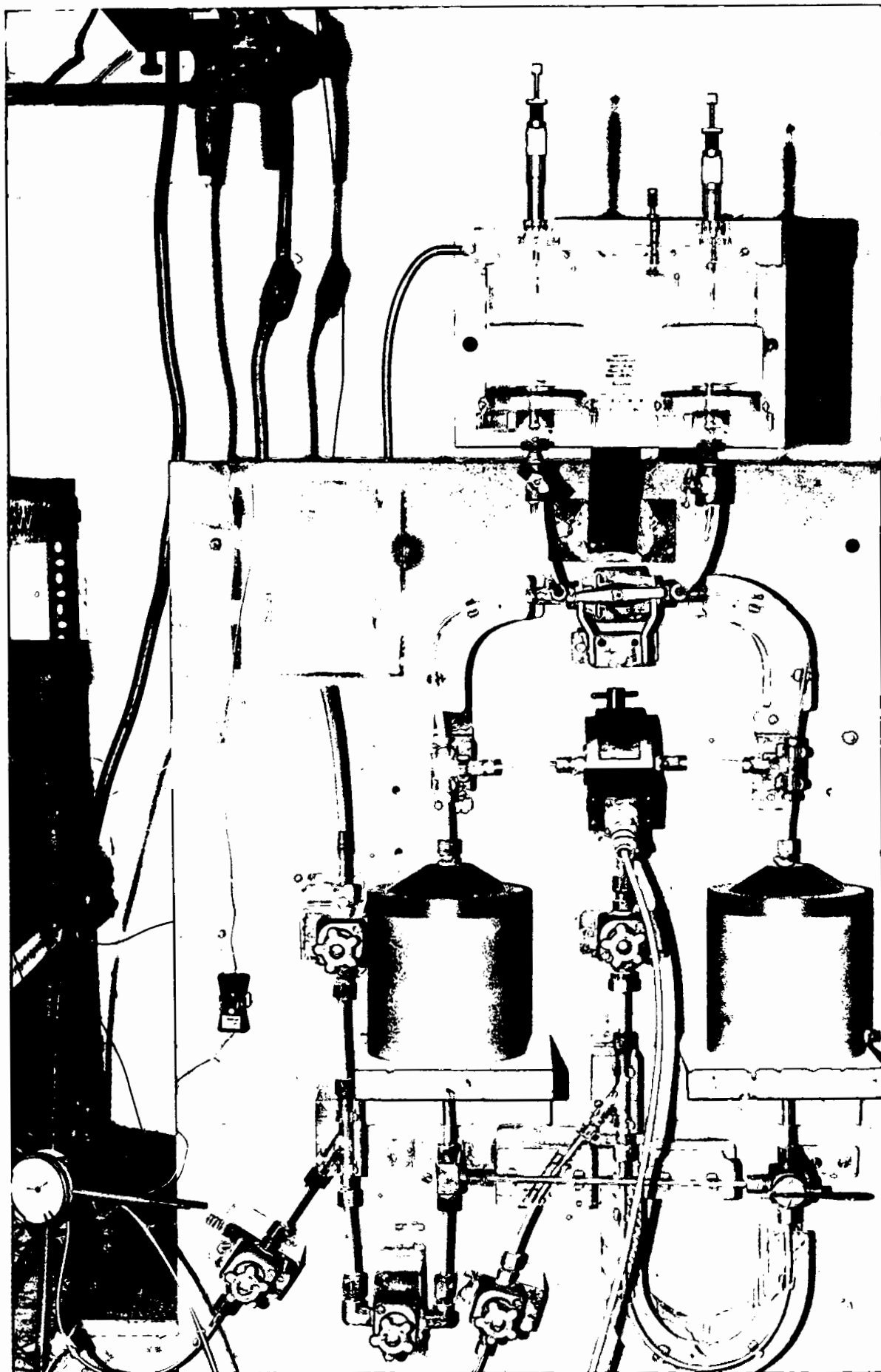


FIGURE 2.6 DIFFERENTIAL PRESSURE MEASURING SYSTEM

differential voltmeter provided direct reading of thermocouple E.m.f.'s.

The e.m.f. from the probe thermocouple was offset by a voltage approximately equal but opposite to the e.m.f. measured at the pipe centre. This voltage was tapped off two Mallory mercury cells and remained very steady. Offset e.m.f.'s were recorded directly on a Series BD Kipp and Zonen Micrograph. Since the maximum offset voltage was less than 500 μV the full range of the recorder could always be utilized. The maximum sensitivity of the recorder was 0.05 mV full scale, thus enabling very small temperature differences to be measured.

By offsetting the probe thermocouple e.m.f.'s. far more accurate temperature readings could be made than by recording e.m.f.'s directly, particularly as this technique enabled better utilization of the recorder scale.

2.7 COOLING WATER

The cooling water system, in which water flowed counter-currently to the mercury, is described by Horsten [2]. Cooling water temperature could be controlled within $\pm 0.1^{\circ}\text{F}$, giving control over the mercury inlet temperature to within $\pm 0.2^{\circ}\text{F}$.

2.8 OPERATION

2.8.1 Cleaning and Filling

Before commencing any experimental work the test loop and the mercury were thoroughly cleaned as described by Horsten [2]. To ensure that the loop had no leaks, it was pressure tested at 100 p.s.i.g. before it was filled. To avoid oxidation of the mercury, all the air was evacuated from the loop and replaced by nitrogen. This procedure was repeated five times before the loop was filled with mercury. During filling, nitrogen was bled into the loop thus avoiding any air being sucked in with the mercury.

2.8.2 Probe Installation and Positioning

The probe was fitted into the traversing mechanism before being carefully inserted through the hole in the pipe and the traversing mechanism screwed onto the pipe nozzle. The probe was vertically positioned by visual observation through the test section exit, making use of its reflection in the mercury. A strip of 0.0015 in. thick paper was used

as a feeler gauge to determine the position of the probe tip relative to the tube wall. The probe was screwed in towards the wall until it just nipped the paper and a lock nut was tightened to prevent it from being advanced beyond this point. Thus, the probe could be advanced to within 0.0015 in. of the wall and retracted to a radial position of $y/R = 1.20$, its position being indicated on a dial gauge which could read to 0.0002 in. Fig. 2.6 is a photograph of the assembled probe mechanism and dial gauge in position, with part of the insulation removed from the test section.

To ensure that no air remained trapped in the probe or its leads, some of the mercury was allowed to run back out of the reservoirs and through the probe while the nylon pressure tubing was being tapped. Tapping the tubing helped to dislodge any air bubbles which were stuck to the tube walls.

2.8.3 Start Up

After long idle periods, it was found that the heating ribbon-to-tube resistance would drop significantly due to water being absorbed by the sodium silicate. Thus, after long inoperative periods, it was necessary to heat the loop with very low currents to avoid shorting between the heating tape and the test section tube.

The procedures dealt with so far were not done regularly, but only when the need arose. In the section to follow normal experimental operating procedures will be discussed.

2.8.4 Operating Procedure

The following steps outline briefly the operating procedure for measuring non-isothermal velocity and temperature profiles:

- (I) The pump was switched on and the variable speed drive adjusted to give the desired flow rate. Finer adjustments were made by utilizing the Saunders diaphragm valve situated immediately below the pump.
- (II) The cooling water system was put into operation and for those runs in which a temperature controller was used, the water heaters and controller were switched on.

- (iii) The bottom power cable was connected to one of its power connections to give the required heating length. For low heat input runs, the additional resistance was included in the heating circuit and the power turned on. The transformer was then adjusted to give the desired heating rate which, at this stage, was set according to the voltmeter and the ammeter.
- (iv) The reference thermocouple was immersed in its ice bath and allowed to reach a steady temperature of 32°F.
- (v) The pressure transducer demodulator, filter circuit and Beckman pen recorder were switched on, a zero position and recorder scale were chosen, and the pressure measuring system calibrated.
- (vi) While steady state was being reached all minor adjustments to the flow rate, heat input and cooling water temperature were made. A period of 2 - 3 hours was allowed for the loop to attain steady state conditions.
- (vii) Once steady state had been reached the probe was positioned at the centre of the tube, the offset voltage source and Kipp Micrograph switched on, and the probe e.m.f. offset by an equal and opposite voltage from the mercury cells. A suitable recorder scale and zero position were chosen and temperature and velocity readings commenced.
- (viii) Pressure differentials and probe thermocouple e.m.f.'s. were recorded at discrete y/R intervals. Because of the large capacitance of the condensers and the fine hypodermic impact tube, it took at least 3 minutes for the differential pressure measuring system to respond to any changes in radial position. Recorder tracings of about 20 minutes at each radial position were thus necessary. The temperature was not recorded for such long periods at each point since the response of the thermocouple was fast. The temperature was, however, referred back to

a radial position of $y/R = 0.50$ at regular intervals to ensure that any minor changes in temperature level would not affect the temperature profile. Zero readings were checked from time to time and where any drift occurred the necessary adjustments were made. After completion of each run, recorder tracings were averaged by eye and the averaged values tabulated.

- (ix) At the end of each run the resistance of the probe thermocouple circuit was measured and in some cases the differential pressure measuring ^{system} was recalibrated.

During all the non-isothermal runs the following parameters were recorded at regular intervals:

1. The pressure drop across the orifice meter.
2. Heat input, by timing a set number of revolutions of the KWH meter disc.
3. Inlet and outlet mixing cup temperatures.
4. The temperature after the pump.
5. Inside and outside insulation temperatures.
6. Cooling water temperature and flow rate.
7. The offset voltage.

CHAPTER 3

EXPERIMENTAL RESULTS

3.1 INTRODUCTION

Table 3.1 summarizes the experimental conditions under which velocity and temperature profiles were measured.

TABLE 3.1

EXPERIMENTAL CONDITIONS

Run	Re ($\times 10^{-3}$)	q (Btu/hr/ft ²)	T _m (°F)	T _w -T _c (°F)	P _r	Ra/Re	L/D
1	53.9	1591	76.59	7.78	0.0241	0.644	83.6
2	54.1	2064	82.22	11.20	0.0236	0.831	83.6
3	55.1	2762	87.79	13.83	0.0231	1.107	83.6
4	36.6	3824	115.16	14.06	0.0210	3.609	83.6
5	35.8	3836	112.56	14.25	0.0212	3.887	60.6
6	35.2	3842	96.77	13.78	0.0224	3.986	35.6
7	32.1	1595	82.00	7.99	0.0236	1.861	83.6
8	33.7	1590	86.16	8.02	0.0233	1.713	60.6
9	34.0	1569	79.45	8.34	0.0238	1.767	35.6
10	32.5	1703	73.64	7.49	0.0243	1.931	16.8
11	31.5	669	83.39	4.57	0.0235	0.810	83.6
12	30.7	682	79.15	4.46	0.0238	0.853	60.6
13	30.6	675	77.77	4.67	0.0240	0.859	35.6
14	31.1	723	74.64	3.59	0.0242	0.898	16.8
1-1	52.2	0	56.54	0	-	0	0
1-2	31.3	0	59.0	0	-	0	0

Temperature and velocity profiles were measured simultaneously by using the combined thermocouple and pitot-static tube probe. The data agreed well with those obtained by Horsten [2] using the same test loop.

Profiles were measured at Reynolds numbers of approximately 33 000 and 54 000 and an L/D of 83.6. Further non-isothermal profiles were measured at a Reynolds number of 33 000 for L/D ratios of 60.6, 35.6 and 16.8. Heat fluxes in the range 670 - 3840 Btu/hr ft² were used. Isothermal velocity profiles were measured at $Re \approx 33\ 000$ and 54 000.

3.2 VELOCITY AND TEMPERATURE PROFILES

Experimental data together with the computed results are tabulated in appendix E. The calculation procedure is given in appendix A.

The mean velocity computed by integration of the velocity profile was generally in good agreement with the mean velocity obtained from the orifice meter. Small differences in these two velocities were probably due to residual inequalities of temperature in the leads from the impact and static tubes to the pressure transducer even though the leads were taken out horizontally so as to minimize the temperature difference effect. For isothermal runs, the integrated mean velocity agreed exactly with the orifice meter velocity.

The agreement between the orifice meter and the heat balance velocities was not as good as the agreement between the orifice meter and integrated mean velocities even though heat losses amounted to less than 2% of the total heat input. The worst disagreement was, however, only 7.5%. The most likely reason for this discrepancy is inaccuracy of the KWH meter. Dimensionless parameters reported in appendix E were computed using the integrated mean velocity.

Since heat losses amounted to less than 2% the axial temperature gradient should be linear [1]. This is experimentally confirmed with mean temperatures based on a linear interpolation between test section inlet and outlet temperatures being only slightly higher than that measured at the probe (see appendix A for details).

3.3 ENTRANCE LENGTH EFFECTS

To study the entrance length effect, sections of the heating coil were reconnected to give L/D ratios of 16.8, 35.6, 60.6 and 83.6 (see

chapter 2) before the probe was reached. Since the total length of the test section to the probe was constant, this meant that the hydrodynamic calming length to the probe was constant, but that the calming length before the start of heating was variable. The relationships are given in Table 3.2.

TABLE 3.2

CALMING LENGTHS TO THE PROBE

Heated Entrance Length, L/D	Hydrodynamic calming length before start of heating, x/D	Total hydrodynamic entrance length.
0	94.6	94.6
16.8	77.8	94.6
35.6	59	94.6
60.6	34	94.6
83.6	11	94.6

Developing velocity and temperature profiles are shown in figs. 3.1 - 3.4 at a Reynolds number of $\approx 33\ 000$.

Hinze [8] recommends that Nikuradse's value of $x/D = 40$ be regarded as a minimum value for the isothermal velocity profile to develop fully. Thus, for runs where $L/D \leq 35.6$ (i.e. $x/D \geq 59$) the isothermal velocity profile can be assumed to have been fully developed before heating began.

It is seen that distortion from the expected pseudo-parabolic velocity profile already exists at an L/D ratio as low as 16.8. At a given heat flux, distortion of the velocity profile increases until flow becomes fully developed. For all the cases considered it appears that both the velocity and temperature profiles are fully developed for an $L/D \geq 60.6$. Slight differences observed between velocity profiles measured at an L/D of 60.6 and 83.6 are small and within the bounds of experimental error.

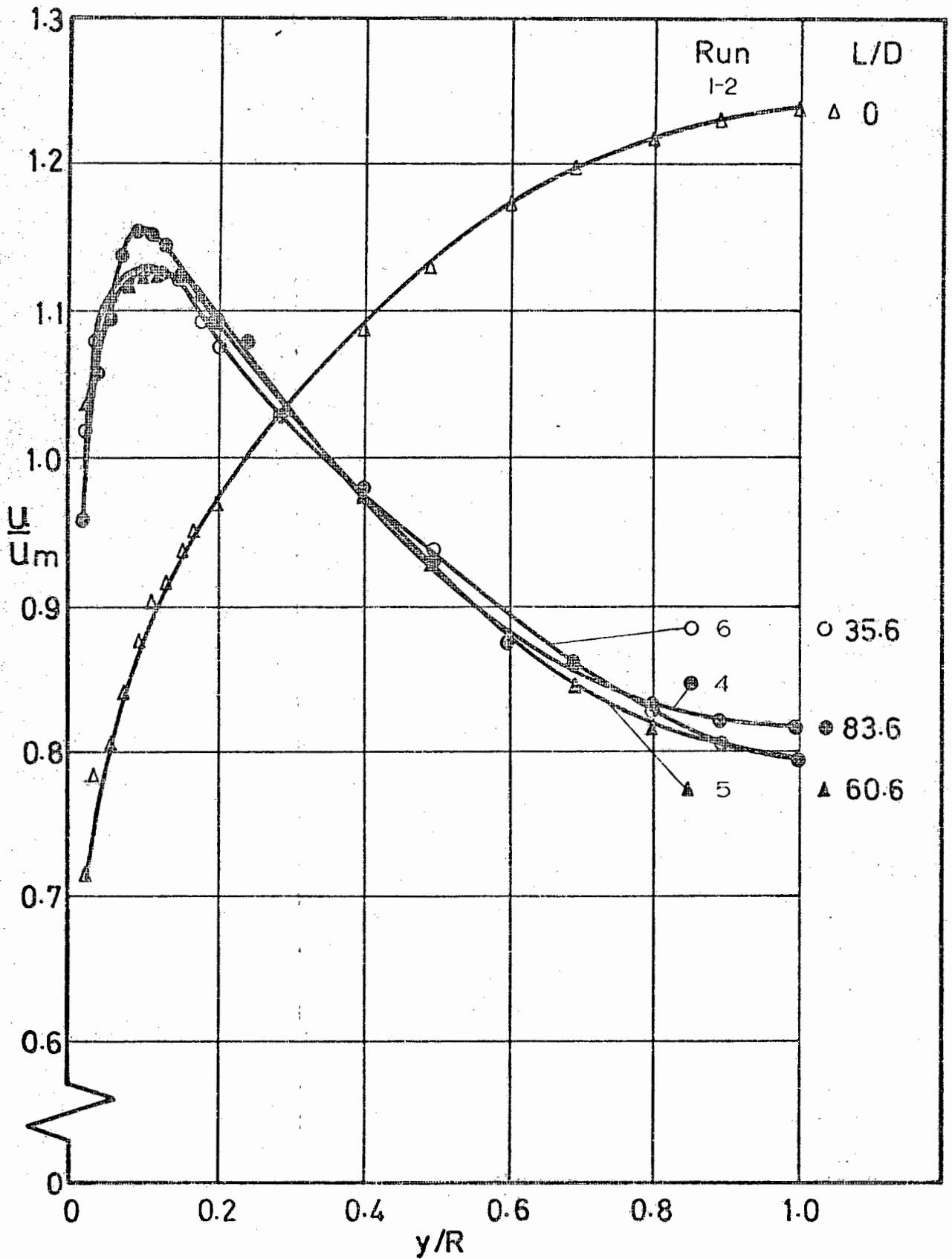


FIGURE 3.1 DEVELOPING VELOCITY PROFILES
At $Re \approx 3.3 \times 10^4$; $Ra \approx 1.4 \times 10^5$

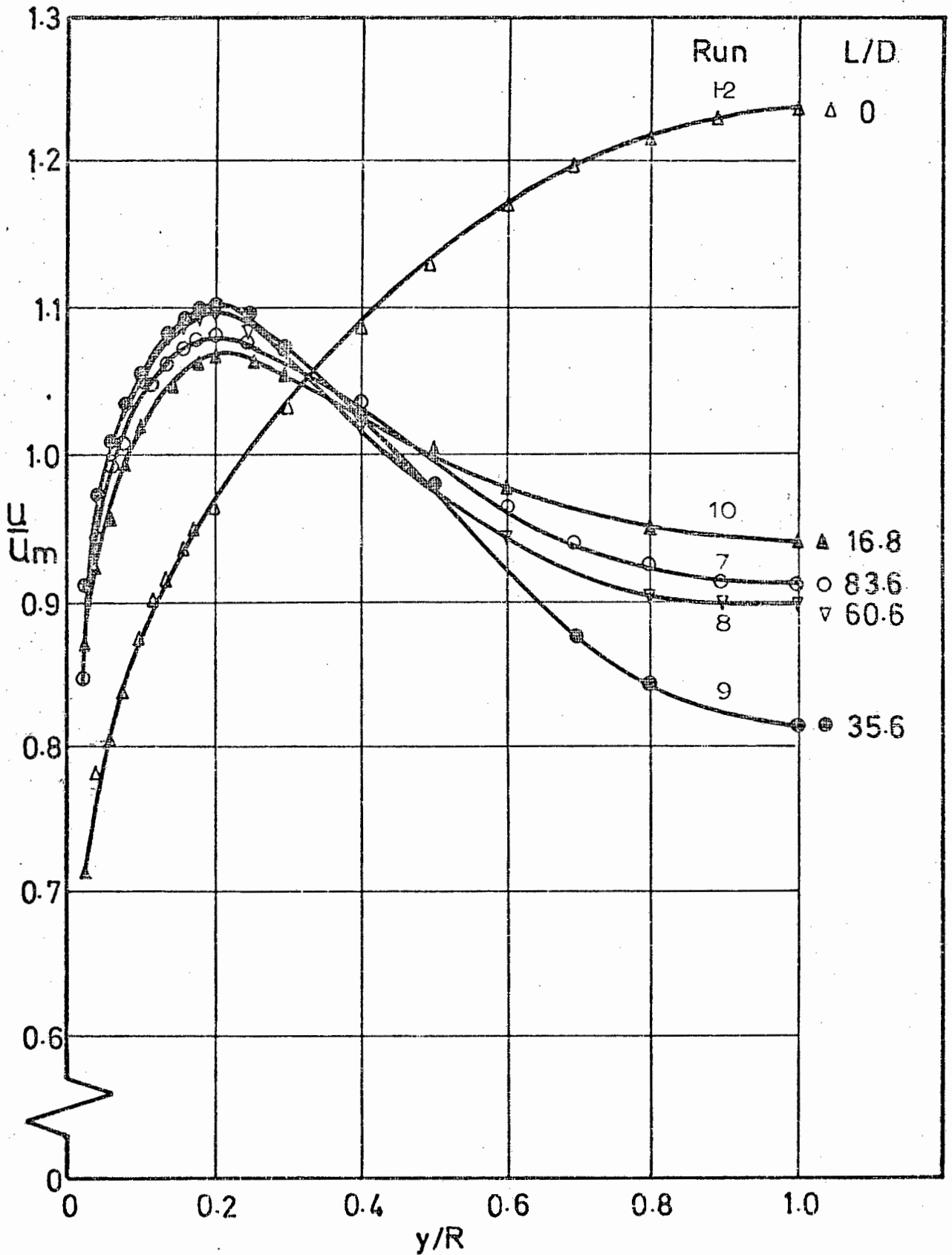


FIGURE 3.2 DEVELOPING VELOCITY PROFILES
At $Re \approx 3.3 \times 10^4$; $Ra \approx 6.0 \times 10^4$

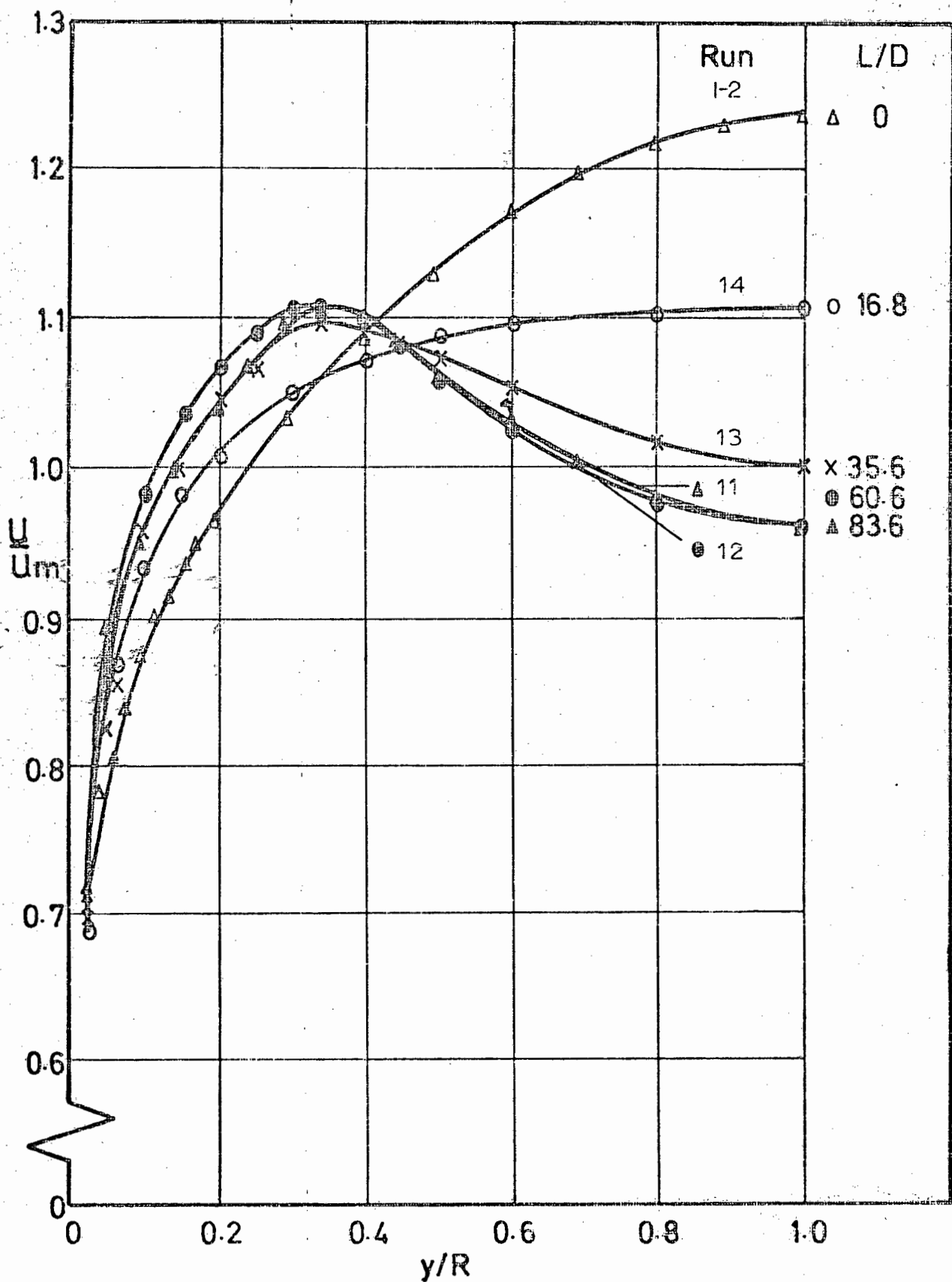


FIGURE 3.3 DEVELOPING VELOCITY PROFILES

At $Re \approx 3.3 \times 10^4$; $Ra \approx 2.5 \times 10^4$

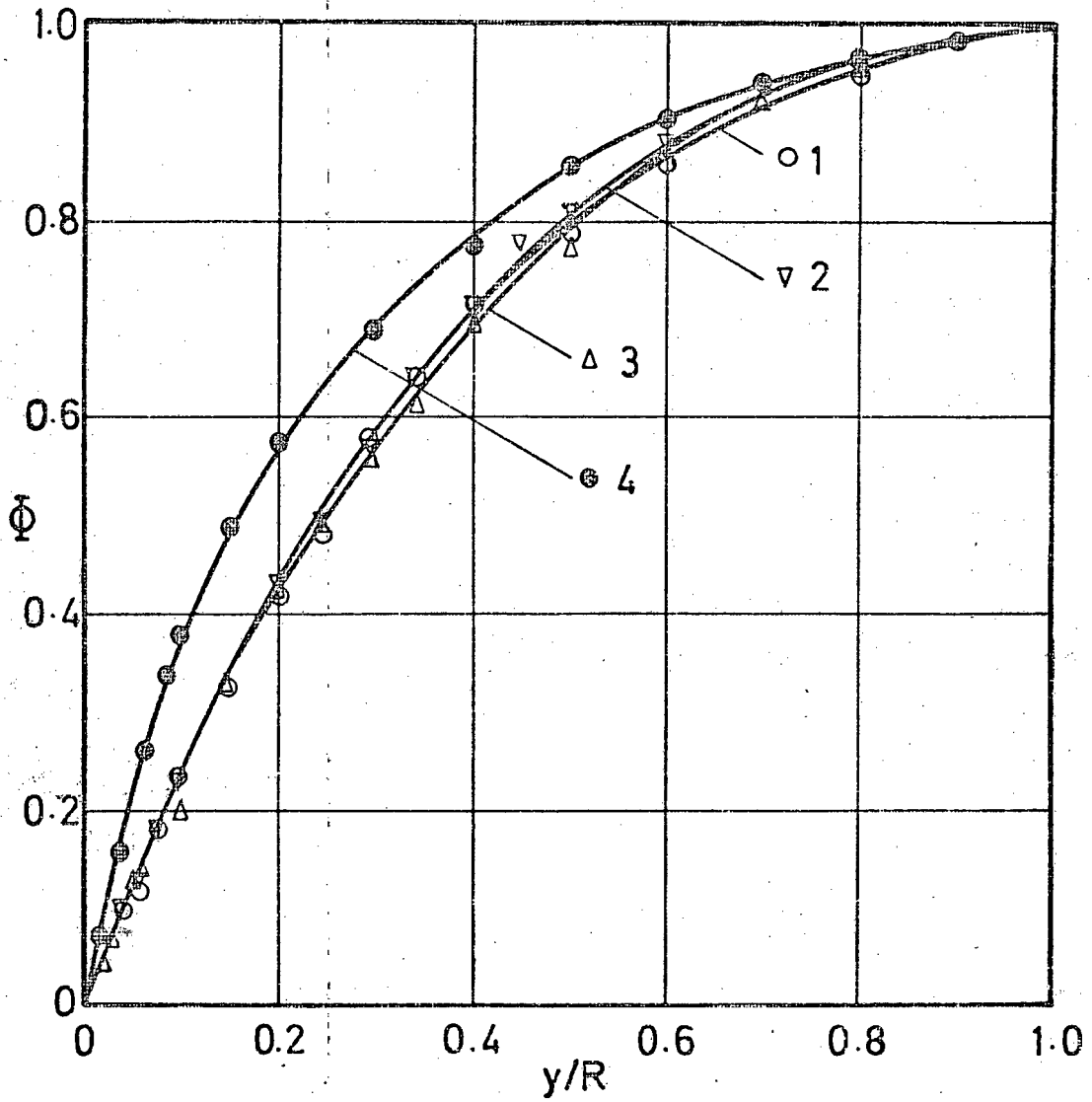


FIGURE 3.4 DEVELOPING TEMPERATURE PROFILES

At $Re \approx 3.3 \times 10^4$; $Ra \approx 2.5 \times 10^4$

- 1. Run No. 13; $L/D = 35.6$
- 2. Run No. 12; $L/D = 61.6$
- 3. Run No. 11; $L/D = 83.6$
- 4. Run No. 14; $L/D = 16.8$

From the results it appears that at high heat fluxes the velocity profile develops more rapidly, for example at a Rayleigh number of 1.39×10^5 the velocity profiles are all very similar at L/D ratios of 83.6, 60.6 and 35.6.

The shape of the temperature profile appears to be more convex at low thermal heating lengths. It appears, however, that the temperature profile approaches its final shape before the velocity profile. At Rayleigh numbers of approximately 5.9×10^4 and 1.37×10^5 there is hardly any difference between the developing temperature profiles.

The data are too incomplete to allow determination of the exact entry lengths required for fully developed flow to be reached but from the results it appears reasonable to assume, however, that fully developed velocity and temperature profiles are reached in the experimental equipment used.

3.4 VELOCITY AND TEMPERATURE PROFILE TRENDS

Fully developed velocity profiles (i.e. for L/D = 83.6) are shown in figs. 3.5 - 3.6. The results confirm the distortion observed by Horsten [2].

From the reported velocity profiles it is clear that at a particular Reynolds number the degree of distortion increases with heat input. Horsten [2] has pointed out that at high heat fluxes a point of saturation is reached beyond which an increase in the heat flux does not cause any further distortion of the velocity profile.

Fully developed temperature profiles are plotted in figs. 3.7 - 3.8 as Φ versus y/R where Φ is defined as

$$\Phi = \frac{T_w - T}{T_w - T_c} \quad (3.1)$$

In the range of Reynolds numbers and heat fluxes used in this investigation it is clear that the temperature profile becomes more convex with increasing heat flux. Horsten [2] has observed, however, that at very low heat fluxes the temperature profile again becomes more convex. The point at which the temperature profile is least convex corresponds to the point at which the velocity profile changes from having a maximum

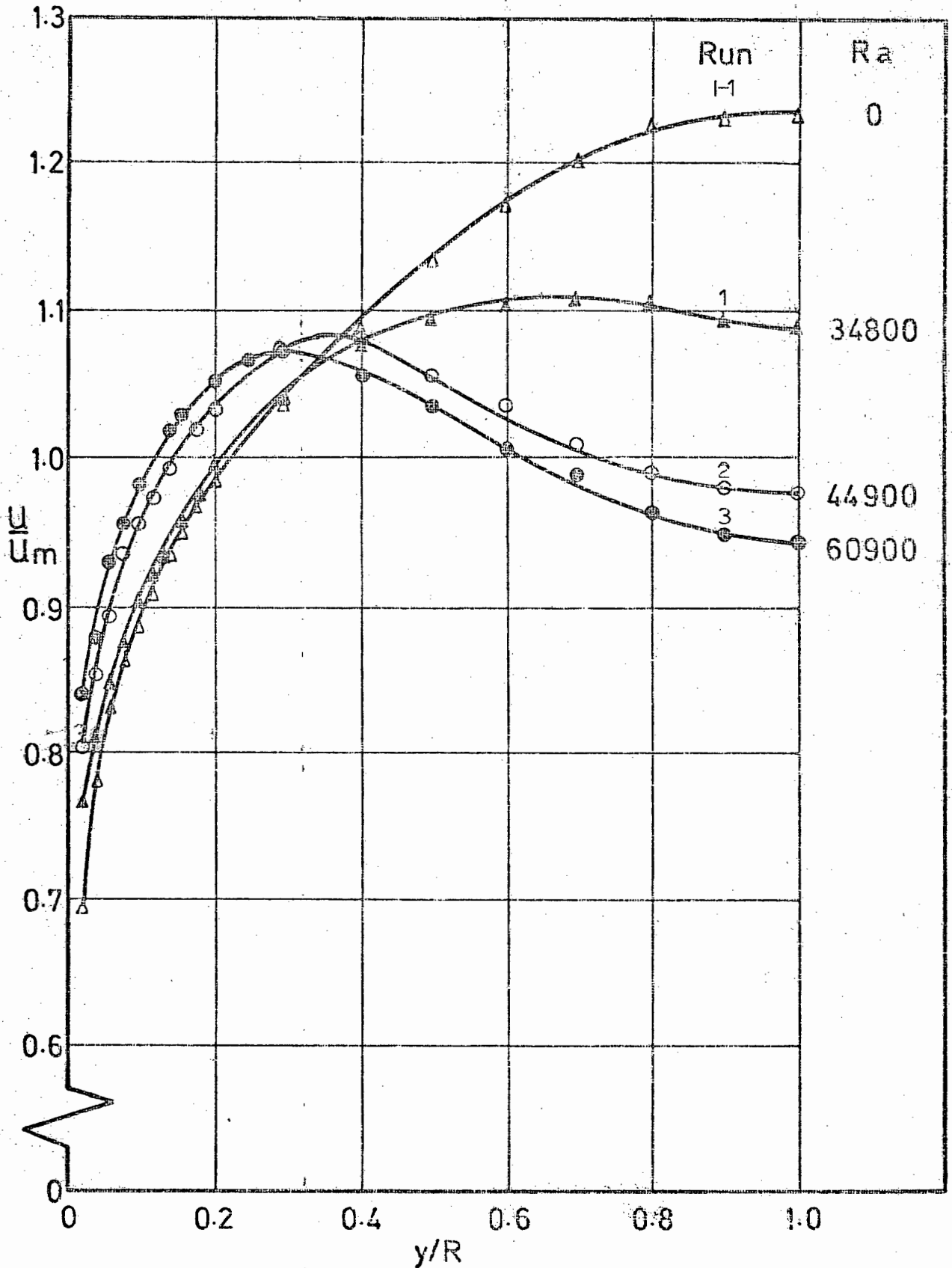


FIGURE 3.5 VELOCITY PROFILES AT $Re \approx 5.4 \times 10^4$; $L/D = 83.6$

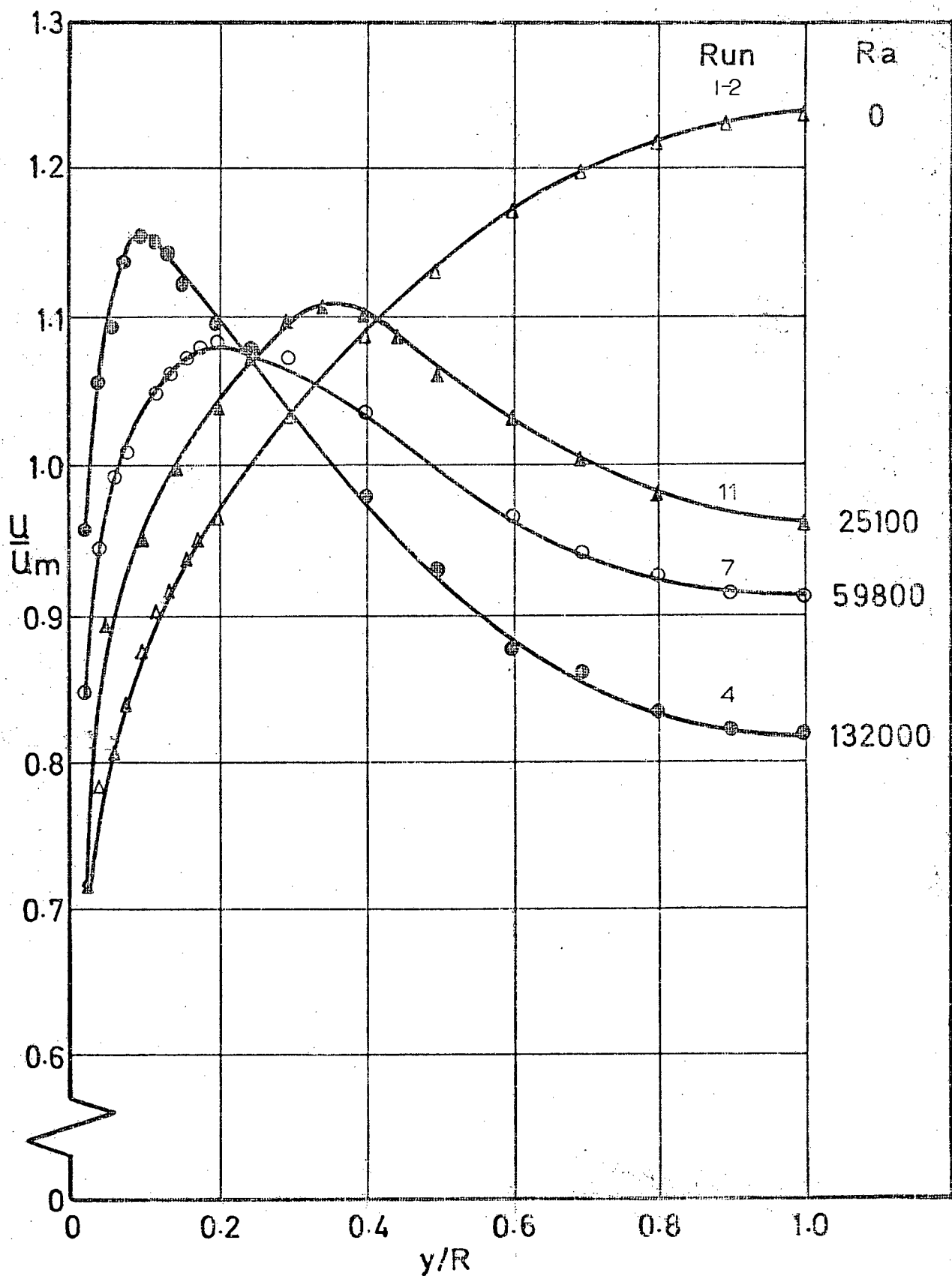


FIGURE 3.6 VELOCITY PROFILES AT $Re \approx 3.3 \times 10^4$; $L/D = 83.6$

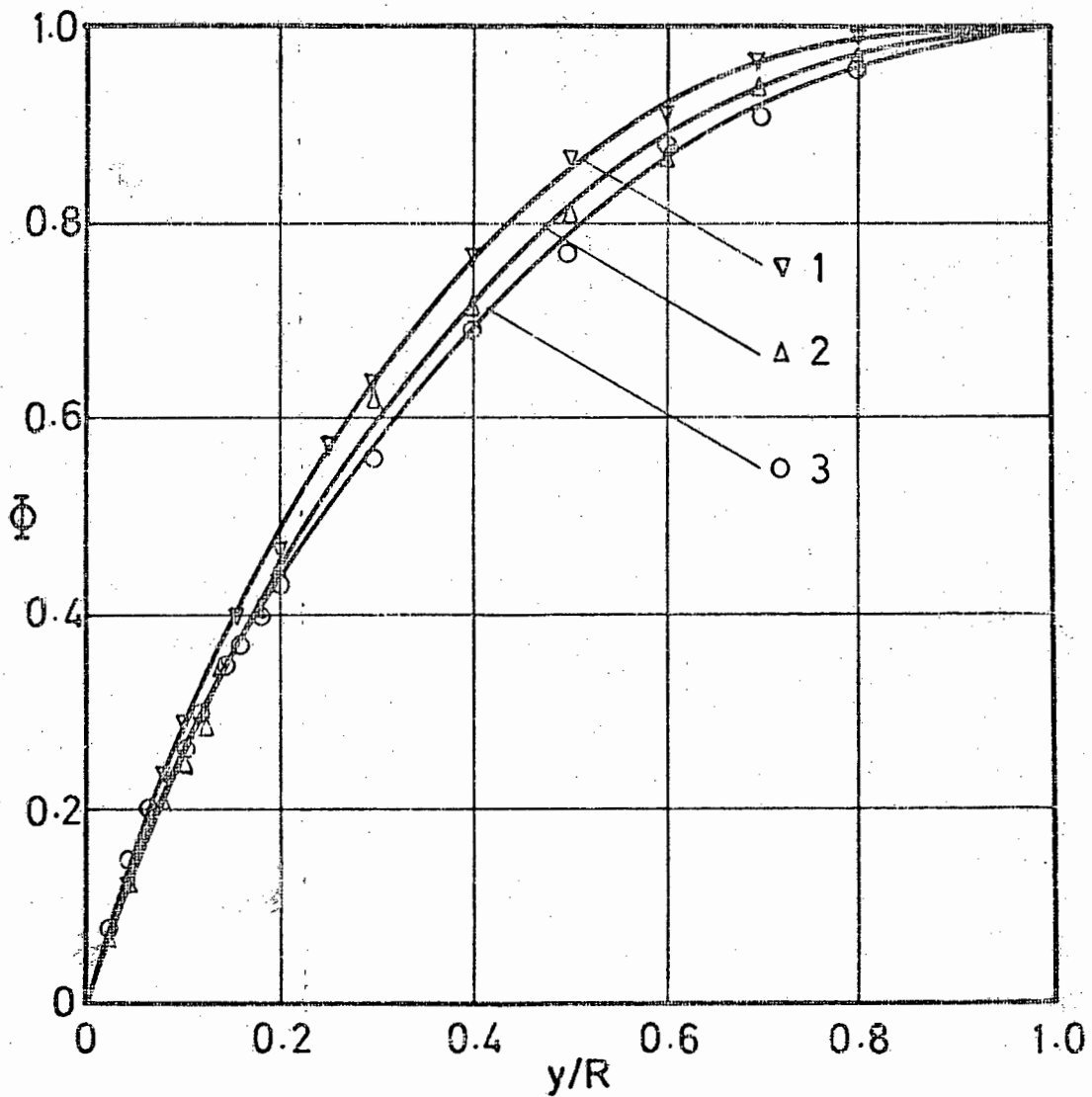


FIGURE 3.7 TEMPERATURE PROFILES AT $Re \approx 5.4 \times 10^4$
 $L/D = 83.6$

- 1. Run No. 3; $Ra = 60\ 900$
- 2. Run No. 2; $Ra = 44\ 900$
- 3. Run No. 1; $Ra = 34\ 800$

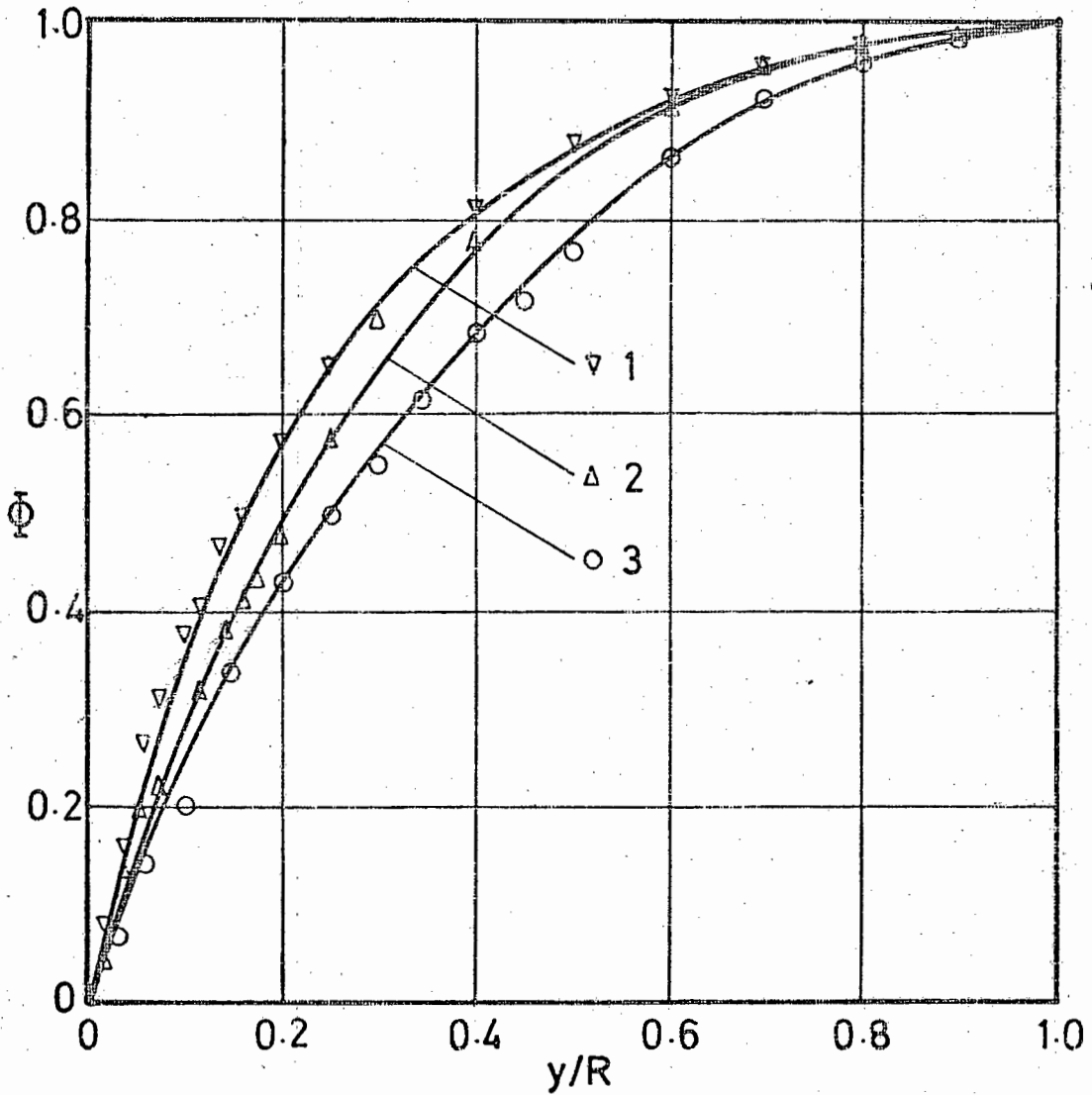


FIGURE 3.8 TEMPERATURE PROFILES AT $Re \approx 3.3 \times 10^4$
 $L/D = 83.6$

- 1. Run No.4; $Ra = 132\ 000$
- 2. Run No.5; $Ra = 59\ 800$
- 3. Run No.6; $Ra = 25\ 100$

at the pipe centre to having a maximum velocity at some other radial position. As in the case of the velocity profile Horsten has pointed out that it appears that the temperature^{profile} also reaches a saturation point beyond which further heating causes no further distortion of the profile.

CHAPTER 4

DISCUSSION OF RESULTS CONCLUSIONS AND RECOMENDATIONS

4.1 EDDY DIFFUSIVITIES OF MOMENTUM

On the basis of the measured velocity and temperature profiles the eddy diffusivity of momentum, ϵ_M , may be calculated from the equation

$$\frac{\epsilon_M}{\nu} + 1 = \frac{-Ra \int_0^\eta \phi \eta d\eta - 0.25 f Re \eta}{8 \eta \frac{dU}{d\eta}} \quad (4.1)$$

Eddy diffusivities of momentum are shown in figs 4.1 - 4.2 and are tabulated in Appendix D.

From equation (4.1) it is clear that, in regions where the velocity profile is fairly flat, a small percentage error in the velocity would cause a large percentage error in $dU/d\eta$ and hence in ϵ_M/ν . The trend in ϵ_M/ν with heat flux and y/R is similar to that reported by Horsten [2] although the agreement in ϵ_M/ν values is only fair.

In some cases ϵ_M/ν values tend to $\pm \infty$ near the point at which the velocity profile goes through a maximum. Clearly, from equation (4.1), the numerator (or driving force) in the first term on the right hand side of the equation and the denominator (or slope of the velocity profile) must pass through zero at the same radial position otherwise ϵ_M/ν values will tend to $\pm \infty$. Experimentally, the difference between the positions at which these two quantities went through zero was never greater than 3% of the total radius.

At this stage no general correlation of ϵ_M/ν values is apparent. Attempts to correlate ϵ_M/Ru^* with Ra and y/R also proved unsuccessful.

4.2 EDDY DIFFUSIVITIES OF HEAT

The eddy diffusivity of heat is computed from the equation

$$\epsilon_H/\alpha + 1 = \frac{0.5 \int_0^\eta U \eta d\eta}{\eta \frac{d\phi}{d\eta}} \quad (4.2)$$

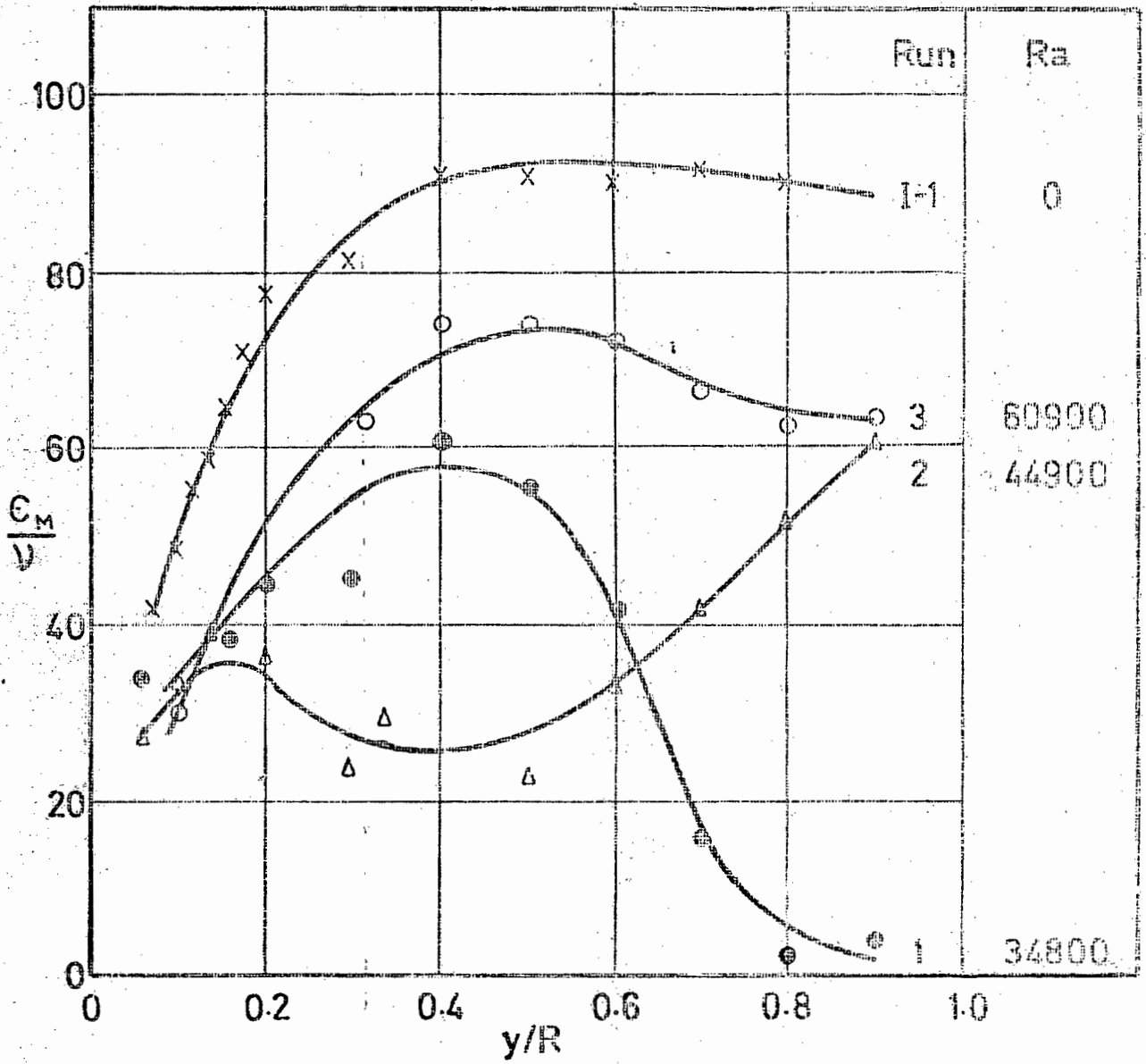


FIGURE 4.1 $\frac{\epsilon_M}{\nu}$ VALUES AT $Re \approx 5.4 \times 10^3$; $L/D = 83.6$

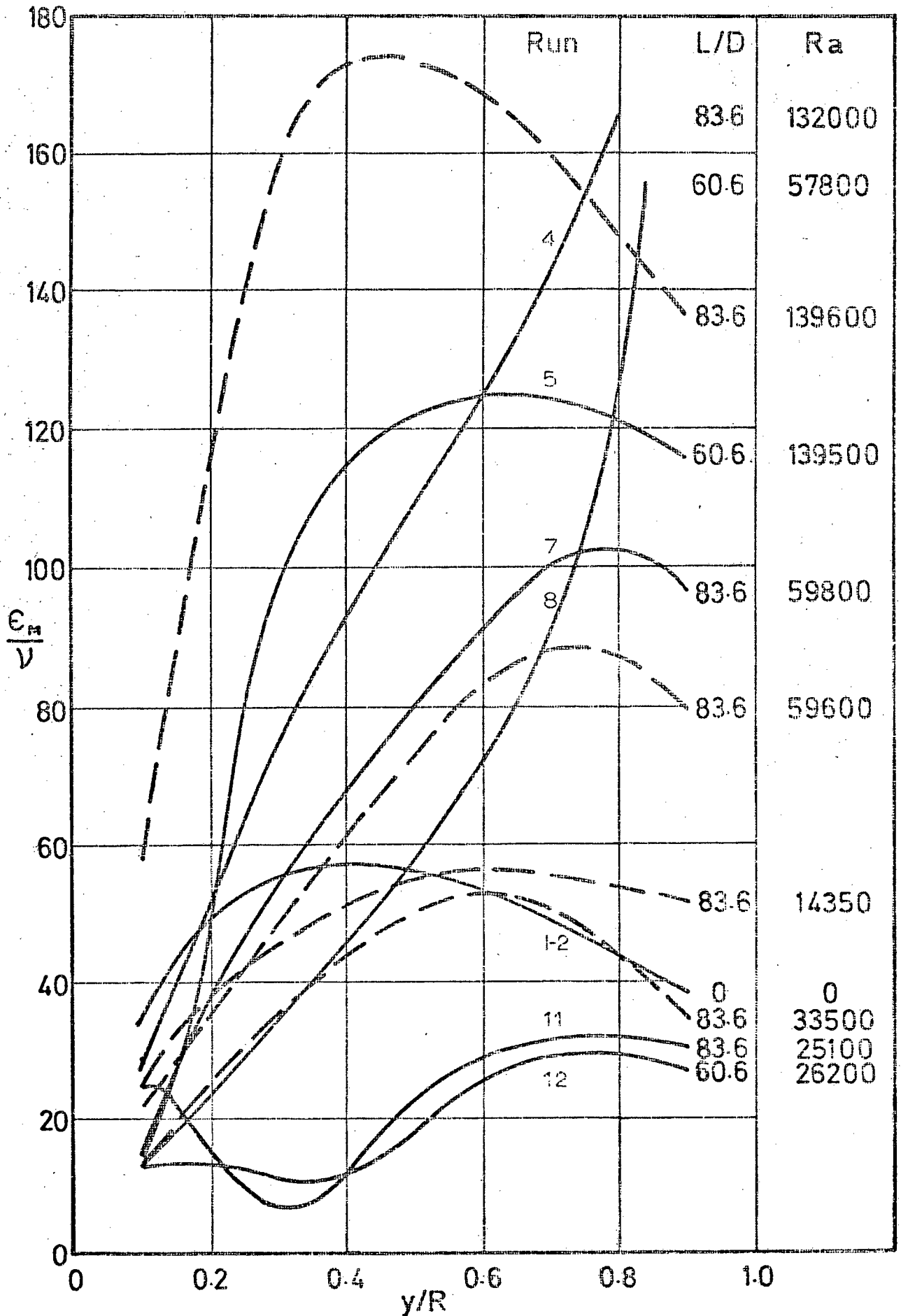


FIGURE 4.2 ϵ_M/ν VALUES AT $Re \approx 3.3 \times 10^4$

— This work
 - - - Horsten [2]

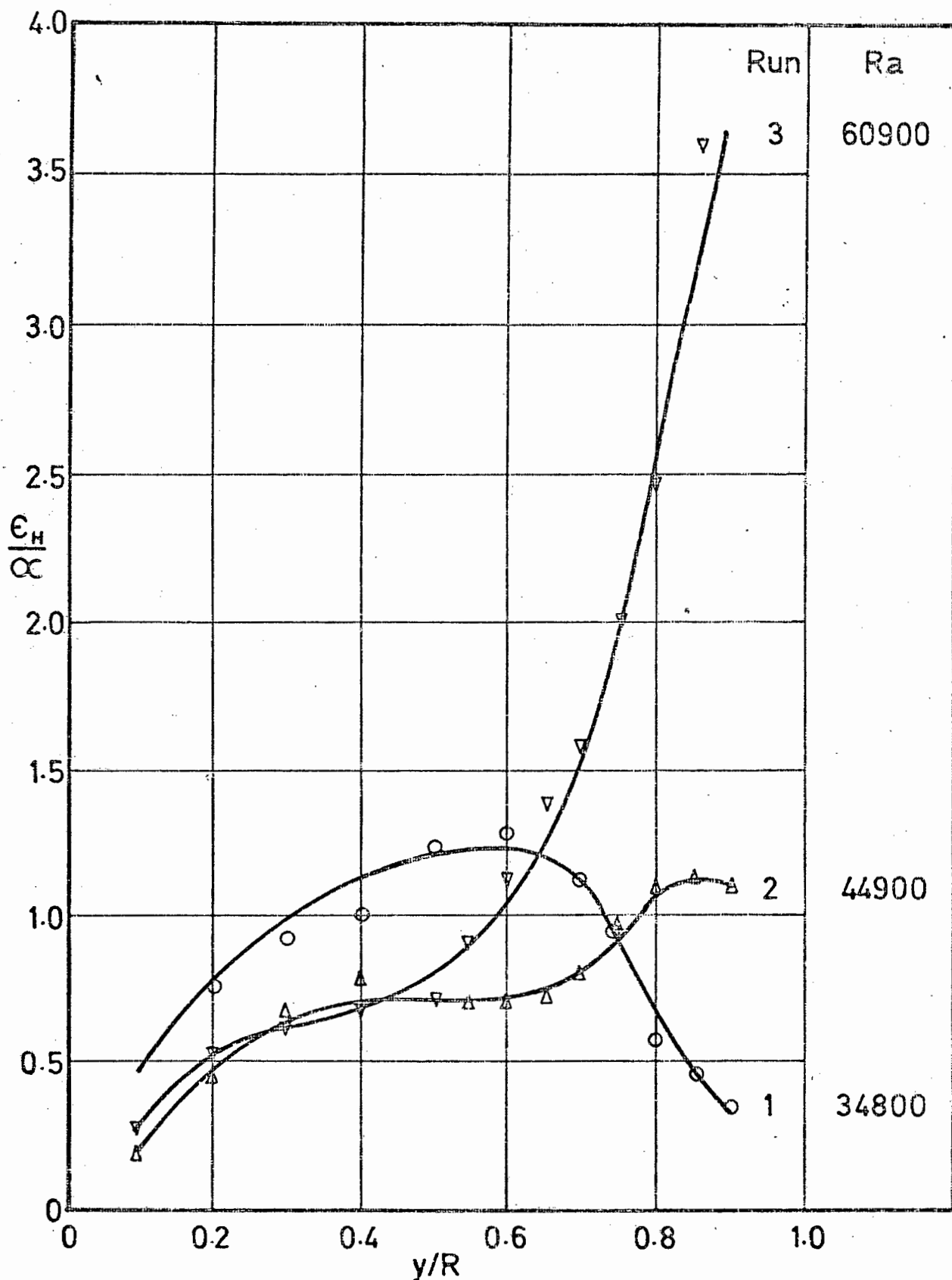


FIGURE 4.3 ϵ_H/α VALUES AT $Re \approx 5.4 \times 10^4$; $L/D = 83.6$

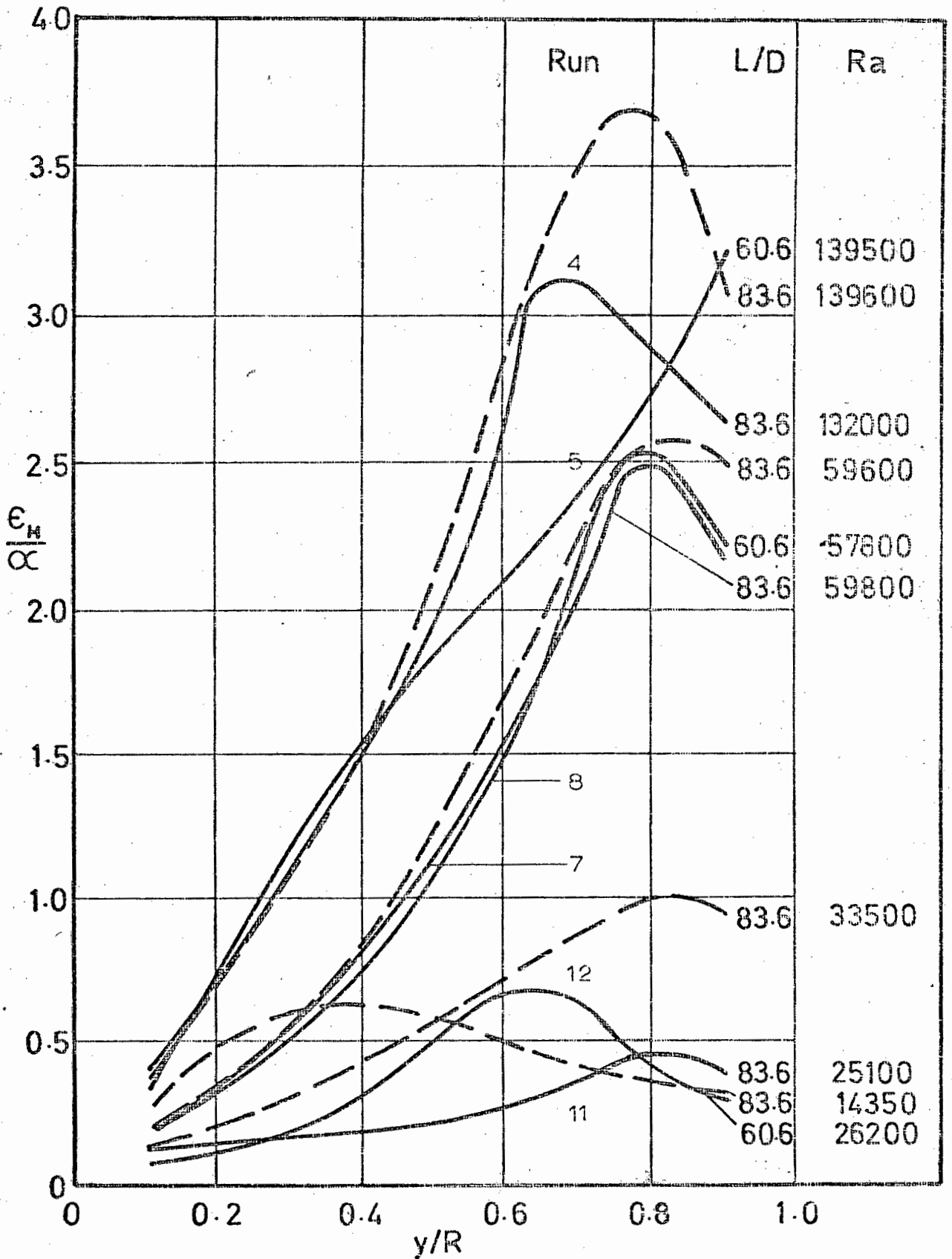


FIGURE 4.4 ϵ_H/α VALUES AT $Re \approx 3.3 \times 10^4$

— This work
 - - - Horsten [2]

Eddy diffusivities of heat are shown in figs 4.3 - 4.4 and the results are tabulated in Appendix D.

The agreement between ϵ_H/α values for fully developed flow in this work and those reported by Horsten [2] is good. The reason why ϵ_H/α values compare better than ϵ_M/ν values do, is explained by the fact that the slope of the temperature profile (up to a radial position of $y/R = 0.8$) is generally greater than it is for the velocity profile and hence $d\phi/d\eta$ is not as sensitive to experimental error.

At this stage no general correlation of ϵ_H/α values is apparent.

4.3 THE RATIO OF EDDY DIFFUSIVITIES

The ratio of the eddy diffusivities of heat to momentum, σ , (which is an indication of the relative rates of heat to momentum transfer) are shown in figs 4.5 - 4.6 and are tabulated in Appendix D.

At $Re \approx 3.3 \times 10^4$ the curves shown are an average of σ values at thermal entrance lengths of 83.6 and 60.6. The data of Horsten [2] and Buhr [10] are also included. σ values were calculated from the smoothed ϵ_H/α and ϵ_M/ν curves. Since both ϵ_H/α and ϵ_M/ν values were obtained by differentiation, the accuracy of σ values is limited. This is particularly evident from fig 4.5 ($Re \approx 5.4 \times 10^4$) where no general trend in σ with heat flux and y/R is apparent. However, at $Re \approx 3.3 \times 10^4$ there appears to be a trend in σ values and the dashed lines in fig. 4.6 show the trend with Ra and y/R .

4.4 CORRELATION OF NON-ISOTHERMAL VELOCITY PROFILES

It has already been pointed out that the degree of distortion of the velocity profile at a particular Reynolds number increases with increasing Rayleigh number until a point of saturation is reached. Closer investigation shows that u/u_m may be correlated by using Ra/Re as the correlating parameter. At a particular radial position the value of u/u_m is approximately constant for a particular value of Ra/Re . Thus, by plotting u/u_m versus Ra/Re at a fixed radial position, the behaviour of the velocity profile at that position may be observed. The same technique was tried using v/u^* versus Ra/Re but the results obtained

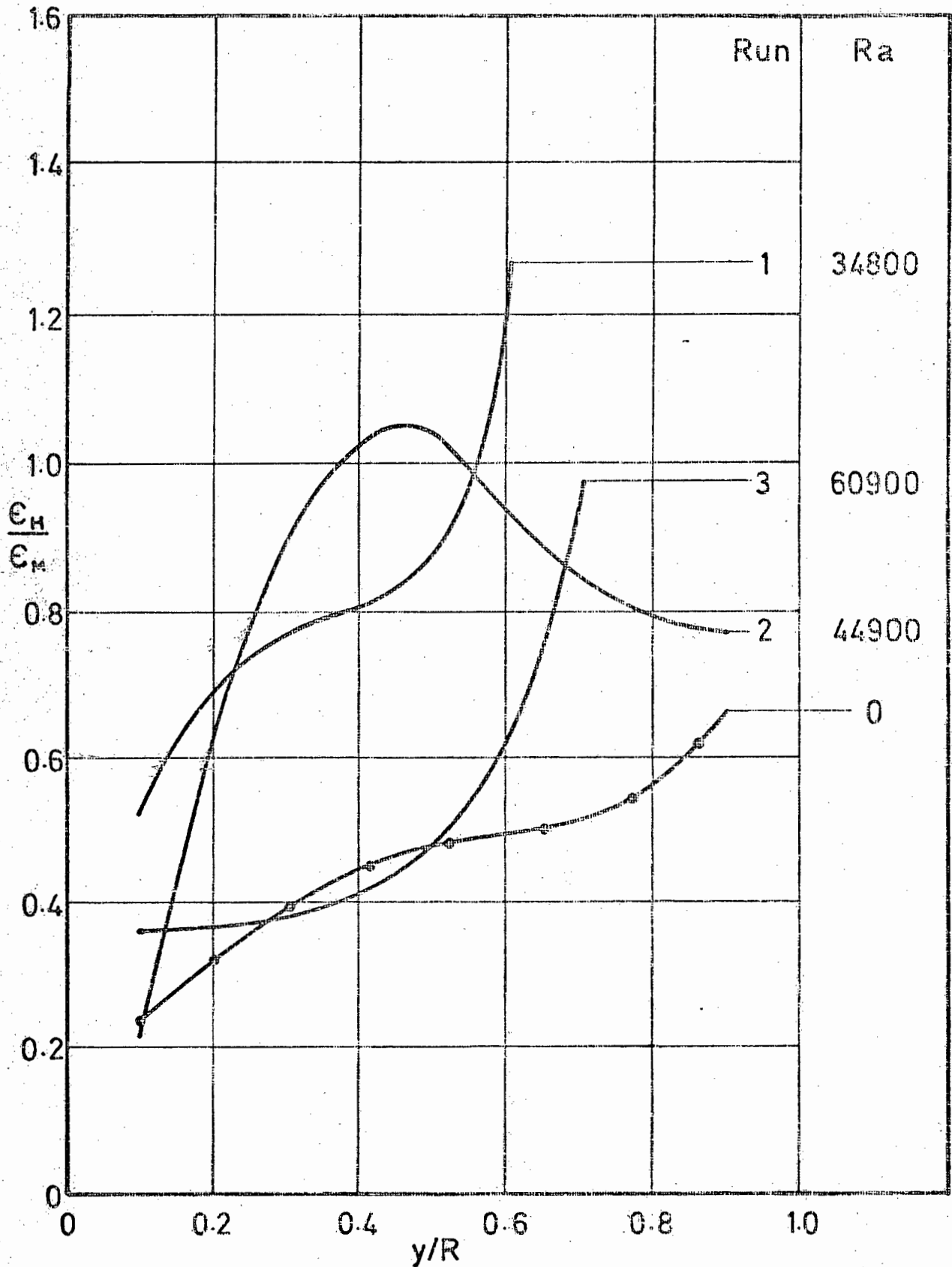


FIGURE 4.5 $\frac{\epsilon_H}{\epsilon_M}$ VALUES AT $Re \approx 5.4 \times 10^4$

— This work (L/D=83.6)
 -●- Buhr [10]

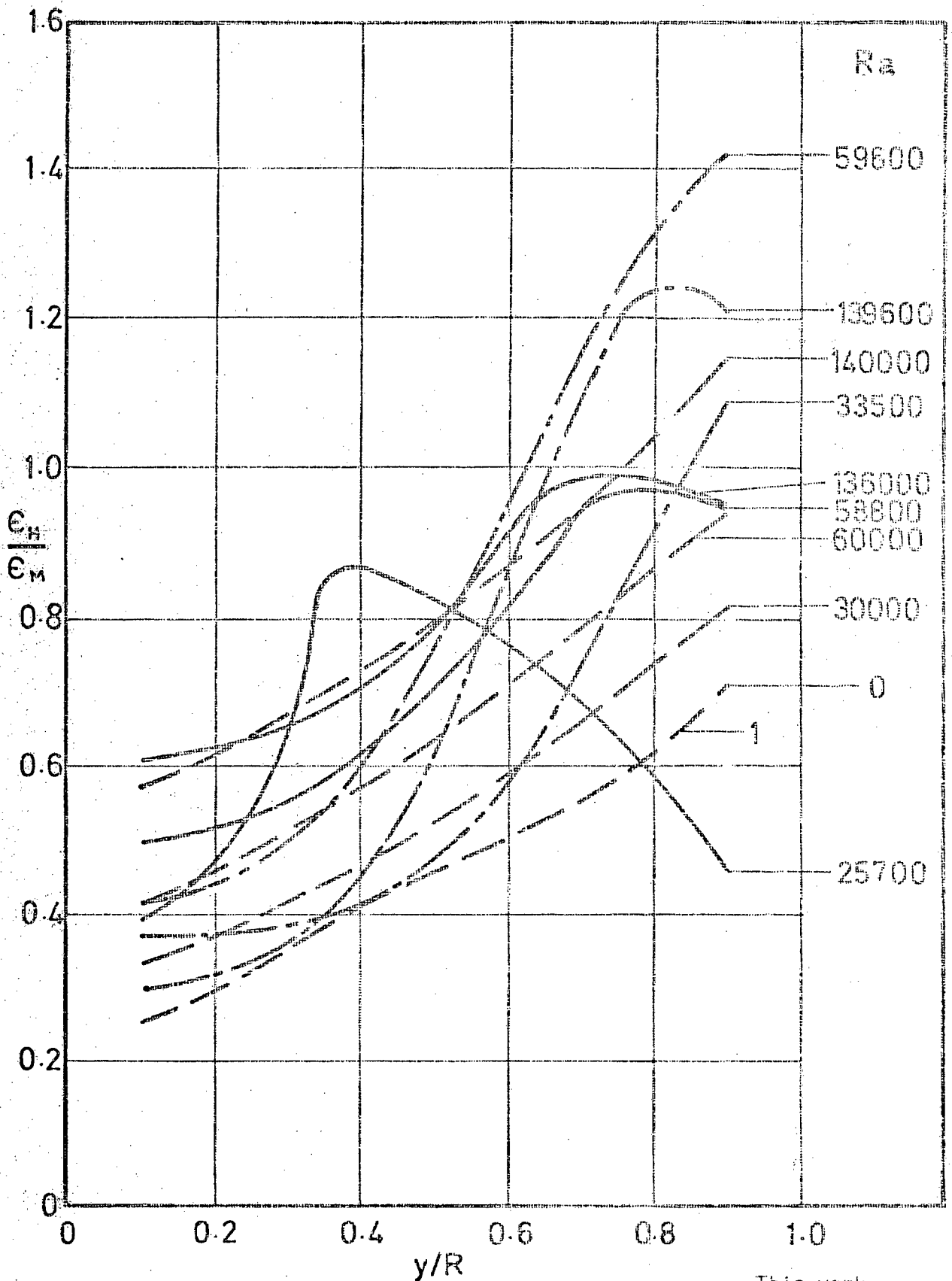


FIGURE 4.6 ϵ_H/ϵ_M VALUES AT $Re \approx 3.3 \times 10^4$

- This work
- - - Horsten [2]
- I Bühr [10]
- · · ϵ_H/ϵ_M trend with Re

yielded no improvement on those using u/u_m .

Curves of u/u_m versus Ra/Re for a number of radial positions are shown in fig 4.7. The data cover a Reynolds number range of 20,000 - 60,000 for $L/D > 60$ and include the data of Horsten [2] and Hochreiter [9]. The scatter is less than $\pm 4\%$ and thus non-isothermal velocity profiles can be predicted with good accuracy in the range of Reynolds numbers and heat fluxes considered in this work. The data of Hochreiter [9], measured at $Re \approx 9.0 \times 10^4$ in a 1.434 inch diameter pipe ($L/D = 65$), lie very close to the smoothed curves, which indicates that the correlation is independent of pipe diameter or L/D , provided flow is fully developed. It also appears that the correlation can be extended over a wider Reynolds number range.

It should be noted that there must be a small Reynolds number effect on the correlation since at $Ra = 0$ the profiles are known to be different but the difference is small for the Reynolds number range considered.

From fig 4.7 it is seen that beyond a value of $Ra/Re \approx 0.4$ the distortion of the velocity profile is significant. Beyond a value of $Ra/Re \approx 4$ only very small changes in u/u_m are noticed which confirms the observation made by Horsten [2] that a point of saturation in the velocity is reached beyond which any increase in Ra/Re causes no further significant distortion of the velocity profile.

Fig 4.8 shows the velocity profiles for various values of Ra/Re , reconstructed using the correlation of fig 4.7.

4.5 NUSSELT NUMBERS

4.5.1 Velocity and Temperature Profile Effects on the Nusselt Number

Ideally, if both the temperature and the velocity profile in a pipe can be predicted, the Nusselt number could be evaluated from the equation:

$$Nu = \frac{hD}{k} = \frac{q}{T_w - T_m} \times \frac{D}{k} \quad (4.3)$$

and no correlation for the Nusselt number itself would be necessary since T_w would be available and T_m could be calculated from the predicted profiles. Attempts to predict the temperature profile have to date been unsuccessful. Buhr [10] proposed a correlation parameter,

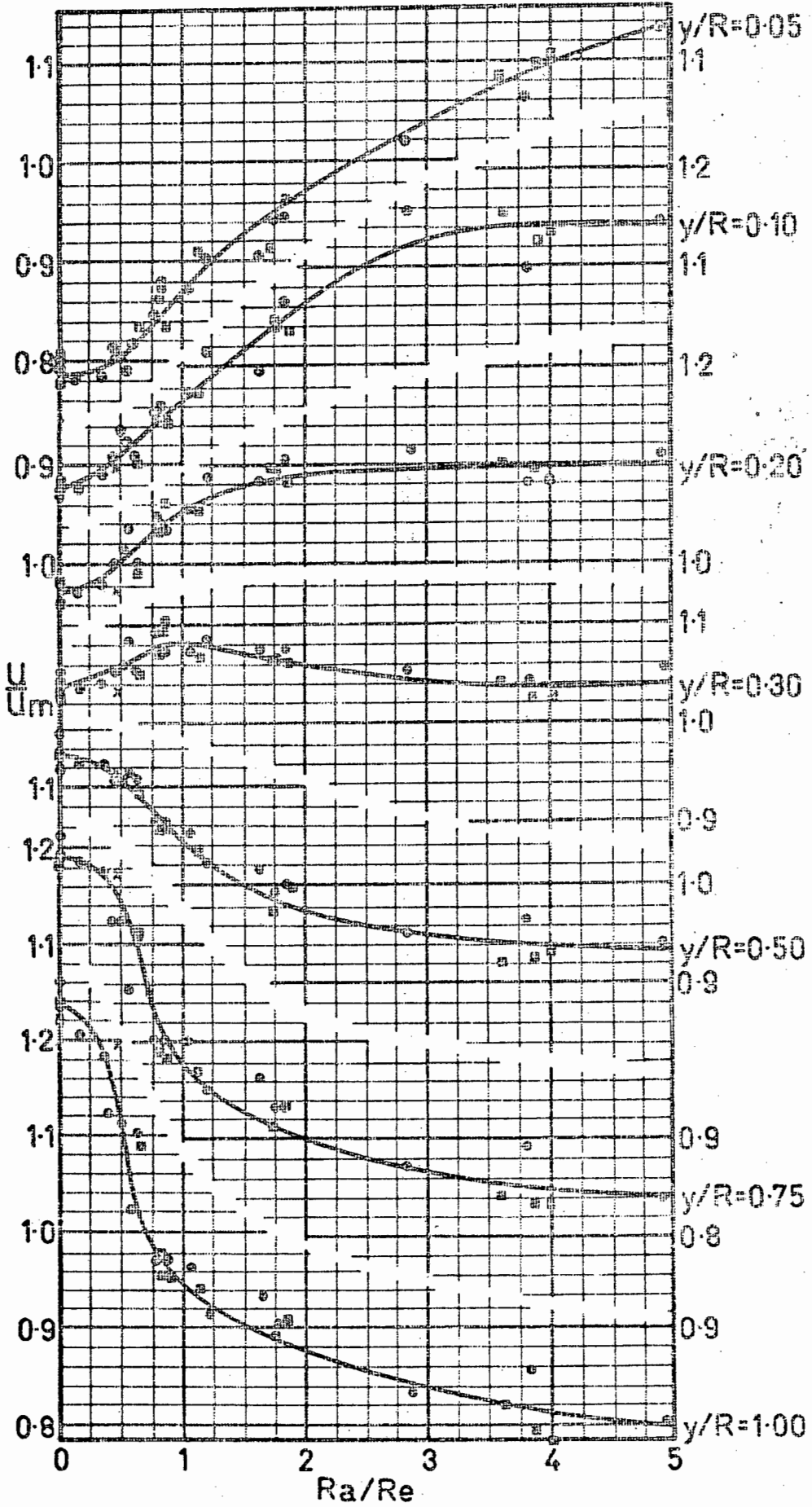


FIGURE 4.7 CORRELATION OF VELOCITY PROFILES

- This work (L/D=83.6, 60.6)
- Horsten [2] L/D = 83.6
- × Hochreiter [9] L/D = 65

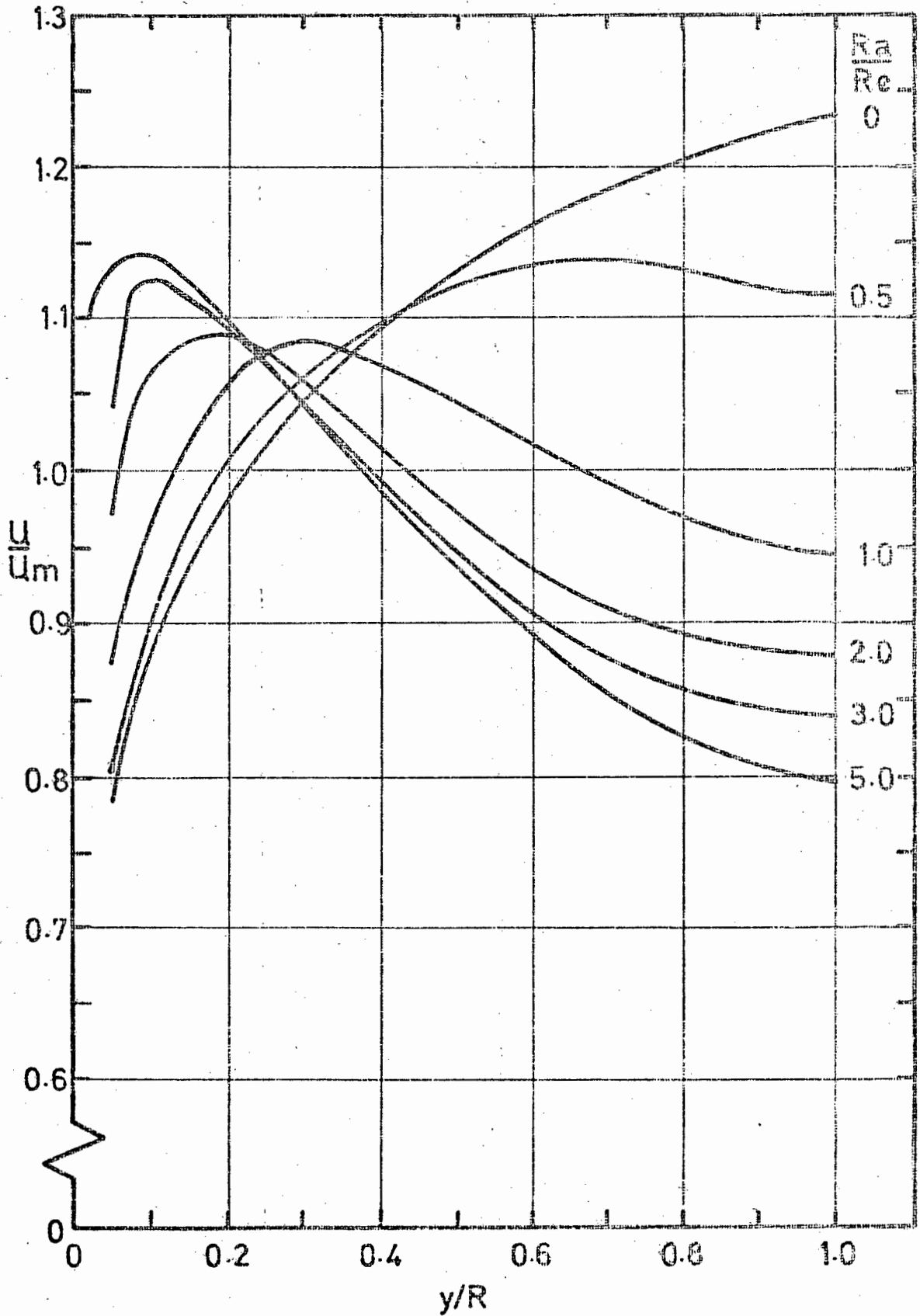


FIGURE 4.8 VELOCITY PROFILES FROM FIG. 4.7

Z, where

$$Z = \frac{Ra}{Re} \times \frac{D}{L} \quad (4.4)$$

for correlating temperature profiles but as has been pointed out by Horsten [2] data obtained from the present equipment show very little agreement with this correlation particularly as this correlation does not make allowance for Φ values to reach a minimum and then again to increase. Although Buhr [10] found the correlation to work fairly well it appears that the Russian data used by him were for non-fully developed flow. Thus, the inclusion of D/L in equation (4.4) probably accounted for both fully and non-fully developed flow conditions.

Attempts to correlate the temperature profile against Ra/Re proved unsuccessful and thus a method of determining Nusselt numbers directly would be desirable.

Many of the Nusselt numbers calculated to date have been erroneously computed on the assumption that an isothermal velocity distribution exists under non-isothermal conditions. Nusselt numbers computed on this basis would be too low since the mean cup temperature based on an isothermal velocity distribution would be lower than that based on the actual non-isothermal velocity distribution.

To illustrate the effect of the velocity profile on the Nusselt number, Nusselt numbers were computed using both the isothermal and non-isothermal velocity profiles in conjunction with the corresponding temperature profile and this effect is illustrated graphically in fig 4.9 as a plot of

$$\frac{Nu(\text{non-isothermal}) - Nu(\text{"isothermal"})}{Nu(\text{"isothermal"})} \quad (4.5)$$

versus Ra/Re . Details of the calculation procedure appear in Appendix A.

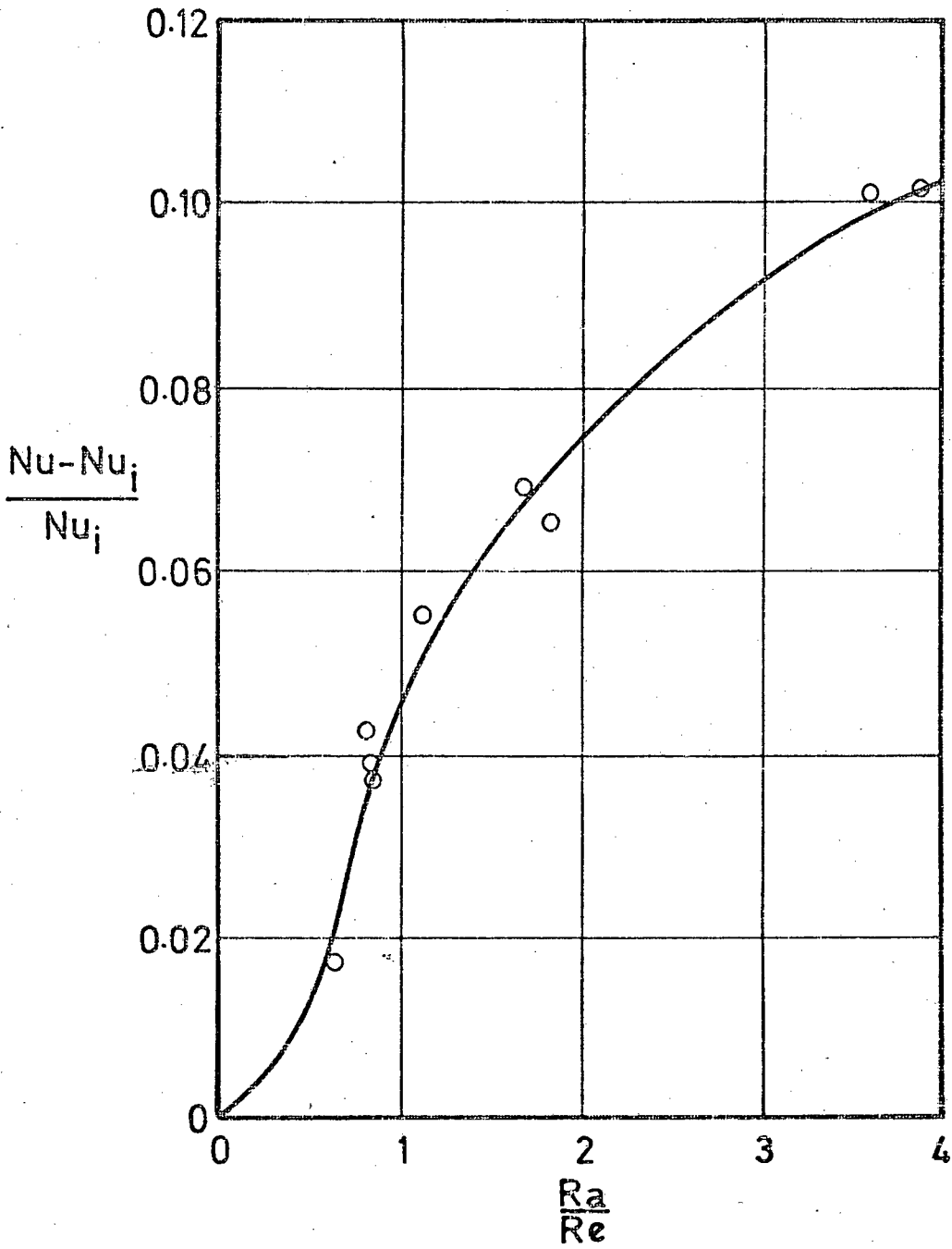


FIGURE 4.9 EFFECT OF VELOCITY PROFILE ON NUSSELT NUMBER

4.5.2 Nusselt Number Correlation

Clearly, the Nusselt number is not only a function of forced convection parameters but also of free convection parameters. Horsten [2] demonstrated the effect of free convection on the Nusselt number by plotting Nu versus Z with Pe as parameter. The parameter Ra/Re is used here in preference to Z, for the reasons mentioned earlier. An equation of the form

$$Nu = a + b Pe^c + d (Ra/Re) + e(Ra/Re)^2 + f(Ra/Re)^3 \quad (4.6)$$

was used to describe the Nusselt number. This form retains the Martinelli-Lyon [11] form of the equation for Ra = 0 while for Ra > 0 the free convection effect is described by a third order polynomial. Equation (4.6) was fitted to Nusselt numbers reported in this work for an L/D = 83.6 and to the Nusselt numbers reported by Horsten [2]. The coefficients were determined using the Newton-Raphson technique for solving a set of non-linear equations. It was found that a = 5.8, b = 0.026 and c = 0.74.

A plot of $Nu - 0.026 Pe^{0.74}$ vs Ra/Re is shown in fig 4.10 and shows the data of Buhr [10] in addition to the data used for the original correlation. The data of Buhr [10] are in fair agreement with the predicted values despite the fact that his Nusselt numbers were computed on the assumption of an isothermal velocity distribution. Data reported by other investigators have not been included in fig. 4.10 since these data were either computed under conditions of non-fully developed flow or on overall measurements rather than using actual velocity and temperature profiles.

Equation (4.6) predicts an initial drop in the Nusselt number from the isothermal value as Ra/Re is increased from zero, and after going through a minimum Nu values increase again. It appears that a point is reached where free convection has no further effect on the Nusselt number i.e. beyond a certain value of Ra/Re the value of $Nu - 0.026 Pe^{0.74}$ remains constant.

The effect of free convection on the Nusselt number is also illustrated in fig 4.11 where the Nusselt number is plotted as a function

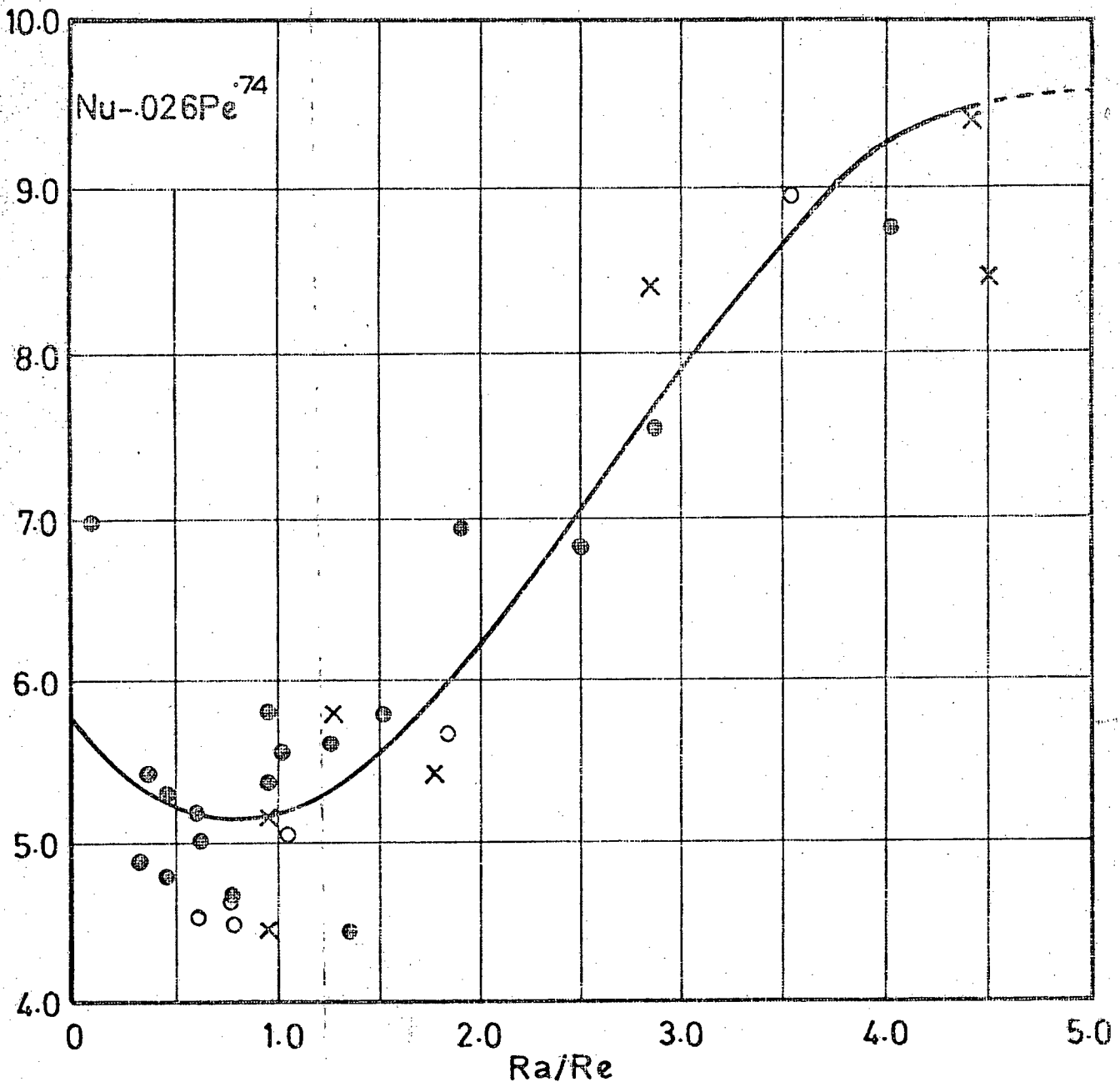


FIGURE 4.10 NUSSELT NUMBER CORRELATION

- This work
- Horsten [2]
- x Buhr [10]

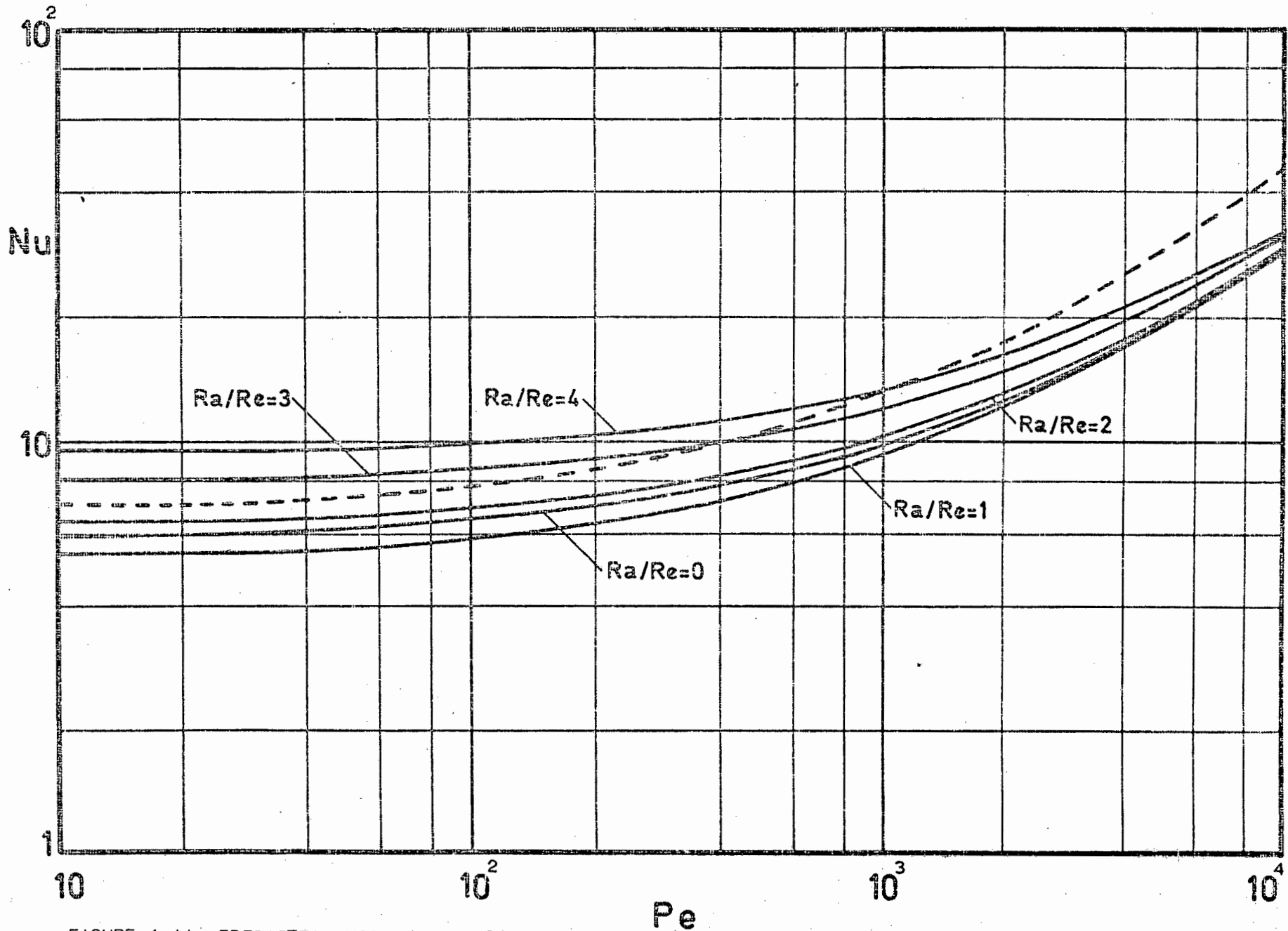


FIGURE 4.11 PREDICTED NUSSULT NUMBERS

— This work - - - Martinelli-Lyon Line [11]

of the Peclet number with Ra/Re as parameter.

4.6 CONCLUSIONS

The conclusions drawn from this work are:

- (i) Readings taken with the combined probe are reproducible and confirm the work of Horsten [2].
- (ii) In turbulent non-isothermal flow of mercury the degree of distortion from the pseudo-parabolic shape of the velocity profile depends on the parameter Ra/Re . The effect of Ra/Re on u/u_m has been correlated and for a value of $Ra/Re > 0.4$ free convection effects on the velocity profile become significant in the range of Reynolds and Rayleigh numbers considered in this work.
- (iii) The temperature profile is also affected by free convection in turbulent non-isothermal flow of mercury.
- (iv) The velocity and temperature profiles distort even at low heating lengths and the higher the heat input the more rapidly do the profiles develop. The point at which flow becomes fully developed is unknown but it appears that fully developed flow was attained in the equipment for an $L/D > 60$.
- (v) Eddy diffusivities of heat and momentum are affected by free convection effects but since both of these depend on the differentiation of the appropriate profile they are subject to large errors and no general correlation can be drawn about the variation observed.
- (vi) Heat transfer coefficients are not only affected by forced convection but also by free convection and these effects have been correlated in the range of data considered. Free convection effects on the Nusselt number provide an explanation as to why there is so much scatter in reported Nusselt numbers for liquid metals. Early workers had attributed this scatter to thermal contact resistance at the tube wall.

4.7 RECOMENDATIONS

As a result of this investigation it is recommended that future work in this field be conducted along the following lines:

- (i) The present method of determining eddy diffusivities should be abandoned because they are so susceptible to error.
- (ii) Since the velocity profile and Nusselt numbers can be predicted fairly accurately in the range of Reynolds and Rayleigh numbers considered in this work extensions to these predictions should be made. The Reynolds number effect should be included in the velocity profile correlation so that the correlation can be extended to cover both lower and higher Reynolds numbers than those considered in this work. Emphasis should be placed on obtaining Nusselt number data at large Ra/Re values (where free convection effects are significant).
- (iii) On the basis of this work it appears feasible, with a little more work, to obtain a correlation of when the flow becomes fully developed.
- (iv) With sufficient entrance length data, a correlation of the Nusselt number in the entrance region would also be made possible.
- (v) In the system used, free and forced convective flow were co-current. A study of heated, vertical downward flow (in which case free and forced convective flow would be counter-current) should be carried out with a view to extending the existing velocity profile and Nusselt number correlations. Only once all the problems for the above two cases have been sorted out would it be worthwhile studying the case of horizontal flow. For horizontal flow the momentum and energy equations would be far more difficult to handle due to the fact that the temperature and velocity profiles would be asymmetrical.

NOMENCLATURE

a, b, c, d, e, f	Polyomial coefficients
A	Axial temperature ^{gradient} , dT/dx , °F/ft
c_p	Pressure coefficient of pitot-static probe
C_p	Specific heat at constant pressure, Btu/lb°F
C_D	Orifice meter coefficient
D	Pipe diameter, ft
D_{or}	Orifice meter diameter, ft
f	Dimensionless friction factor, $2g_c \tau_w / \rho u_m^2$
g	Acceleration due to gravity, ft/hr ²
g_x	Acceleration due to gravity parallel to pipe axis, ft/hr ²
g_c	Gravitational constant, 4.17×10^8 ft lb _m /lb _f hr ²
G	Fluid mass flow rate, lb/hr
h	Heat transfer coefficient, Btu/hr ft ² °F
k	Thermal conductivity, Btu/hr ft °F
L	Heating length, ft
p	Static fluid pressure, lb _f /ft ²
\bar{p}_1	Mean impact pressure at pitot tube tip, lb _f /ft ²
q	Heat flux, Btu/hr ft ²
Q	Heat flux, Btu/hr
r	Distance measured along a radius from the pipe centre, ft
t	Time, hrs
T	Fluid temperature at radius r, °F
T'	Temperature fluctuation at radius r, °F
T_{av}	Arithmetic mean temperature at a fixed axial position, °F
T_m	Mean fluid temperature at a fixed axial position, °F

T_w	Fluid temperature at the wall at a fixed axial position, $^{\circ}\text{F}$
u	Fluid velocity parallel to tube axis at radius r , ft/hr
u'_x	Turbulent velocity fluctuation in x direction, ft/hr
u'_r	Turbulent velocity fluctuation in r direction, ft/hr
u_m	Average fluid velocity, ft/hr
u^+	Dimensionless velocity, u/u^*
u^*	Friction velocity, $\frac{u_m \sqrt{f/2}}{3 \cdot 600}$, ft/sec
u_c	Velocity at centre of pipe, ft/hr
u_{or}	Velocity through orifice meter, ft/hr
U	Dimensionless fluid velocity, u/u_m
v	Fluid velocity parallel to tube axis at radius r , ft/sec
x	Direction of mean flow and distance along pipe axis, ft
y	Radial distance from wall, ft
y^+	Dimensionless radial distance from wall, yu^*/v
Y	Yantovskii's free convection criterion, Gr^*/Re^{*2}
Z	Free convection parameter, $(Ra/Re) \cdot (D/L)$
α	Thermal diffusivity, $k/\rho c_p$, ft^2/hr
β	Coefficient of thermal expansion, $^{\circ}\text{F}^{-1}$
β_o	Orifice meter parameter, ratio of orifice diameter to pipe diameter
Δh	Pressure differential, in. of fluid
Δp	Pressure differential, lb_f/ft^2
ϵ_M	Eddy diffusivity of momentum, ft^2/hr
ϵ_H	Eddy diffusivity of heat, ft^2/hr

η	Dimensionless radius, $2r/D$
θ	Radial temperature difference, $T - T_{av}$, $^{\circ}F$
μ	Fluid viscosity, $lb_m/ft \cdot hr$
ν	Kinetic viscosity, μ/ρ , ft^2/hr
ρ	Density, lb_m/ft^3
σ	Diffusivity ratio (ϵ_H/ϵ_M)
τ	Fluid shear stress, lb_f/ft^2
τ_w	Fluid shear stress at the wall, lb_f/ft^2
ϕ	Dimensionless temperature difference, $2k\theta/\rho_{av} u_m c_p AD^2$
Φ	$(T_w - T)/T_w - T_c$ dimensionless temperature difference ratio
ψ	Angular coordinate, radians

Dimensionless Groups

Nu	=	Nusselt number = hD/k
Nu_f	=	"Isothermal" Nusselt number
Re	=	Reynolds number = $Du_m \rho/\mu$
Re^*	=	Friction Reynolds number, $Re\sqrt{f/2}$
Pr	=	Prandtl number = $c_p \mu/k$
Ra	=	Rayleigh number = $Gr^* Pr = \rho^2 \beta g C_p AD^4/\mu k$
Gr	=	Grashof number based on radial temperature difference, $\rho^2 \beta g (T_w - T_c) D^3/\mu^2$
Gr^*	=	Grashof number = $\rho^2 \beta g AD^4/\mu^2$
Pe	=	Peclet number = $Re \cdot Pr$

LIST OF REFERENCES

1. Ojalvo, M.S. and Grosh, R.J. "Combined free and forced turbulent convection in a vertical tube", Argonne National Laboratory Report, ANL - 6528 (1962).
2. Horsten, E.A. "Combined free and forced convection in turbulent flow of mercury", Ph.D. Thesis, Univ. of Cape Town (1971).
3. Kays, W.M., "Convective Heat and Mass Transfer", McGraw Hill (1966).
4. Azer, N.Z., "Thermal entry length for turbulent flow of liquid metals in pipes with constant wall heat flux", Trans. ASME - J. Heat Transfer, 483 - 485 (1968).
5. Bird, R.B., Stewart, W.E. and Lightfoot, E.N., "Transport Phenomena", John Wiley, New York (1963).
6. Brodkey, R.S., "The Phenomena of Fluid Motions", Addison-Wesley (1967).
7. Mc Abe, W.L. and Smith J.C., "Unit Operations of Chemical Engineering", McGraw-Hill (1956).
8. Hinze, J.O., "Turbulence", McGraw-Hill, New York, (1959).
9. Hochreiter, L.E., "Turbulent structure of isothermal and non-isothermal liquid metal pipe flow", Ph.D. Thesis, Purdue University (1971).
10. Buhr, H.O., "Heat transfer to liquid metals, with observations on the effect of superimposed free convection in turbulent flow", Ph.D. Thesis, University of Cape Town (1967).
11. Lyon, R.N., "Liquid metal heat transfer coefficients", Chem. Engng. Prog., 47, 75 - 79 (1951).
12. Rein, P.W., "The turbulent velocity distribution, with particular reference to measurements in mercury", M.Sc. Thesis, University of Cape Town (1967).
13. "Smithsonian Physical Tables", 9th rev. ed., Washington D.C. (1954) Table 291, reproduced in J.H. Perry, "Chemical Engineers' Handbook", 4th ed., McGraw-Hill, New York (1963) pp. 3 - 71.
14. Kutateladze, S.S., Borishanskii, V.M., Novikov, I.I. and Fedynskii, O.S., "Liquid metal heat transfer media", Consultants Bureau Inc., New York (1959) pp. 2 - 5.
15. Lyon, R.N. (editor), "Liquid - Metals Handbook", 2nd ed., U.S. Govt. Printing Office, Washington (1954) pp. 42 - 43.

APPENDICES

APPENDIX A	CALCULATION PROCEDURE
APPENDIX B	CALIBRATION
APPENDIX C	PHYSICAL PROPERTIES
APPENDIX D	EDDY DIFFUSIVITIES
APPENDIX E	EXPERIMENTAL RESULTS

APPENDIX A

CALCULATION PROCEDURE

Run number 7 has been chosen for the purpose of illustrating the calculation procedure utilized in processing a non-isothermal run. For the isothermal case only parts of run 1-2 are processed where the technique differs from that used to process non-isothermal runs.

A.1 OVERALL MEASUREMENTS

A.1.1 Heat Balance

The heat input measured on the KWH meter is 3.46 KWH and from table B.3 the percentage error in this reading is 2.73% i.e. corrected heat input

$$\begin{aligned} &= 3.56 \text{ KWH} \\ &= 12 \text{ 150 Btu/hr.} \end{aligned}$$

The inlet mixing cup thermocouple e.m.f. measured on a Fluke Differential Voltmeter is 0.832 mV.

$$\begin{aligned} &\text{Thus inlet mixing cup temperature (see table B.2)} \\ &= 49.43 + (0.832 - 0.5) \times 34.108 \\ &= 60.76^\circ\text{F} \end{aligned}$$

and similarly for the other thermocouples:

Thermocouple	e.m.f. (mV)	Temp. ($^\circ\text{F}$)
Inlet mixing cup	0.832	60.76
Outlet mixing cup	1.508	83.65
Inside insulation	3.043	135.02
Outside insulation	2.043	101.62

$$\begin{aligned} \therefore \text{The temperature difference over the insulation} &= 33.40^\circ\text{F} \\ \text{and the mean insulation temperature} &= 118.32^\circ\text{F} \end{aligned}$$

The thermal conductivity of the fibre-glass insulation, k , is given by:

$$\begin{aligned} k &= 0.01878 + 0.000034 T \text{ (}^\circ\text{F)} \\ &= 0.0228 \text{ Btu/hr ft }^\circ\text{F} \end{aligned}$$

Insulation thickness = 1.25 in.

and the log mean area of the insulation (see Horsten [2])
= 20.64 ft²

$$\begin{aligned} \therefore \text{Heat loss} &= 20.64 \times 33.4 \times 0.0228 \times 12/1.25 \\ &= 151 \text{ Btu/hr} \\ &= 1.24\% \text{ loss.} \end{aligned}$$

\therefore Net heat input = 12 000 Btu/hr.

Since $L/D = 83.6$ the inside area of the heated tube = 7.525 ft².

\therefore Net wall heat flux = 1 595 Btu/hr/ft²

The heat gained by the mercury as it flows up the pipe is

$$Q = G \int_{T_{In}}^{T_{Out}} C_p dt \quad (\text{A.1})$$

The specific heat of mercury, C_p (see Appendix C)

$$= 0.03348 - 0.0000036 T \text{ (}^\circ\text{F)}$$

and hence the mass flow, G , can be computed:

$$\begin{aligned} G &= \frac{1\,595}{(0.03348 T - 0.0000018 T^2)^{83.65}} \\ &= 15\,820 \text{ lb/hr.} \end{aligned}$$

The mean temperature in the test section is 72.21^oF and hence $\rho = 845.4 \text{ lb/ft}^3$ (see appendix C).

The mean velocity is thus

$$\begin{aligned} u_m &= \frac{4G}{\pi D^2 \rho} = \frac{4 \times 144 \times 15\,820}{\pi \times (1.968)^2 \times 845.4 \times 3\,600} \\ &= 0.246 \text{ ft/sec.} \end{aligned}$$

This velocity, based on the heat balance, will be referred to as the heat balance mean velocity.

A.1.2 Mean Velocity

The orifice meter equation (see appendix B) is

$$u_m = 3.29 \sqrt{\frac{\Delta h \text{ (cm mercury)}}{\rho_{\text{mercury}}}} \quad (\text{A.2})$$

The temperature difference between the outlet mixing cup and the pump was never more than about 1°F and thus the temperature at the orifice meter was taken to be equal to the outlet mixing cup temperature.

At the outlet mixing cup temperature of 83.65°F the density of mercury is 844.4 lb/ft³ (see appendix C). The pressure drop across the orifice meter was 4.20 cm. mercury.

$$\begin{aligned} \therefore u_m &= 3.29 \sqrt{\frac{4.20}{844.4}} \\ &= 0.232 \text{ ft/sec.} \end{aligned}$$

A.2 VELOCITY PROFILE

Point velocities were measured with a pitot-static tube. For the non-isothermal runs no pitot-tube corrections were made since no data is available on pitot-tube errors in a temperature field. On the basis of corrections made to pitot-tubes in isothermal flow (see later in this section) corrections are expected to be negligible for non-isothermal flow.

The pitot-static tube equation used in this investigation is

$$v = \sqrt{\frac{2g_c \Delta h \rho_{\text{water}}}{12 \rho_{\text{mercury}}}} \quad (\text{A.3})$$

where Δh is the pressure difference between the impact and static pressures in inches of water. The mercury density used in equation (A.3) was computed from point temperatures.

The transducer calibration for run 7 is (see appendix B.4):

$$\Delta h \text{ (Inches water)} = -0.00283 + 0.00238 \Delta \text{ chart.}$$

Typically at $y/R = 0.70$, 53.0 chart divisions were recorded and hence

$$\begin{aligned}\Delta h &= -0.00283 + 0.00238 \times 53.0 \\ &= 0.123 \text{ inches water.}\end{aligned}$$

At this radial position the temperature was 79.09°F and hence

$$\rho_{\text{mercury}} = 844.8 \text{ lb/ft}^3.$$

The density of water at the calibrating temperature of 70°F is 62.3 lb/ft^3 and hence the point velocity is

$$\begin{aligned}v &= \sqrt{\frac{2 \times 32.17 \times 62.3 \times 0.123}{844.8 \times 12}} \\ &= 0.221 \text{ ft/sec.}\end{aligned}$$

The mean velocity is obtained by integrating the velocity profile, i.e.

$$u_m = \frac{2 \int_0^1 T v \rho_m d\eta}{\rho_m} \quad (\text{A.4})$$

where ρ_m is evaluated at T_m and for run 7 $\rho_m = 844.6 \text{ lb/ft}^3$ and hence

$$u_m = 0.235 \text{ ft/sec.}$$

For more details on the numerical technique used to integrate the velocity profile see appendix D.

The velocities obtained from the heat balance, orifice meter and from integration are thus 0.246, 0.232 and 0.235 ft/sec. respectively. The largest difference between velocities is 6%. The integrated mean velocity was used to compute dimensionless parameters etc.

For isothermal runs, readings near the wall were corrected for turbulence according to the relationship

$$\frac{v}{v_{\text{measured}}} = \left[1 - \left(\frac{\sqrt{u^{+2}}}{u^*} - \frac{1}{u^+} \right)^2 \right]^{\frac{1}{2}} \quad (\text{A.5})$$

The turbulence intensity is obtained from Laufer's air data as suggested by Horsten [2] and Hochreiter [9].

Considering run 1 - 2

At $y/R = 0.04$, $y^+ = 33.60$, $u^+ = 14.40$ and $u_{\text{meas}} = 0.188$ ft/sec.

The turbulence intensity from Laufer's data (see ReIn[12]) is 2.45

$$\begin{aligned} \therefore v &= 0.188 [1 - (2.45/14.40)^2]^{\frac{1}{2}} \\ &= 0.185 \text{ ft/sec.} \end{aligned}$$

The velocities were only corrected for turbulence effects up to $y^+ = 60$ since beyond this radial position the correction amounts to less than 1%. No correction was made for y^+ due to the effective centre of the impact tube being displaced since this had very little effect on a plot of U versus y/R .

A.3 TEMPERATURE PROFILE

Point temperatures were measured by means of an iron-constantan thermocouple. The calibration is the same as that used for the other thermocouples and appears in table B.2.

The offset e.m.f. from the probe thermocouple was recorded on a millivolt recorder. External resistance changed the recorder scale factor by the ratio:

$$\frac{\text{Internal resistance} + \text{External resistance}}{\text{Internal resistance}}$$

Operating conditions were:

Reference voltage	=	1.347 mV
Resistance of thermocouple plus reference voltage system	=	697 ohms
Range of recorder	=	0.5 mV full scale deflection
\therefore Internal resistance	=	5 000 ohms
\therefore Effective recorder scale factor	=	$0.5 \left(\frac{5\ 000 + 697}{5\ 000} \right)$
	=	0.569 mV full-scale.

At $y/R = 0.70$ the average chart reading was 4.2 divisions and represents a difference of

$$\frac{4.2}{100} \times 0.569 = 0.024 \text{ mV}$$

from the reference voltage:

$$\begin{aligned} \therefore \text{Thermocouple voltage} &= 1.347 + 0.024 \\ &= 1.371 \text{ mV.} \end{aligned}$$

$$\therefore \text{Temperature} = 79.09^\circ\text{F} \text{ (see appendix B.2).}$$

The centre line temperature = 78.83°F

$$\therefore T - T_c = 0.26^\circ\text{F}$$

Point temperatures are recorded as $T - T_c$ in appendix E.

A.3.1 Wall Temperature

The slope of the temperature profile at the wall is calculated from a modified form of Fourier's law

$$\begin{aligned} \left[\frac{dT}{d(y/R)} \right]_w &= - \frac{Rq_w}{k} & \text{(A.6)} \\ &= - \frac{1.968}{2 \times 12} \times \frac{1.595}{5.17} \\ &= - 25.28^\circ\text{F/unit } (y/R). \end{aligned}$$

This slope was fitted by eye to the data near the wall, giving an extrapolated wall temperature of 86.82°F .

A.3.2 Mean Temperature

The mean mixed cup temperature at the probe was obtained by integrating the equation

$$T_m = \frac{\int_0^1 T u p \eta d \eta}{\int_0^1 u p \eta d \eta} \quad \text{(A.7)}$$

and is 82.00°F .

The distance between the probe tip and the top of the heating ribbon = 0.875 ft, and the total heated length = 14.6 ft. The mean

probe temperature can also be calculated from linear interpolation between inlet and outlet mixing cup temperatures.

$$\begin{aligned}\therefore T_m &= \text{Outlet temperature} - \frac{(\text{Inlet-Outlet temperature}) \times 0.875}{14.6} \\ \therefore T_m &= 83.65 - (83.65 - 60.76) \times 0.0599 \\ &= 82.28^\circ\text{F}.\end{aligned}$$

The difference between the interpolated and integrated mean temperature is only small and this is the case for most of the runs.

The arithmetic mean temperature is computed from the equation

$$T_{av} = 2 \int_0^1 T_n \, dn \quad (\text{A.9})$$

and is 82.02°F .

A.4 DIMENSIONLESS PARAMETERS

At the integrated mean probe temperature of 82.00°F the relevant physical properties of mercury (see appendix C) are:

$$\begin{aligned}\rho &= 844.58 \text{ lb/ft}^3 \\ \mu &= 1.508 \text{ centipoise} \\ \beta &= 0.00010^\circ\text{F}^{-1} \\ k &= 5.13 \text{ Btu/hr ft}^\circ\text{F} \\ C_p &= 0.0332 \text{ Btu/lb}^\circ\text{F}\end{aligned}$$

$$\begin{aligned}\therefore \text{Reynolds number, } Re &= \frac{D u_m \rho}{\mu} \\ &= \frac{1.968 \times 0.235 \times 844.58 \times 1488}{12 \times 1.508} \\ &= 32101.\end{aligned}$$

The von Karman friction factor is calculated from the relationship [7]

$$\frac{1}{\sqrt{f}} = 4.0 \log_{10} (Re \sqrt{f}) - 0.40 \quad (\text{A.10})$$

and hence $f = 0.00575$

$$\therefore u^* = u_m \sqrt{f/2} = 0.0126 \text{ ft/sec.}$$

$$\begin{aligned} \text{Prandtl number, Pr} &= \frac{C_p \mu}{k} \\ &= 0.0236 \end{aligned}$$

$$\text{Peclet number, Pe} = \text{Re} \cdot \text{Pr} = 757.$$

$$A = \frac{dT}{dx} \text{ and since } L/D = 83.6$$

$$\begin{aligned} \therefore A &= \frac{(T_{out} - T_{in})}{14.6} = \frac{22.89}{14.6} \\ &= 1.568^\circ\text{F/ft.} \end{aligned}$$

$$\begin{aligned} \text{Grashoff number, Gr} &= \frac{D^3 \rho \beta g (T_w - T_c)}{\mu^2} \\ &= \left(\frac{1.968}{12}\right)^3 \times 844.58 \times 0.0001 \times 32.17 \times 7.99 \times \left(\frac{1488}{1.508}\right)^2 \\ &= 78\,667\,000. \end{aligned}$$

$$\begin{aligned} \text{Gr}^* &= \frac{\text{Gr}}{T_w - T_c} \times \frac{dT}{dx} \times \frac{D}{12} \\ &= \frac{78\,667\,000 \times 1.568 \times 1.968}{12} \\ &= 2\,531\,500. \end{aligned}$$

$$\begin{aligned} \text{Rayleigh number, Ra} &= \text{Gr}^* \times \text{Pr} \\ &= 59\,744. \end{aligned}$$

$$\begin{aligned} \text{Ra}_R &= \text{Ra}/16 \\ &= 3\,734. \end{aligned}$$

$$\text{Ra/Re} = \frac{59\,744}{32\,101} = 1.86$$

$$\begin{aligned} \text{and } Z &= \frac{\text{Ra}}{\text{Re}} \cdot \frac{D}{L} \\ &= 0.022. \end{aligned}$$

$$\begin{aligned} Y &= \frac{\rho^2 \beta g (T_w - T_c) D^3}{\mu^2} \\ &= \left(\frac{1488}{1.508}\right)^2 \times (844.58)^2 \times 0.0001 \times 32.17 \times 7.99 \times \left(\frac{1.968}{12}\right)^3 \\ &= 25.9. \end{aligned}$$

Other dimensionless parameters computed at various radial positions are computed below using a typical radial position of $y/R = 0.70$.

$$\begin{aligned}y^+ &= \frac{y u^* \rho}{\mu} \\&= \frac{0.7 \times 0.0126 \times 844.58 \times 1488 \times 1.968}{1.508 \times 2 \times 12} \\&= 613.8.\end{aligned}$$

$$\begin{aligned}u^+ &= \frac{v}{u^*} \\&= \frac{0.221}{0.0126} = 17.5.\end{aligned}$$

$$u/u_c = \frac{0.221 \times 3600}{0.214 \times 3600} = 1.031.$$

$$\begin{aligned}U &= u/u_m = \frac{0.221}{0.235} \\&= 0.940.\end{aligned}$$

$$\begin{aligned}\phi &= \frac{T_w - T}{T_w - T_c} = \frac{86.82 - 79.09}{86.82 - 78.83} \\&= 0.96.\end{aligned}$$

$$\begin{aligned}T^+ &= \frac{(T_w - T) u^* \rho C_p}{q_w} \\&= \frac{7.73 \times 0.0126 \times 844.58 \times 0.0332 \times 3600}{1595} \\&= 6.25.\end{aligned}$$

A.5 NUSSELT NUMBERS

Nusselt numbers are computed from the equation

$$Nu = \frac{D}{k} \frac{q_w}{T_w - T_m} \quad (A.11)$$

Thus for run 7 ($Ra/Re = 1.86$)

$$\begin{aligned}Nu &= \frac{1.968}{12 \times 5.13} \times \frac{1595}{4.82} \\&= 10.2.\end{aligned}$$

Some previous workers have computed Nusselt numbers assuming an isothermal velocity distribution. To illustrate the difference between Nusselt numbers computed on the basis of the actual velocity distribution and those computed using an isothermal velocity distribution, mean cup temperatures were evaluated using an isothermal velocity profile and "isothermal" Nusselt numbers computed and compared with the actual Nusselt numbers.

For run 7 isothermal velocity profile 1 - 2 was used in evaluating T_m ("isothermal"), the resulting mean temperature being 81.69°F .

$$\begin{aligned} \text{Thus } T_w - T_m(\text{"isothermal"}) &= 86.82 - 81.69 \\ &= 5.13^\circ\text{F} \end{aligned}$$

$$\begin{aligned} \therefore Nu_1 &= \frac{1.968}{12 \times 5.13} \times \frac{1.595}{5.13} \\ &= 9.58 \end{aligned}$$

$$\therefore \frac{Nu - Nu_1}{Nu_1} = \frac{10.2 - 9.58}{9.58} = 0.0647$$

The effect of the velocity profile on the Nusselt number is illustrated graphically in fig 4.9 as a plot of

$\frac{Nu - Nu_1}{Nu_1}$ vs Ra/Re and results are tabulated in table A.1.

TABLE A.1

THE EFFECT OF THE VELOCITY PROFILE ON THE NUSSELT NUMBER

Run	Ra/Re	L/D	$T_w - T_{\text{mean}} (^{\circ}\text{F})$ (isothermal)	$T_w - T_{\text{mean}} (^{\circ}\text{F})$ (non-isothermal)	Nu_1	Nu	$\frac{Nu - Nu_1}{Nu_1}$
1	0.644	83.6	4.60	4.52	10.71	10.9	0.0177
2	0.831	83.6	6.83	6.58	9.25	9.6	0.0378
3	1.11	83.6	8.74	8.29	9.67	10.2	0.055
4	3.61	83.6	9.74	8.88	11.40	12.5	0.105
5	3.89	60.6	9.61	8.67	11.82	13.1	0.108
7	1.86	83.6	5.13	4.82	9.58	10.2	0.0647
8	1.71	60.6	5.19	4.85	9.44	10.1	0.0699
11	0.810	83.6	2.66	2.55	7.77	8.1	0.0424
12	0.853	60.6	2.66	2.56	7.99	8.3	0.0388

A.5.1 Nusselt Number Correlation

Nusselt numbers were correlated against Pe and Ra/Re using the data from the runs where L/D = 83.6 and the data of Horsten [2].

The form of the equation used in correlating the Nusselt numbers is

$$Nu = a + b Pe^c + d(Ra/Re) + e(Ra/Re)^2 + f(Ra/Re)^3 \quad (A.12)$$

Equation (A.2) was fitted to 25 data points using the Newton-Raphson technique for solving a set of non-linear equations.

The resulting coefficients are

$$\begin{aligned} a &= 5.8 \\ b &= 0.026 \\ c &= 0.74 \\ d &= -1.78 \\ e &= 1.35 \\ f &= -0.171 \end{aligned}$$

To fit all the data onto one curve a plot of $Nu - 0.026 Pe^{0.74}$ versus Ra/Re is presented in fig. 4.10. A Plot of this form tends to exaggerate errors and a better idea of the goodness of fit can be obtained by referring to table A.2 where the percentage between the actual and predicted Nusselt numbers is tabulated.

Typically for run 7,

$$\begin{aligned} Nu &= 10.2 \\ Pe &= 758 \\ Ra/Re &= 1.86 \\ \therefore 0.026 Pe^{0.74} &= 3.52 \\ \therefore Nu - 0.026 Pe^{0.74} &= 6.68 \\ \text{and } Nu \text{ calculated from equation (A.12)} &= 9.49 \\ \therefore \% \text{ error in Nusselt number} & \end{aligned}$$

$$\begin{aligned} &= \frac{Nu - Nu \text{ (calculated)}}{Nu} \times 100 \\ &= 6.99\% \end{aligned}$$

TABLE A.2

NUSSELT NUMBER CORRELATION DATA

This Work						
Run	Pe	Nu(given)	Nu(calculated)	%error	$Nu-0.026Pe^{0.74}$	Ra/Re
1	1297	10.9	10.33	5.21	5.669	0.644
2	1274	9.6	10.24	-6.65	4.44	0.831
3	1273	10.2	10.32	-1.18	5.04	1.11
4	768	12.5	12.32	1.46	8.95	3.61
7	757	10.2	9.49	6.99	6.68	1.86
11	740	8.1	8.56	-5.66	4.65	0.81
NV and T	Horsten [2]					
1	428	11.2	11.0	1.38	8.90	5.36
2	439	9.9	10.0	-1.49	7.55	2.84
3	462	9.4	8.53	9.23	6.96	1.90
4	451	8.0	7.72	3.54	5.61	1.25
5	457	7.1	7.54	-6.19	4.68	0.790
6	455	7.4	7.57	-2.31	5.00	0.572
7	459	7.2	7.64	-6.13	4.78	0.466
8	463	7.3	7.75	-6.19	4.86	0.343
9	723	12.2	12.7	-4.29	8.71	4.02
10	753	10.3	10.5	-2.36	6.80	2.48
11	772	8.9	8.70	2.27	5.34	0.955
12	759	8.8	10.5	0.96	5.28	0.470
13	1396	11.3	11.06	2.10	5.78	0.161
14	1426	10.0	10.98	-9.84	4.39	1.37
15	1443	10.8	10.75	0.47	5.14	1.53
16	1515	12.8	11.39	11.0	6.93	0.118
T18,NVII	765	9.1	8.69	4.45	5.56	0.620
T19,NVII	758	9.4	8.64	8.04	5.88	0.935
T20	784	9.0	9.10	-1.14	5.40	0.161

APPENDIX B

CALIBRATION

B.1 ORIFICE METER

The orifice meter had previously been calibrated by Horsten [2] using water. The orifice diameter was 0.6875 in. and the pipe I.D. was 1.624 in.

The orifice equation is

$$u_{or} = \frac{C_D}{\sqrt{1 - \beta_o^4}} \sqrt{\frac{2g_c \Delta p}{\rho}} \quad (B.1)$$

where $\beta_o = \frac{0.6875}{1.624} = 0.423$

and $\sqrt{1 - \beta_o^4} = 0.984$

Using the average over a number of runs, Horsten found C_D to be 0.627 and since

$$u_m = \frac{D_{or}^2}{D^2} \times u_{or} \quad (B.2)$$

$$\begin{aligned} \therefore u_m &= \left(\frac{0.6875}{1.968}\right)^2 \times \frac{0.627}{0.984} \sqrt{\frac{2 \times 32.17 \times 27.85 \Delta h \text{ (cm H}_g\text{)}}{\rho_{\text{mercury}}}} \\ &= 3.27 \sqrt{\frac{\Delta h \text{ (cm H}_g\text{)}}{\rho_{\text{mercury}}}} \quad (B.3) \end{aligned}$$

B.2 THERMOCOUPLES

All the thermocouples (including the probe thermocouple) used in this investigation were of the iron-constantan type.

The thermocouples were calibrated in the range 50-160°F with reference to an iron-constantan thermocouple in melting ice. Thermocouples were strapped to a standard thermometer and calibrated in either a stream of hot air or an insulated beaker of warm oil, either method giving the same results. Emfs were measured on a voltmeter with an accuracy of ± 0.001 mV.

All the thermocouples gave the same results which were in very good agreement with Horsten's [2] calibration of the same. The temperature conversion table as used by Horsten was thus used in this work and is reproduced in table B.2

TABLE B.2

TEMPERATURE CONVERSION FACTORS FOR
IRON-CONSTANTAN THERMOCOUPLES USED IN THIS INVESTIGATION

<u>mV</u>	<u>°F</u>		<u>°F/mV</u>
0.5	49.43		
1.0	66.49	}	34.108
1.5	83.47	}	33.963
2.0	100.28	}	33.632
2.5	116.96	}	33.360
3.0	133.63	}	33.338
3.5	150.34	}	33.405
4.0	166.77	}	33.873
4.5	183.28	}	33.021

B.3 KILOWATT-HOUR METER

Since the KWH meter was designed to operate at 220 volts it had to be recalibrated for this investigation as the voltages used were generally a lot less than 220 volts. The calibration was performed by the Cape Town Electricity Department at a power factor of unity and at the conditions of each run (i.e. at the same currents and voltages). The results are tabulated in table B.3.

TABLE B.3

KWH METER CALIBRATION

Run	Volts	Amps	KWH (measured)	KWH (actual)	% error
1	75	46	3.45	3.55	2.94
2	86	52	4.49	4.61	2.60
3	100	60	6.03	6.17	2.40
4	120	70	8.44	8.55	1.30
5	86.5	70	6.20	6.35	2.50
6	54	70	3.79	3.94	3.90
7	73.5	46	3.46	3.56	2.73
8	56	46	2.54	2.63	3.61
9	37	46	1.53	1.61	5.41
10	20	46	0.880	0.95	6.79
11	50	30	1.42	1.50	5.88
12	37.8	30	1.07	1.14	6.20
13	23.5	30	0.660	0.70	6.25
14	13	30	0.358	0.40	11.76

B.4 THE PRESSURE MEASURING SYSTEM

The pressure measuring system was calibrated by imposing a differential water pressure across the ports of the pressure transducer. Pressure differentials were measured by means of an Inverted Dwyer hook gauge with an accuracy of $\pm .001$ inches water.

Since the response of the pressure transducer was linear over the range of pressure differentials used in this investigation, a first order polynomial of the form

$$\Delta h \text{ (Inches water)} = a + b \Delta \text{ chart} \quad (\text{B.4})$$

was fitted to the calibration data and used to calculate the differential pressure from recorded velocity points.

The transducer was calibrated before each run and in some cases afterwards as well. It was found, however, that the calibration never changed and in fact it remained constant for a number of days provided no adjustments were made to the amplifier gain etc. Calibration data for run 7 are shown in table B.4

TABLE B.4

CALIBRATION OF PRESSURE MEASURING SYSTEM FOR RUN 7

Δh (Inches water)	Δ chart
0.172	73.0
0.163	70.0
0.155	66.3
0.126	54.0
0.105	45.7
0.079	33.9
0.063	27.8

The calibration equation is thus

Δh (Inches water) = $-0.00283 + 0.00238 \Delta$ chart. This is illustrated graphically in fig. B.4.

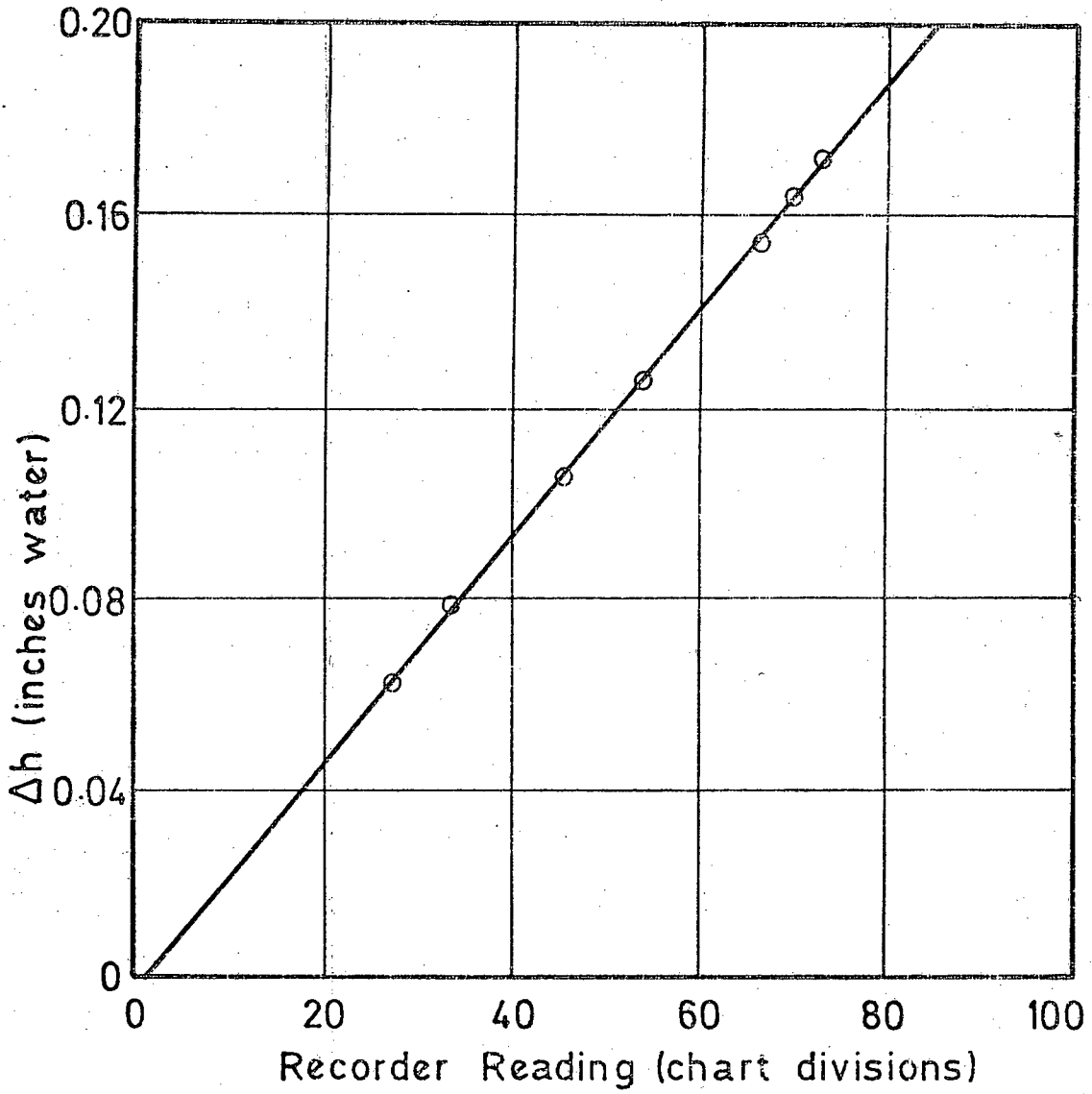


FIGURE B.4 DIFFERENTIAL PRESSURE TRANSDUCER CALIBRATION LINE

FOR RUN 7

B.5 PITOT-STATIC TUBE

The pitot static tube was calibrated against a standard Dwyer stainless steel $1/8''$ 166 - 12 pocket pitot-static tube in air. Differential pressures were measured on a Flow Corporation Model M M 3 micromanometer. The agreement between the two probes was excellent and thus the pitot-static tube equation

$$p_1 - p = c_p \rho v^2 / 2g_c \quad (B.5)$$

was used to calculate the point velocities from recorded pressure differentials. c_p was assumed to be constant and equal to 1 in this investigation.

The final working form of equation (B.5) is

$$v = \sqrt{\frac{2g_c \Delta h \rho_{\text{water}}}{12 \rho_{\text{mercury}}}} \quad (B.6)$$

APPENDIX C.

PHYSICAL PROPERTIES

The physical properties used in this work are the same as those used by Buhr [10] and are shown in fig. C.1. Density data for mercury were taken from Smithsonian tables [13] and are in good agreement with other references [14, 15]. Thermal conductivity, specific heat and viscosity data were obtained from the Liquid - metals Handbook [15] and fig. C.1 also shows the data given by Kutateladze et al. [14].

These physical properties were approximated by a series of straight lines by Horsten [2] over the temperature range of 60-200°F. The resulting equations are:

Density: $\rho = 851.55 - 0.0850 T \text{ lb/ft}^3$.

Specific Heat: $C_p = 0.03348 - 0.0000036 T \text{ Btu/lb}^\circ\text{F}$

Thermal Conductivity: $k = 4.49 + 0.00785 T \text{ Btu/hr ft}^2\text{ }^\circ\text{F/ft}$.

Viscosity (centipoise):

$60 < T < 80, \mu = 1.766 - 0.00315 T$

$80 < T < 120, \mu = 1.738 - 0.0028 T$

$120 < T < 140, \mu = 1.690 - 0.0024 T$

Buhr [10] has shown that β , the coefficient of thermal expansion is $0.00010^\circ\text{F}^{-1}$ over a wide temperature range.

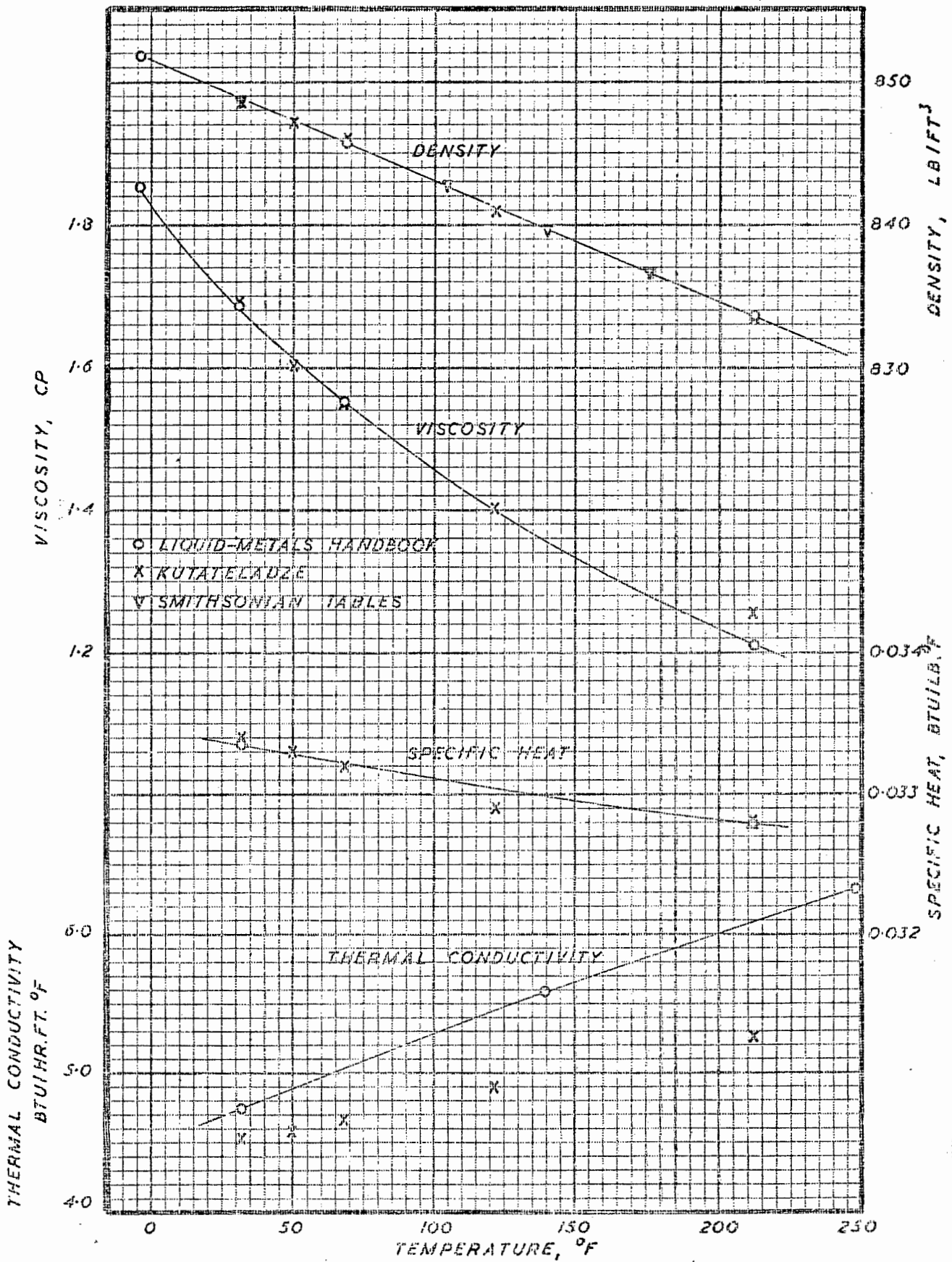


FIGURE C.1. PHYSICAL PROPERTIES OF MERCURY [10]

APPENDIX D

EDDY DIFFUSIVITIES

Run number 7 will be used to demonstrate the method of calculating the eddy diffusivities of heat and momentum.

D.1 FITTING OF EQUATIONS TO VELOCITY AND TEMPERATURE PROFILES

Velocity and temperature profiles were smoothed by hand and the smoothed data were processed on an IBM 1130 digital computer. In regions where the slope of the velocity profile was steep, such as near the wall and the profile peak, or where a point of inflection occurred, data was fed into the computer at intervals of $\eta = 0.02$. For the rest of the profile data was fed in at intervals of $\eta = 0.05$. The corresponding temperature point was fed in for every velocity point.

In the region of the velocity profile peak a third order polynomial of the form

$$U = a + b\eta + c\eta^2 + d\eta^3 \quad (D.1)$$

was fitted to the data and in the regions where the slope was less steep a second order polynomial of the form

$$U = a + b\eta + c\eta^2 \quad (D.2)$$

was fitted using a least squares technique.

In the region of the wall a rational function of the form

$$U = \frac{a\eta}{1 + b\eta} \quad (D.3)$$

was used to fit the velocity data and a rational function of the form

$$T = \frac{a + b\eta}{1 + c\eta} \quad (D.4)$$

was fitted to the temperature data using the Newton-Raphson technique for solving a set of non-linear equations.

For the purpose of differentiation curves were fitted to 5 points at a time, the derivative being evaluated at the centre point. Thus, to obtain $dU/d\eta$ and $d\phi/d\eta$ at $\eta = 0.30$ ($y/R = 0.70$) for run 7 the following data are required:

η	0.4	0.35	0.30	0.25	0.20
U	0.967	0.951	0.940	0.936	0.925
ϕ	-0.02652	-0.02819	-0.02957	-0.03026	-0.03076

Since the slope of the velocity profile is not very steep in this region, a second equation is fitted to the data - i.e.

$$U = 0.925 - 0.0934\eta + 0.486\eta^2$$

and

$$\phi = -0.0280 - 0.0308\eta + 0.0866\eta^2$$

$$\therefore \frac{dU}{d\eta} = -0.0934 + 2 \times 0.486\eta$$
$$= 0.199$$

and

$$\frac{d\phi}{d\eta} = 0.0211$$

For integration 6 data points were fitted at a time, the integral being evaluated over the middle interval. Slopes of the isothermal velocity profiles were determined in a similar manner to the non-isothermal profiles and integration was performed using Simpson's rule.

D.2 CALCULATION PROCEDURE

At the mean probe temperature of 82.00°F the relevant physical properties of mercury are:

$$\begin{aligned} \rho &= 844.58 \text{ lb/ft}^3 \\ \mu &= 1.508 \text{ centipoise} \\ \beta &= 0.0001 \text{ } ^\circ\text{F}^{-1} \\ k &= 5.13 \text{ Btu/hr ft}^2 \text{ } ^\circ\text{F/ft} \\ C_p &= 0.0332 \text{ Btu/lb } ^\circ\text{F} \end{aligned}$$

At the arithmetic mean temperature of 82.02°F the density of mercury, $\rho_{av} = 844.57 \text{ lb/ft}^3$.

The eddy diffusivity of momentum is calculated from the equation (see chapter 1).

$$\epsilon_M/\nu = \left[\frac{-Ra \int_0^{\eta} \phi \eta d\eta - 0.25 f Re \eta}{8\eta \frac{dU}{d\eta}} \right] - i \quad (D.5)$$

The mean velocity used is the arithmetic average of the orifice meter, integrated and heat balance velocities.

$$\begin{aligned} \therefore U_m &= 1/3 (0.235 + 0.232 + 0.246) \\ &= 0.238 \text{ ft/sec.} \end{aligned}$$

$$\begin{aligned} \therefore Re &= \frac{D u_m \rho}{\mu} \\ &= \frac{1.968 \times 0.238 \times 844.58 \times 1488}{12 \times 1.508} \\ &= 32\ 452 \end{aligned}$$

$$\begin{aligned} Pr &= \frac{C_p \mu}{k} \\ &= \frac{0.0332 \times 1.508 \times 2.42}{5.13} \\ &= 0.0236 \end{aligned}$$

$$Ra = \frac{\rho_{av}^2 \beta g C_p AD^4}{\mu k}$$

$$= \frac{(844.57)^2 \times 0.0001 \times 32.17 \times 0.0332 \times 1.568 \times (0.164)^4 \times 1488 \times 3600}{1.508 \times 5.13}$$

$$= 59\ 800$$

$$\phi = \frac{2k(T - T_{av})}{\rho u_m C_p A D^2}$$

$$= \frac{2 \times 12^2 \times 5.13 \times (T - T_{av})}{844.58 \times 0.238 \times 0.0332 \times 1.568 \times 1.198^2 \times 3600}$$

$$= 0.01013 (T - T_{av}).$$

$$f = 0.00575$$

$$\therefore u^* = u_m \sqrt{f/2}$$

$$= 0.238 (\sqrt{0.00575/2})$$

$$= 0.0128 \text{ ft/sec.}$$

For run 7 at $y/R = 0.70$, $\eta = 0.30$ and $dU/d\eta = 0.199$.

$$\text{Buoyancy term} = \frac{-Ra \int_0^{\eta} \phi \eta d\eta}{8\eta}$$

$$= \frac{- \int_0^{0.30} \phi \eta d\eta}{8 \times 0.30}$$

and since $\int_0^{0.30} \phi \eta d\eta = -0.00138$

$$\therefore \text{buoyancy term} = 34.42.$$

$$\text{Friction term} = -0.25f Re\eta$$

$$= -0.25 \times 0.00575 \times 32\ 452 \times 0.30$$

$$= -14.$$

$$\begin{aligned} \frac{\epsilon_M}{\nu} &= \frac{(34.42 - 1.4) - 1}{0.199} \\ &= 101.7. \end{aligned}$$

$$\begin{aligned} \frac{\epsilon_M}{Ru^*} &= \frac{\epsilon_M}{\nu} \times \frac{\mu}{\rho} \times \frac{1}{Ru^*} \\ &= \frac{101.7 \times 1.508 \times 2 \times 12}{844.58 \times 1.968 \times 0.0128 \times 1488} \\ &= 0.1169. \end{aligned}$$

isothermal eddy diffusivities of momentum are computed from a simplified form of equation (D.5):

$$\frac{\epsilon_M}{\nu} = \frac{-0.25 f Re \eta}{dU/d\eta} \quad -1 \quad (D.6)$$

The eddy diffusivity of heat is computed from the equation (see chapter 1):

$$\frac{\epsilon_H}{\alpha} = \frac{0.5 \int_0^\eta U \eta \, d\eta}{\eta \, d\phi/d\eta} \quad (D.7)$$

and since the heat flux distribution is given as

$$\frac{q}{q_w} = \frac{2 \int_0^\eta U \eta \, d\eta}{\eta} \quad (D.8)$$

$\frac{\epsilon_H}{\alpha}$ may be written as

$$\frac{\epsilon_H}{\alpha} = \frac{q/q_w}{4 \, d\phi/d\eta} \quad -1 \quad (D.9)$$

For run 7 at $\eta = 0.30$

$$q/q_w = 0.278$$

$$\text{and } d\phi/d\eta = 0.0211$$

$$\begin{aligned} \therefore \frac{\epsilon_H}{\alpha} &= \frac{0.278}{4 \times 0.0211} \quad -1 \\ &= 2.298. \end{aligned}$$

σ values are computed from smoothed ϵ_H/α and ϵ_M/ν curves.

$$\sigma = \frac{\epsilon_H}{\epsilon_M} = \frac{\epsilon_H/\alpha}{Pr(\epsilon_M/\nu)} \quad (D.10)$$

Smoothed values of ϵ_H/α and ϵ_M/ν are (see table D.2):

$$\frac{\epsilon_H}{\alpha} = 2.20$$

$$\frac{\epsilon_M}{\nu} = 101.0$$

$$\begin{aligned} \therefore \sigma &= \frac{2.20}{0.0236 \times 101.0} \\ &= 0.92. \end{aligned}$$

At $Re \approx 33\ 000$ the σ values computed for L/D ratios of 83.6 and 60.6 were averaged and are tabulated in table D.2.

For run 8 ($L/D = 60.6$) and $\eta = 0.30$ $\sigma = 1.01$ and the average for run 7 ($L/D = 83.6$) and run 8 ($Re \approx 33\ 000$, $Ra \approx 58\ 000$) is

$$\begin{aligned} \sigma \text{ (averaged)} &= \frac{0.92 + 1.01}{2} \\ &= 0.97 \end{aligned}$$

It must be pointed out that the Rayleigh numbers reported in table D.1 are Ra_R as used by Ojalvo and Grosh [1],

$$\text{where } Ra_R = Ra/16 = \frac{\rho_{av}^2 Bg C_p AD^4}{16 \mu k} \quad (D.11)$$

$$\text{For run 7: } Ra_R = 3734.$$

TABLE D.1

EDDY DIFFUSIVITIES OF HEAT AND MOMENTUM.

(BASED ON RUN NO. 1)

REYNOLDS NUMBER 54947. RAYLEIGH NUMBER 2171
 FRICTION FACTOR 0.00511 PRANDTL NUMBER 0.0241

UMEAN(AVERAGED) 0.406 FT/SEC
 PHYSICAL PROPERTIES WERE EVALUATED AT 76.6 DEG.F.

y/R	U	ϕ	dU/dn	d ϕ /dn	Buoyancy Term	Friction Term	ϵ_H/ν	ϵ_H/Ru^*	ϵ_H/α	q/q _w
1.00	1.091	-0.03514	0.000	0.0000	0.00	0.00	0.0	0.0000	0.000	0.000
0.95	1.092	-0.03495	0.056	0.0111	3.81	-3.50	4.3	0.0031	0.233	0.055
0.90	1.097	-0.03408	0.107	0.0202	7.52	-7.01	3.7	0.0027	0.351	0.109
0.88	1.099	-0.03360	0.112	0.0226	8.97	-8.41	3.9	0.0028	0.453	0.131
0.85	1.101	-0.03321	0.131	0.0242	10.38	-9.82	3.2	0.0023	0.587	0.153
0.84	1.104	-0.03263	0.096	0.0247	11.76	-11.22	4.5	0.0032	0.781	0.176
0.82	1.106	-0.03215	0.325	0.0261	13.11	-12.62	0.5	0.0003	0.895	0.198
0.80	1.112	-0.03166	0.123	0.0285	14.43	-14.03	2.2	0.0016	0.930	0.220
0.78	1.112	-0.03108	0.013	0.0319	15.72	-15.43	21.0	0.0152	0.901	0.243
0.76	1.111	-0.03031	-0.043	0.0363	16.97	-16.84	-3.7	-0.0026	0.827	0.265
0.74	1.111	-0.02963	-0.057	0.0367	18.16	-18.24	0.5	0.0003	0.955	0.287
0.72	1.110	-0.02876	-0.038	0.0372	19.31	-19.64	7.7	0.0055	1.080	0.310
0.70	1.109	-0.02818	-0.037	0.0392	20.42	-21.05	15.9	0.0114	1.119	0.332
0.68	1.109	-0.02731	-0.029	0.0406	21.47	-22.45	31.6	0.0228	1.180	0.354
0.66	1.108	-0.02644	-0.042	0.0435	22.48	-23.85	31.2	0.0225	1.162	0.376
0.64	1.107	-0.02557	-0.052	0.0425	23.42	-25.26	33.6	0.0242	1.342	0.399
0.62	1.106	-0.02470	-0.063	0.0450	24.32	-26.66	36.0	0.0259	1.339	0.421
0.60	1.105	-0.02393	-0.068	0.0483	25.16	-28.07	41.4	0.0298	1.290	0.443
0.58	1.103	-0.02277	-0.076	0.0517	25.94	-29.47	45.2	0.0326	1.246	0.465
0.56	1.102	-0.02170	-0.078	0.0542	26.65	-30.87	52.4	0.0378	1.247	0.487
0.54	1.100	-0.02064	-0.091	0.0542	27.29	-32.28	53.2	0.0383	1.348	0.509
0.52	1.099	-0.01957	-0.102	0.0566	27.86	-33.68	55.7	0.0401	1.345	0.531
0.50	1.096	-0.01841	-0.117	0.0614	28.37	-35.08	55.8	0.0402	1.249	0.552
0.48	1.094	-0.01716	-0.128	0.0667	28.79	-36.49	58.8	0.0423	1.151	0.574
0.46	1.091	-0.01571	-0.139	0.0716	29.12	-37.89	61.8	0.0445	1.081	0.596
0.44	1.088	-0.01426	-0.155	0.0769	29.36	-39.30	62.9	0.0453	1.007	0.617
0.42	1.084	-0.01271	-0.171	0.0793	29.50	-40.70	64.2	0.0463	1.013	0.639
0.40	1.081	-0.01097	-0.203	0.0822	29.53	-42.10	60.7	0.0437	1.007	0.660
0.38	1.077	-0.00942	-0.235	0.0861	29.45	-43.51	58.5	0.0421	0.978	0.681
0.36	1.072	-0.00768	-0.279	0.0880	29.26	-44.91	55.0	0.0396	0.995	0.702
0.34	1.065	-0.00575	-0.323	0.0919	28.95	-46.31	52.6	0.0379	0.967	0.723
0.32	1.059	-0.00400	-0.382	0.0957	28.52	-47.72	49.2	0.0354	0.942	0.744
0.30	1.051	-0.00207	-0.452	0.0986	27.96	-49.12	45.7	0.0329	0.936	0.764
0.28	1.041	0.00005	-0.522	0.1040	27.27	-50.53	43.5	0.0313	0.885	0.784
0.26	1.029	0.00208	-0.571	0.1083	26.45	-51.93	43.6	0.0314	0.855	0.804
0.24	1.018	0.00430	-0.614	0.1117	25.47	-53.33	44.3	0.0319	0.842	0.823
0.22	1.005	0.00662	-0.656	0.1189	24.36	-54.74	45.2	0.0326	0.769	0.842
0.20	0.991	0.00894	-0.726	0.1228	23.08	-56.14	44.5	0.0320	0.751	0.860
0.18	0.977	0.01165	-0.798	0.1262	21.63	-57.54	43.9	0.0316	0.739	0.878
0.16	0.959	0.01407	-0.986	0.1277	20.02	-58.95	38.5	0.0277	0.753	0.895
0.14	0.941	0.01668	-0.998	0.1262	18.23	-60.35	41.2	0.0297	0.807	0.912
0.12	0.910	0.01919	-1.000	0.1335	16.28	-61.76	44.5	0.0320	0.738	0.928
0.10	0.901	0.02171	-1.038	0.1426	14.16	-63.16	46.2	0.0333	0.653	0.943
0.08	0.879	0.02490	-1.131	0.1557	11.35	-64.56	45.6	0.0328	0.536	0.958
0.06	0.853	0.02809	-1.611	0.1804	9.33	-65.97	34.1	0.0246	0.347	0.972
0.04	0.821	0.03157	-1.821	0.2111	6.59	-67.37	32.4	0.0233	0.167	0.985
0.02	0.769	0.03641	-G.160	0.2883	3.50	-68.77	9.6	0.0069	-0.134	0.997
0.00	0.000	0.04349	*****	0.2551	-0.00	-70.18	-0.6	0.0004	-0.019	1.000

TABLE D.1 (Continued)

EDDY DIFFUSIVITIES OF HEAT AND MOMENTUM.

(BASED ON RUN NO. 2)

REYNOLDS NUMBER 55404. RAYLEIGH NUMBER 2808
 FRICTION FACTOR 0.00510 PRANDTL NUMBER 0.0236

U_{MEAN}(AVERAGED) 0.405 FT/SEC
 PHYSICAL PROPERTIES WERE EVALUATED AT 82.2 DEG.F.

y/R	U	ψ	$du/d\eta$	$d\psi/d\eta$	Buoyancy Term	Friction Term	ϵ_M/ν	ϵ_M/Ru^*	ϵ_H/α	q/q_w
1.00	0.977	-0.03806	0.000	0.0000	0.01	0.01	0.0	0.0000	0.060	0.600
0.95	0.979	-0.03775	0.027	0.0058	5.32	-3.52	65.2	0.0466	1.101	0.049
0.90	0.980	-0.03729	0.057	0.0113	10.57	-7.05	60.2	0.0430	1.160	0.098
0.85	0.984	-0.03668	0.085	0.0156	15.70	-10.58	59.0	0.0422	1.355	0.147
0.80	0.989	-0.03576	0.123	0.0225	20.69	-14.11	52.4	0.0374	1.184	0.197
0.75	0.996	-0.03461	0.164	0.0312	25.44	-17.64	46.6	0.0333	0.974	0.247
0.70	1.005	-0.03269	0.202	0.0409	29.86	-21.17	41.9	0.0300	0.817	0.297
0.65	1.017	-0.03040	0.238	0.0502	33.83	-24.70	37.4	0.0268	0.735	0.349
0.60	1.029	-0.02764	0.263	0.0585	37.25	-28.23	33.3	0.0238	0.714	0.401
0.55	1.043	-0.02458	0.279	0.0664	40.04	-31.76	28.7	0.0205	0.710	0.454
0.50	1.058	-0.02098	0.278	0.0746	42.11	-35.29	23.5	0.0168	0.706	0.509
0.48	1.063	-0.01952	0.255	0.0760	42.73	-36.70	22.6	0.0162	0.745	0.531
0.46	1.069	-0.01791	0.245	0.0777	43.21	-38.11	19.7	0.0141	0.778	0.553
0.44	1.073	-0.01638	0.213	0.0793	43.56	-39.52	17.9	0.0123	0.814	0.575
0.42	1.077	-0.01477	0.192	0.0873	43.79	-40.93	13.8	0.0099	0.711	0.598
0.40	1.080	-0.01317	0.136	0.0865	43.85	-42.35	10.0	0.0072	0.792	0.620
0.38	1.084	-0.01079	0.060	0.0869	43.77	-43.76	-0.8	-0.0005	0.849	0.643
0.36	1.083	-0.00972	-0.017	0.0877	43.55	-45.17	88.2	0.0631	0.897	0.665
0.34	1.082	-0.00780	-0.109	0.0911	43.19	-46.58	29.8	0.0213	0.887	0.688
0.32	1.079	-0.00589	-0.187	0.1022	42.68	-47.99	27.3	0.0195	0.737	0.710
0.30	1.075	-0.00359	-0.308	0.1088	41.99	-49.41	23.1	0.0165	0.684	0.732
0.28	1.069	-0.00160	-0.316	0.1191	41.12	-50.82	29.6	0.0212	0.584	0.754
0.26	1.062	0.00092	-0.381	0.1264	40.03	-52.23	31.0	0.0221	0.535	0.776
0.24	1.054	0.00375	-0.439	0.1289	38.72	-53.64	33.0	0.0236	0.547	0.797
0.22	1.044	0.00635	-0.505	0.1340	37.19	-55.05	34.5	0.0246	0.527	0.818
0.20	1.034	0.00856	-0.561	0.1444	35.42	-56.47	36.4	0.0261	0.452	0.839
0.18	1.022	0.01191	-0.624	0.1592	33.41	-57.88	38.1	0.0273	0.349	0.859
0.16	1.009	0.01541	-0.699	0.1756	31.11	-59.29	39.3	0.0281	0.251	0.879
0.14	0.994	0.01884	-0.788	0.1825	28.49	-60.70	39.8	0.0285	0.230	0.898
0.12	0.978	0.02265	-0.958	0.1847	25.53	-62.11	37.1	0.0266	0.240	0.917
0.10	0.959	0.02654	-1.182	0.1969	22.25	-63.52	33.9	0.0242	0.186	0.934
0.08	0.931	0.03004	-1.474	0.2091	18.61	-64.94	30.4	0.0218	0.138	0.952
0.06	0.899	0.03484	-1.893	0.2175	14.60	-66.35	26.3	0.0188	0.112	0.968
0.04	0.860	0.03941	-2.089	0.2460	10.21	-67.76	26.5	0.0190	-0.000	0.983
0.02	0.805	0.04360	-6.963	0.2807	5.36	-69.17	8.2	0.0058	-0.112	0.996
0.00	0.600	0.05061	*****	0.2575	-0.00	-70.58	-0.6	-0.0004	-0.028	1.000

TABLE D.1 (Continued)

EDDY DIFFUSIVITIES OF HEAT AND MOMENTUM.

(BASED ON RUN NO. 3)

REYNOLDS NUMBER 55923. RAYLEIGH NUMBER 3809
 FRICTION FACTOR 0.00508 PRANDTL NUMBER 0.0231

U_{MEAN}(AVERAGED) 0.405 FT/SEC
 PHYSICAL PROPERTIES WERE EVALUATED AT 87.8 DEG.F.

y/R	U	φ	du/dn	dφ/dn	Buoyancy Term	Friction Term	ϵ_M/ν	ϵ_M/Ru^*	ϵ_H/a	q/q_w
1.00	0.945	-0.03352	0.000	0.0000	0.07	0.07	0.0	0.0000	0.000	0.000
0.95	0.946	-0.03341	0.045	0.0017	6.37	-3.54	61.3	0.0435	5.864	0.047
0.90	0.950	-0.03330	0.087	0.0041	12.73	-7.10	63.8	0.0453	4.791	0.095
0.85	0.955	-0.03309	0.131	0.0077	19.03	-10.65	62.8	0.0446	3.598	0.143
0.80	0.962	-0.03265	0.173	0.0138	25.23	-14.20	62.5	0.0444	2.462	0.191
0.75	0.973	-0.03179	0.209	0.0198	31.22	-17.75	63.4	0.0450	2.026	0.240
0.70	0.984	-0.03050	0.231	0.0280	36.93	-21.31	66.5	0.0472	1.586	0.289
0.65	0.995	-0.02921	0.243	0.0355	42.21	-24.86	70.3	0.0498	1.394	0.340
0.60	1.008	-0.02695	0.253	0.0455	46.97	-28.41	72.4	0.0514	1.149	0.391
0.55	1.022	-0.02459	0.260	0.0584	51.06	-31.96	72.3	0.0513	0.901	0.444
0.50	1.035	-0.02137	0.248	0.0731	54.27	-35.52	74.5	0.0529	0.700	0.497
0.48	1.040	-0.01977	0.246	0.0746	55.27	-36.94	73.5	0.0521	0.740	0.519
0.46	1.044	-0.01827	0.222	0.0781	56.07	-38.36	78.7	0.0558	0.729	0.541
0.44	1.049	-0.01677	0.190	0.0803	56.69	-39.78	87.8	0.0623	0.751	0.562
0.42	1.052	-0.01506	0.208	0.0856	57.12	-41.20	75.6	0.0536	0.705	0.584
0.40	1.057	-0.01334	0.195	0.0910	57.35	-42.52	74.5	0.0529	0.666	0.606
0.38	1.060	-0.01142	0.169	0.0964	57.35	-44.04	77.7	0.0552	0.630	0.628
0.36	1.062	-0.00949	0.150	0.1038	57.13	-45.47	76.9	0.0546	0.566	0.651
0.34	1.066	-0.00735	0.129	0.1031	56.66	-46.89	74.5	0.0529	0.555	0.673
0.32	1.068	-0.00499	0.121	0.1103	55.92	-48.31	61.7	0.0438	0.576	0.695
0.30	1.070	-0.00285	-0.143	0.1113	54.92	-49.73	-36.9	-0.0262	0.611	0.717
0.28	1.072	-0.00071	-0.027	0.1124	53.66	-51.15	-90.6	-0.0642	0.645	0.740
0.26	1.069	0.00163	-0.063	0.1199	52.15	-52.57	5.8	0.0041	0.589	0.762
0.24	1.066	0.00399	-0.241	0.1242	50.34	-53.99	-14.1	0.0100	0.578	0.784
0.22	1.060	0.00677	-0.344	0.1285	48.25	-55.41	19.8	0.0140	0.568	0.806
0.20	1.052	0.00913	-0.451	0.1349	45.85	-56.83	23.3	0.0165	0.534	0.828
0.18	1.042	0.01191	-0.512	0.1424	43.14	-58.26	28.5	0.0202	0.490	0.849
0.16	1.030	0.01491	-0.655	0.1531	40.10	-59.68	28.9	0.0205	0.420	0.869
0.14	1.020	0.01812	-0.787	0.1627	36.69	-61.10	30.0	0.0213	0.367	0.890
0.12	0.997	0.02133	-0.937	0.1734	32.88	-62.52	30.6	0.0217	0.311	0.909
0.10	0.979	0.02497	-1.110	0.1831	28.66	-63.94	30.8	0.0218	0.268	0.928
0.08	0.956	0.02883	-1.302	0.1970	23.99	-65.36	30.8	0.0218	0.201	0.946
0.06	0.929	0.03268	-1.715	0.2131	18.25	-66.78	26.9	0.0191	0.131	0.964
0.04	0.892	0.03718	-1.935	0.2358	13.19	-68.20	27.4	0.0194	0.039	0.980
0.02	0.839	0.04210	-6.571	0.2727	6.93	-69.62	8.5	0.0061	-0.087	0.995
0.00	0.000	0.04810	*****	0.2559	-0.00	-71.05	-0.6	-0.0004	-0.022	1.000

TABLE D.1 (Continued)

EDDY DIFFUSIVITIES OF HEAT AND MOMENTUM.

(BASED ON RUN NO. 4)

REYNOLDS NUMBER 37228.
 FRICTION FACTOR 0.00557

RAYLEIGH NUMBER 8254
 PRANDTL NUMBER 0.0210

U_{MEAN}(AVERAGED) 0.257 FT/SEC

PHYSICAL PROPERTIES WERE EVALUATED AT 115.2 DEG.F.

y/R	U	φ	du/dn	dφ/dn	Buoyancy Term	Friction Term	ϵ_M/ν	ϵ_M/Ru^*	ϵ_H/α	q/q _w
1.00	0.820	-0.02233	0.000	0.0000	0.01	0.01	0.0	0.0000	0.000	0.000
0.95	0.821	-0.02225	0.025	0.0027	9.20	-2.58	260.1	0.2649	2.739	0.041
0.90	0.823	-0.02202	0.061	0.0059	18.32	-5.17	215.3	0.2192	2.455	0.082
0.85	0.826	-0.02172	0.105	0.0088	27.25	-7.76	184.8	0.1881	2.492	0.123
0.80	0.833	-0.02111	0.154	0.0110	35.89	-10.35	165.0	0.1680	2.763	0.165
0.75	0.842	-0.02050	0.206	0.0134	44.21	-12.95	150.8	0.1535	2.868	0.207
0.70	0.853	-0.01989	0.260	0.0152	52.11	-15.54	139.5	0.1420	3.111	0.251
0.65	0.867	-0.01897	0.316	0.0180	59.56	-18.13	130.2	0.1326	3.097	0.295
0.60	0.885	-0.01806	0.368	0.0236	66.50	-20.72	123.3	0.1255	2.598	0.340
0.55	0.905	-0.01692	0.412	0.0305	72.72	-23.31	119.0	0.1211	2.172	0.387
0.50	0.926	-0.01501	0.466	0.0379	77.96	-25.90	110.8	0.1128	1.866	0.435
0.45	0.950	-0.01288	0.527	0.0457	81.93	-28.49	100.4	0.1023	1.652	0.485
0.40	0.979	-0.01059	0.575	0.0530	84.40	-31.08	91.6	0.0933	1.532	0.537
0.35	1.010	-0.00770	0.609	0.0619	85.16	-33.68	83.5	0.0850	1.389	0.591
0.30	1.040	-0.00434	0.621	0.0741	83.94	-36.27	75.7	0.0771	1.187	0.648
0.25	1.071	-0.00053	0.614	0.0877	80.29	-38.86	66.5	0.0677	1.014	0.707
0.20	1.104	0.00433	0.623	0.1077	73.76	-41.45	50.8	0.0517	0.783	0.768
0.18	1.113	0.00646	0.632	0.1113	70.20	-42.49	42.8	0.0436	0.781	0.793
0.16	1.128	0.00898	0.602	0.1218	66.03	-43.52	36.4	0.0371	0.679	0.818
0.14	1.140	0.01114	0.553	0.1381	61.22	-44.56	29.1	0.0296	0.529	0.844
0.12	1.150	0.01418	0.292	0.1424	55.63	-45.59	33.4	0.0340	0.528	0.870
0.10	1.157	0.01767	-0.249	0.1732	49.33	-46.63	-11.7	-0.0119	0.295	0.897
0.08	1.148	0.01995	-1.070	0.2013	42.07	-47.67	4.2	0.0043	0.146	0.923
0.06	1.115	0.02557	-2.414	0.2297	33.67	-48.70	5.2	0.0053	0.052	0.948
0.04	1.063	0.03035	-3.349	0.2619	23.95	-49.74	6.7	0.0068	-0.072	0.972
0.02	0.955	0.03544	-10.584	0.2666	12.78	-50.78	2.6	0.0026	-0.068	0.992
0.00	0.000	0.04121	*****	0.2601	-0.00	-51.81	-0.7	-0.0007	-0.038	1.000

TABLE D.1 (Continued)

EDDY DIFFUSIVITIES OF HEAT AND MOMENTUM.

(BASED ON RUN NO. 5)

REYNOLDS NUMBER 35744. RAYLEIGH NUMBER 8705
 FRICTION FACTOR 0.00562 PRANDTL NUMBER 0.0212

UMEAN(AVERAGED) 0.248 FT/SEC
 PHYSICAL PROPERTIES WERE EVALUATED AT 112.6 DEG.F.

y/R	U	ϕ	du/dy	$d\phi/dy$	Buoyancy Term	Friction Term	ϵ_M/ν	ϵ_M/Ru^*	ϵ_H/α	q/q_w
1.00	0.795	-0.02293	0.000	0.0000	0.02	0.02	0.0	0.0000	0.000	0.000
0.95	0.797	-0.02285	0.067	0.0013	9.95	-2.50	110.5	0.1166	6.558	0.040
0.90	0.802	-0.02277	0.126	0.0038	19.90	-5.01	117.0	0.1235	4.275	0.080
0.85	0.810	-0.02260	0.184	0.0076	29.73	-7.52	119.7	0.1263	2.976	0.120
0.80	0.820	-0.02211	0.235	0.0132	39.33	-10.03	123.6	0.1304	2.069	0.162
0.75	0.834	-0.02129	0.283	0.0184	48.45	-12.55	125.8	0.1328	1.763	0.204
0.70	0.849	-0.02013	0.329	0.0224	56.92	-15.06	126.2	0.1332	1.758	0.247
0.65	0.867	-0.01898	0.368	0.0257	64.63	-17.57	126.7	0.1337	1.837	0.291
0.60	0.886	-0.01766	0.406	0.0288	71.49	-20.08	125.7	0.1327	1.926	0.337
0.55	0.907	-0.01610	0.435	0.0336	77.45	-22.59	125.0	0.1320	1.862	0.384
0.50	0.930	-0.01437	0.459	0.0393	82.32	-25.10	123.7	0.1306	1.753	0.433
0.45	0.953	-0.01223	0.468	0.0454	85.89	-27.61	123.4	0.1303	1.662	0.484
0.40	0.978	-0.00976	0.477	0.0518	87.93	-30.12	120.3	0.1269	1.584	0.536
0.35	1.001	-0.00705	0.503	0.0583	88.23	-32.63	109.4	0.1155	1.531	0.590
0.30	1.026	-0.00400	0.584	0.0670	86.61	-35.15	87.1	0.0919	1.408	0.645
0.25	1.055	-0.00055	0.705	0.0795	82.75	-37.66	62.9	0.0664	1.209	0.703
0.20	1.096	0.00372	0.754	0.0995	76.21	-40.17	46.8	0.0494	0.918	0.763
0.18	1.113	0.00586	0.539	0.1119	72.69	-41.17	57.5	0.0607	0.761	0.788
0.16	1.123	0.00816	0.373	0.1275	68.56	-42.18	69.7	0.0736	0.594	0.813
0.14	1.126	0.01080	0.129	0.1444	63.69	-43.18	157.7	0.1664	0.452	0.839
0.12	1.126	0.01401	-0.045	0.1646	57.99	-44.18	-299.6	-0.3163	0.313	0.865
0.10	1.124	0.01738	-0.180	0.1766	51.29	-45.19	-34.5	-0.0364	0.260	0.890
0.08	1.119	0.02133	-0.443	0.1917	43.54	-46.19	5.0	0.0053	0.193	0.915
0.06	1.111	0.02480	-1.047	0.2116	34.68	-47.20	11.0	0.0116	0.110	0.940
0.04	1.088	0.02947	-1.495	0.2318	24.59	-48.20	14.8	0.0156	0.039	0.964
0.02	1.033	0.03447	-5.377	0.2656	13.07	-49.21	5.7	0.0060	-0.071	0.986
0.00	0.000	0.04002	*****	0.2534	-0.00	-50.21	-0.3	-0.0008	-0.012	1.000

TABLE D.1 (Continued)

EDDY DIFFUSIVITIES OF HEAT AND MOMENTUM.

(BASED ON RUN NO. 7)

REYNOLDS NUMBER 32452. RAYLEIGH NUMBER 3734
 FRICTION FACTOR 0.00576 PRANDTL NUMBER 0.0236

MEAN (AVERAGED) 0.238 FT/SEC
 PHYSICAL PROPERTIES WERE EVALUATED AT 82.0 DEG.F.

y/R	U	ϕ	du/dy	dp/dy	Buoyancy Term	Friction Term	ϵ_M/ν	ϵ_M/Ru^*	ϵ_H/α	q/q_w
1.00	0.913	-0.03235	0.000	0.0000	0.19	*****	0.0	0.0000	0.000	0.000
0.95	0.913	-0.03204	0.029	0.0045	6.00	-2.33	125.9	0.1446	1.518	0.046
0.90	0.915	-0.03164	0.050	0.0079	11.93	-4.66	119.2	0.1369	1.898	0.091
0.85	0.919	-0.03125	0.112	0.0089	17.75	-7.00	95.0	0.1091	2.872	0.137
0.80	0.925	-0.03076	0.135	0.0102	23.44	-9.33	103.2	0.1186	3.483	0.184
0.75	0.936	-0.03026	0.161	0.0146	29.02	-11.67	106.9	0.1228	2.955	0.231
0.70	0.940	-0.02957	0.199	0.0211	34.42	-14.00	101.7	0.1169	2.298	0.278
0.65	0.951	-0.02819	0.245	0.0305	39.52	-16.34	93.6	0.1075	1.692	0.326
0.60	0.967	-0.02652	0.300	0.0394	44.18	-18.68	84.0	0.0965	1.379	0.375
0.58	0.972	-0.02553	0.297	0.0435	45.88	-19.61	87.5	0.1005	1.270	0.395
0.56	0.978	-0.02475	0.304	0.0468	47.47	-20.54	87.5	0.1005	1.220	0.416
0.54	0.985	-0.02376	0.307	0.0502	48.95	-21.48	88.5	0.1016	1.169	0.436
0.52	0.991	-0.02278	0.323	0.0542	50.32	-22.41	85.3	0.0979	1.106	0.456
0.50	0.997	-0.02159	0.333	0.0591	51.56	-23.35	83.8	0.0962	1.018	0.477
0.48	1.003	-0.02041	0.336	0.0640	52.65	-24.28	83.5	0.0959	0.944	0.498
0.46	1.010	-0.01903	0.327	0.0670	53.59	-25.22	85.8	0.0985	0.937	0.519
0.44	1.017	-0.01765	0.307	0.0709	54.38	-26.15	90.8	0.1043	0.905	0.540
0.42	1.023	-0.01627	0.337	0.0758	54.99	-27.08	81.8	0.0939	0.852	0.562
0.40	1.030	-0.01470	0.348	0.0827	55.43	-28.02	77.8	0.0894	0.763	0.583
0.38	1.036	-0.01293	0.317	0.0912	55.68	-28.95	83.3	0.0957	0.661	0.605
0.36	1.043	-0.01105	0.328	0.0985	55.70	-29.89	77.8	0.0893	0.592	0.627
0.34	1.050	-0.00899	0.338	0.1069	55.49	-30.82	72.0	0.0827	0.519	0.650
0.32	1.056	-0.00682	0.352	0.1138	55.02	-31.76	65.1	0.0748	0.476	0.672
0.30	1.062	-0.00436	0.208	0.1207	54.28	-32.69	102.5	0.1178	0.439	0.695
0.28	1.058	-0.00199	0.270	0.1276	53.24	-33.62	71.7	0.0824	0.406	0.717
0.26	1.072	0.00066	0.259	0.1345	51.90	-34.56	66.0	0.0758	0.376	0.740
0.24	1.077	0.00342	0.208	0.1458	50.24	-35.49	69.8	0.0802	0.308	0.763
0.22	1.082	0.00637	0.142	0.1517	48.22	-36.43	82.1	0.0943	0.295	0.786
0.20	1.084	0.00972	0.025	0.1456	45.82	-37.36	331.4	0.3806	0.408	0.809
0.18	1.083	0.01268	-0.179	0.1404	43.08	-38.30	-27.4	-0.0315	0.482	0.832
0.16	1.077	0.01465	-0.399	0.1431	40.03	-39.23	-2.9	-0.0033	0.494	0.855
0.14	1.066	0.01796	-0.586	0.1582	36.68	-40.16	5.0	0.0057	0.387	0.878
0.12	1.052	0.02139	-0.762	0.1818	32.96	-41.10	9.7	0.0111	0.237	0.900
0.10	1.037	0.02511	-0.969	0.1950	28.79	-42.03	12.7	0.0145	0.181	0.921
0.08	1.015	0.02923	-1.315	0.2126	24.15	-42.97	13.3	0.0153	0.107	0.942
0.06	0.987	0.03354	-2.269	0.2322	19.00	-43.90	10.0	0.0115	0.035	0.961
0.04	0.945	0.03844	-2.957	0.2456	13.28	-44.84	9.7	0.0111	-0.002	0.980
0.02	0.845	0.04373	-9.352	0.2586	6.95	-45.77	3.2	0.0036	-0.036	0.996
0.00	0.000	0.04875	*****	0.2586	-0.00	-46.70	-0.7	-0.0008	-0.017	1.000

TABLE D.1 (Continued)

EDDY DIFFUSIVITIES OF HEAT AND MOMENTUM.

(BASED ON RUN NO. 8)

REYNOLDS NUMBER 33760.
FRICTION FACTOR 0.00570

RAYLEIGH NUMBER 3611
PRANDTL NUMBER 0.0233

UMEAN(AVERAGED) 0.245 FT/SEC
PHYSICAL PROPERTIES WERE EVALUATED AT 86.2 DEG.F.

y/R	U	ϕ	$du/d\eta$	$d\phi/d\eta$	Buoyancy Term	Friction Term	ϵ_M/ν	ϵ_M/Ru^*	ϵ_H/α	q/q_w
1.00	0.898	-0.03229	0.000	0.0000	0.03	0.03	0.0	0.0000	0.000	0.000
0.95	0.899	-0.03189	0.012	0.0078	5.79	-2.40	274.8	0.3048	0.439	0.045
0.90	0.900	-0.03138	0.031	0.0150	11.47	-4.81	216.5	0.2402	0.497	0.090
0.85	0.901	-0.03038	0.055	0.0202	16.94	-7.21	176.1	0.1953	0.669	0.135
0.80	0.905	-0.02928	0.098	0.0210	22.11	-9.62	126.6	0.1404	1.144	0.180
0.75	0.911	-0.02788	0.147	0.0142	26.96	-12.03	100.5	0.1115	2.983	0.226
0.70	0.920	-0.02738	0.193	0.0213	31.77	-14.44	88.6	0.0982	2.196	0.272
0.65	0.931	-0.02779	0.237	0.0302	36.35	-16.84	81.3	0.0902	1.641	0.319
0.60	0.943	-0.02400	0.278	0.0410	40.51	-19.25	75.6	0.0838	1.240	0.367
0.55	0.958	-0.02201	0.325	0.0486	44.02	-21.66	67.8	0.0752	1.141	0.416
0.50	0.976	-0.02002	0.375	0.0446	46.77	-24.07	59.5	0.0660	1.614	0.466
0.45	0.996	-0.01703	0.428	0.0487	49.00	-26.47	51.6	0.0573	1.658	0.518
0.40	1.018	-0.01504	0.470	0.0545	50.59	-28.88	45.2	0.0501	1.623	0.571
0.38	1.028	-0.01405	0.463	0.0639	51.02	-29.84	44.7	0.0496	1.321	0.593
0.36	1.037	-0.01275	0.471	0.0727	51.32	-30.81	42.6	0.0472	1.117	0.615
0.34	1.047	-0.01106	0.477	0.0871	51.46	-31.77	40.3	0.0447	0.830	0.638
0.32	1.056	-0.00927	0.501	0.1006	51.40	-32.73	36.2	0.0402	0.642	0.661
0.30	1.067	-0.00708	0.492	0.1125	51.10	-33.70	34.3	0.0381	0.519	0.684
0.28	1.078	-0.00469	0.452	0.1245	50.52	-34.66	34.0	0.0378	0.420	0.707
0.26	1.085	-0.00210	0.383	0.1364	49.64	-35.62	35.6	0.0395	0.338	0.730
0.24	1.092	0.00068	0.281	0.1454	48.43	-36.58	41.2	0.0457	0.297	0.754
0.22	1.097	0.00387	0.157	0.1543	46.87	-37.55	58.4	0.0648	0.260	0.778
0.20	1.099	0.00685	-0.022	0.1633	44.94	-38.51	-279.9	-0.3105	0.228	0.802
0.18	1.097	0.01024	-0.207	0.1723	42.62	-39.47	-16.0	-0.0177	0.198	0.826
0.16	1.090	0.01383	-0.400	0.1862	39.89	-40.44	0.4	0.0004	0.140	0.849
0.14	1.081	0.01761	-0.593	0.1992	36.72	-41.40	6.9	0.0076	0.095	0.873
0.12	1.067	0.02179	-0.763	0.2061	33.07	-42.36	11.2	0.0124	0.086	0.895
0.10	1.049	0.02617	-0.985	0.2131	29.92	-43.33	13.6	0.0151	0.076	0.917
0.08	1.029	0.03016	-1.276	0.2270	24.28	-44.29	14.7	0.0163	0.033	0.938
0.06	1.001	0.03474	-2.141	0.2494	19.11	-45.25	11.2	0.0124	-0.039	0.959
0.04	0.963	0.04021	-2.785	0.2537	13.33	-46.21	10.8	0.0120	-0.035	0.978
0.02	0.868	0.04609	-3.958	0.2462	6.96	-47.18	3.5	0.0039	0.010	0.995
0.00	0.000	0.04987	*****	0.2564	-0.01	-48.14	-0.7	-0.0008	-0.024	1.000

TABLE D.1 (Continued)

EDDY DIFFUSIVITIES OF HEAT AND MOMENTUM.

(BASED ON RUN NO.11)

REYNOLDS NUMBER 32125. RAYLEIGH NUMBER 1595
 FRICTION FACTOR 0.00578 PRANDTL NUMBER 0.0235
 UMEAN(AVERAGED) 0.235 FT/SEC
 PHYSICAL PROPERTIES WERE EVALUATED AT 83.4 DEG.F.

y/R	U	ϕ	du/dn	$d\phi/dn$	Buoyancy Term	Friction Term	ϵ_M/v	ϵ_H/Ru^*	ϵ_H/a	q/q_w
1.00	0.958	-0.05082	0.000	0.0000	0.05	0.05	0.0	0.0000	0.000	0.000
0.95	0.961	-0.05074	0.060	0.0099	4.05	-2.31	27.9	0.0323	0.216	0.048
0.90	0.966	-0.04974	0.112	0.0174	8.03	-4.63	29.3	0.0339	0.381	0.096
0.85	0.972	-0.04881	0.150	0.0247	11.91	-6.95	31.9	0.0370	0.469	0.145
0.80	0.980	-0.04743	0.189	0.0327	15.55	-9.27	32.7	0.0379	0.485	0.194
0.75	0.991	-0.04573	0.237	0.0438	19.21	-11.59	31.1	0.0361	0.394	0.244
0.70	1.003	-0.04311	0.275	0.0579	22.51	-13.91	30.2	0.0350	0.272	0.295
0.65	1.020	-0.04003	0.302	0.0713	25.45	-16.23	29.5	0.0342	0.214	0.347
0.60	1.035	-0.03579	0.314	0.0823	27.94	-18.55	28.9	0.0335	0.214	0.400
0.55	1.051	-0.03155	0.321	0.0921	29.92	-20.87	27.1	0.0314	0.232	0.454
0.50	1.066	-0.02678	0.351	0.0987	31.34	-23.19	22.2	0.0257	0.289	0.509
0.48	1.074	-0.02462	0.379	0.1006	31.74	-24.12	19.1	0.0221	0.321	0.532
0.46	1.082	-0.02277	0.398	0.1032	32.05	-25.05	16.6	0.0192	0.342	0.554
0.44	1.090	-0.02061	0.366	0.1079	32.27	-25.97	16.2	0.0187	0.338	0.577
0.42	1.098	-0.01846	0.331	0.1186	32.38	-26.90	15.5	0.0180	0.265	0.600
0.40	1.103	-0.01599	0.235	0.1248	32.38	-27.83	18.3	0.0212	0.249	0.623
0.38	1.107	-0.01322	0.116	0.1325	32.26	-28.76	29.1	0.0338	0.220	0.647
0.36	1.108	-0.01075	0.004	0.1333	32.00	-29.68	637.6	0.7386	0.257	0.670
0.34	1.107	-0.00782	-0.129	0.1364	31.62	-30.61	-8.6	-0.0099	0.272	0.694
0.32	1.103	-0.00536	-0.301	0.1187	31.09	-31.54	0.5	0.0006	0.509	0.717
0.30	1.096	-0.00228	-0.368	0.1155	30.46	-32.47	4.5	0.0052	0.601	0.740
0.28	1.087	-0.00165	-0.472	0.1268	29.74	-33.40	6.8	0.0078	0.503	0.762
0.26	1.077	0.00186	-0.529	0.1465	28.91	-34.32	9.2	0.0107	0.338	0.784
0.24	1.065	0.00524	-0.588	0.1763	27.94	-35.25	11.4	0.0132	0.143	0.806
0.22	1.054	0.00891	-0.632	0.1832	26.78	-36.18	13.9	0.0161	0.129	0.827
0.20	1.040	0.01244	-0.680	0.1901	25.43	-37.11	16.2	0.0187	0.115	0.848
0.18	1.027	0.01658	-0.834	0.2008	23.90	-38.04	15.9	0.0185	0.081	0.868
0.16	1.011	0.02041	-0.823	0.2138	22.17	-38.96	19.4	0.0225	0.038	0.888
0.14	0.985	0.02501	-0.846	0.2223	20.22	-39.89	22.2	0.0258	0.019	0.906
0.12	0.978	0.02961	-0.907	0.2315	18.04	-40.82	24.1	0.0279	-0.000	0.925
0.10	0.958	0.03421	-1.104	0.2338	15.62	-41.75	22.7	0.0262	0.008	0.942
0.08	0.933	0.03896	-1.716	0.2361	12.97	-42.68	16.3	0.0189	0.016	0.959
0.06	0.897	0.04371	-2.881	0.2345	10.09	-43.60	10.6	0.0123	0.040	0.975
0.04	0.837	0.04846	-3.827	0.2491	6.98	-44.53	8.8	0.0102	-0.006	0.990
0.02	0.718	0.05291	-10.969	0.2768	3.62	-45.46	2.8	0.0033	-0.095	1.001
0.00	0.000	0.05950	*****	0.2590	-0.00	-46.39	-0.5	-0.0006	-0.034	1.000

TABLE D.1 (Continued)

EDDY DIFFUSIVITIES OF HEAT AND MOMENTUM.

(BASED ON RUN NO.12)

REYNOLDS NUMBER 31385.
FRICTION FACTOR 0.00581

RAYLEIGH NUMBER 1670
PRANDTL NUMBER 0.0238

MEAN(AVERAGED) 0.231 FT/SEC
PHYSICAL PROPERTIES WERE EVALUATED AT 79.2 DEG.F.

y/R	U	ψ	dh/dn	$d\phi/dn$	Buoyancy Term	Friction Term	ϵ_M/ν	ϵ_M/Ru^*	ϵ_H/a	q/q_w
1.00	0.955	-0.04626	0.000	0.0000	0.19	*****	0.0	0.0000	0.000	0.000
0.95	0.957	-0.04626	0.058	0.0082	3.87	-2.27	26.4	0.0312	0.466	0.048
0.90	0.962	-0.04560	0.107	0.0171	7.68	-4.55	28.3	0.0335	0.401	0.096
0.85	0.968	-0.04455	0.146	0.0266	11.39	-6.83	30.3	0.0358	0.358	0.144
0.80	0.976	-0.04284	0.181	0.0339	14.93	-9.10	31.2	0.0369	0.424	0.193
0.75	0.986	-0.04100	0.219	0.0395	18.25	-11.38	30.3	0.0359	0.539	0.243
0.70	0.998	-0.03889	0.248	0.0450	21.32	-13.66	29.8	0.0352	0.631	0.293
0.65	1.012	-0.03666	0.275	0.0502	24.13	-15.94	28.7	0.0340	0.715	0.345
0.60	1.026	-0.03376	0.304	0.0587	26.63	-18.22	26.6	0.0315	0.693	0.397
0.55	1.041	-0.03100	0.335	0.0685	28.78	-20.50	23.7	0.0280	0.644	0.451
0.50	1.059	-0.02705	0.385	0.0828	30.50	-22.78	19.0	0.0225	0.526	0.505
0.48	1.066	-0.02548	0.391	0.0865	31.05	-23.69	17.8	0.0210	0.526	0.528
0.46	1.075	-0.02363	0.406	0.0894	31.51	-24.60	16.0	0.0189	0.538	0.550
0.44	1.083	-0.02179	0.377	0.1000	31.88	-25.51	15.9	0.0188	0.433	0.573
0.42	1.091	-0.01995	0.330	0.1052	32.15	-26.42	16.3	0.0193	0.416	0.596
0.40	1.097	-0.01732	0.279	0.1138	32.30	-27.33	16.8	0.0199	0.361	0.619
0.38	1.102	-0.01535	0.177	0.1230	32.34	-28.25	22.1	0.0262	0.306	0.643
0.36	1.105	-0.01272	0.090	0.1296	32.24	-29.16	33.1	0.0392	0.285	0.666
0.34	1.105	-0.00995	0.015	0.1401	32.02	-30.07	124.7	0.1474	0.230	0.689
0.32	1.104	-0.00706	-0.067	0.1486	31.64	-30.98	-10.4	-0.0123	0.198	0.713
0.30	1.103	-0.00417	-0.105	0.1552	31.10	-31.89	6.6	0.0077	0.185	0.736
0.28	1.099	-0.00075	-0.233	0.1592	30.40	-32.80	9.3	0.0110	0.192	0.759
0.26	1.093	0.00240	-0.347	0.1631	29.53	-33.71	11.0	0.0131	0.178	0.781
0.24	1.085	0.00556	-0.466	0.1644	28.49	-34.63	12.2	0.0144	0.222	0.804
0.22	1.075	0.00898	-0.594	0.1723	27.28	-35.54	12.9	0.0153	0.198	0.826
0.20	1.062	0.01240	-0.733	0.1835	25.89	-36.45	13.4	0.0158	0.155	0.847
0.18	1.045	0.01621	-0.895	0.1973	24.32	-37.36	13.6	0.0161	0.100	0.868
0.16	1.027	0.02029	-1.097	0.2059	22.53	-38.27	13.3	0.0158	0.079	0.889
0.14	1.002	0.02476	-1.301	0.2105	20.52	-39.18	13.3	0.0158	0.073	0.908
0.12	0.973	0.02871	-1.522	0.2125	18.29	-40.10	13.3	0.0158	0.090	0.927
0.10	0.942	0.03305	-1.717	0.2197	15.84	-41.01	13.6	0.0161	0.074	0.944
0.08	0.905	0.03739	-2.018	0.2282	13.17	-41.92	13.2	0.0157	0.051	0.960
0.06	0.865	0.04239	-2.435	0.2368	10.26	-42.83	12.4	0.0146	0.029	0.975
0.04	0.810	0.04686	-2.690	0.2482	7.10	-43.74	12.6	0.0149	-0.003	0.988
0.02	0.746	0.05199	-3.437	0.2601	3.68	-44.65	3.9	0.0046	-0.038	1.000
0.00	0.000	0.05745	*****	0.2516	-0.00	-45.56	-0.6	-0.0007	-0.005	1.000

TABLE D.2

RATIO OF EDDY DIFFUSIVITIES

Run 1 Re = 53 906 Ra = 34 800 Pr = .0241 L/D = 83.6			
y/R	ϵ_M/ν	ϵ_H/α	σ
0.9	3.5	0.35	4.16
0.8	7.0	0.70	4.16
0.7	14.0	1.15	3.41
0.6	42.0	1.25	1.24
0.5	58.0	1.20	0.86
0.4	60.0	1.13	0.78
0.3	52.0	1.0	0.78
0.2	43.5	0.77	0.74
0.1	36.0	0.47	0.54
Run 2 Re = 54 053 Ra = 44 900 Pr = 0.0236 L/D = 83.6			
y/R	ϵ_M/ν	ϵ_H/α	σ
0.9	1.1	60.0	0.78
0.8	1.05	52.5	0.85
0.7	0.8	42.0	0.81
0.6	0.72	33.0	0.93
0.5	0.72	29.0	1.05
0.4	0.72	29.0	1.05
0.3	0.65	31.0	0.89
0.2	0.45	36.0	0.53
0.1	0.20	34.0	0.25
Run 3 Re = 55 062 Ra = 60 900 Pr = 0.0231 L/D = 83.6			
y/R	ϵ_M/ν	ϵ_H/α	σ
0.9	63.0	3.6	2.47
0.8	63.5	2.5	1.7
0.7	66.0	1.5	0.98
0.6	72.0	1.05	0.63
0.5	75.5	0.82	0.47
0.4	76.0	0.68	0.39
0.3	70.0	0.63	0.39
0.2	54.0	0.505	0.40
0.1	30.0	0.25	0.36

TABLE D.2 (Continued)

RATIO OF EDDY DIFFUSIVITIES

Run 4 Re=36 592 Pr=0.0210 Ra=132 000 L/D=83.6				Run 5 Re=35 836 Pr=0.0212 Ra=139 500 L/D=60.6			
y/R	ϵ_M/ν	ϵ_H/α	σ	ϵ_M/ν	ϵ_H/α	σ	Mean σ
0.9	190	2.65	0.66	117	3.2	1.29	0.975
0.8	162	2.9	0.85	122	2.75	1.07	0.96
0.7	140	3.15	1.07	125	2.4	0.91	0.99
0.6	122	2.7	1.05	125	2.12	0.80	0.925
0.5	110	1.95	0.844	123	1.85	0.71	0.78
0.4	92	1.50	0.78	116	1.55	0.63	0.71
0.3	75	1.15	0.73	98	1.23	0.59	0.66
0.2	52	0.75	0.69	47	0.80	0.81	0.75
0.1	28	0.37	0.63	13	0.30	1.09	0.86
Run 7 Re=32 101 Pr=0.0236 Ra=59 800 L/D=83.6				Run 8 Re=33 721 Pr=0.0233 Ra=57 800 L/D=60.6			
y/R	ϵ_M/ν	ϵ_H/α	σ	ϵ_M/ν	ϵ_H/α	σ	Mean σ
0.9	98	2.2	0.95	-	-	-	-
0.8	104	2.51	1.02	125	2.48	0.85	0.94
0.7	101	2.2	0.92	90	2.12	1.01	0.97
0.6	92	1.5	0.69	72	1.55	0.93	0.81
0.5	80	1.15	0.61	59	1.12	0.82	0.72
0.4	68	0.77	0.48	46	0.80	0.75	0.62
0.3	53	0.52	0.42	35	0.55	0.68	0.55
0.2	37	0.35	0.40	24	0.35	0.63	0.52
0.1	12	0.17	0.60	13	0.15	0.50	0.55
Run 11 Re=31 525 Pr=0.0235 Ra=25 100 L/D=83.6				Run 12 Re=30 719 Pr=0.0238 Ra=26 200 L/D=60.6			
y/R	ϵ_M/ν	ϵ_H/α	σ	ϵ_M/ν	ϵ_H/α	σ	Mean σ
0.9	30	0.32	0.45	27	0.30	0.47	0.46
0.8	32	0.46	0.60	30	0.42	0.59	0.60
0.7	31	0.37	0.50	29	0.62	0.88	0.69
0.6	28	0.27	0.40	26	0.67	1.08	0.74
0.5	23	0.22	0.40	18	0.52	1.21	0.81
0.4	12	0.20	0.70	12	0.33	1.15	0.93
0.3	7	0.17	1.02	11	0.18	0.69	0.86
0.2	16	0.15	0.39	14	0.12	0.36	0.46
0.1	22	0.12	0.123	13	0.06	0.19	0.39

TABLE D.3

ISOTHERMAL EDDY DIFFUSIVITIES OF MOMENTUM

RUN 1 -1

Reynolds number = 52 240
 Friction factor = 0.00518
 Mean velocity = 0.402 ft/sec.
 u^* = 0.0205 ft/sec.

y/R	U	dU/d η	.25 f Re η	ϵ_M/v	ϵ_M/Ru^*
0.90	1.216	-0.047	6.77	143	0.107
0.80	1.208	-0.148	13.5	90.2	0.0677
0.70	1.186	-0.219	20.3	91.7	0.0688
0.60	1.153	-0.301	27.1	90.0	0.0675
0.50	1.115	-0.373	33.8	90.5	0.0679
0.40	1.073	-0.439	40.6	91.5	0.0687
0.30	1.025	-0.580	47.4	81.7	0.0613
0.20	0.968	-0.687	54.1	77.7	0.0583
0.18	0.954	-0.768	55.5	71.3	0.0537
0.16	0.936	-0.874	56.8	64.0	0.0480
0.14	0.919	-0.985	58.2	58.1	0.0438
0.12	0.898	-1.076	59.5	54.3	0.0408
0.10	0.874	-1.241	60.9	48.1	0.0361
0.08	0.851	-1.466	62.23	41.4	0.0311

RUN 1 -2

Reynolds number = 31 320
 Friction factor = .00582
 Mean velocity = 0.240 ft/sec.
 u^* = 0.0129 ft/sec.

y/R	U	dU/d η	.25 f Re η	ϵ_M/v	ϵ_M/Ru^*
0.90	1.288	-0.074	4.56	60.6	0.072
0.80	1.214	-0.200	9.11	44.6	0.053
0.70	1.187	-0.271	13.7	49.7	0.059
0.60	1.160	-0.325	18.2	55.0	0.065
0.50	1.123	-0.419	22.8	53.4	0.063
0.40	1.076	-0.489	27.3	54.8	0.065
0.30	1.024	-0.550	31.9	57.0	0.068
0.20	0.968	-0.751	36.5	47.6	0.056
0.18	0.947	-0.837	37.5	43.8	0.052
0.16	0.930	-0.924	38.3	40.5	0.048
0.14	0.912	-0.936	39.2	40.9	0.049
0.12	0.893	-1.042	40.1	37.5	0.044
0.10	0.871	-1.183	41.0	33.7	0.040

APPENDIX E

EXPERIMENTAL RESULTS

The Raleigh number reported in table E.1 is

$$Ra_R = \frac{\rho^2 \beta g C_p AD^4}{16 \mu k}$$

All the other dimensionless parameters and variables are defined in the nomenclature.

TABLE E.1

VELOCITY AND TEMPERATURE PROFILE MEASUREMENTS.

 RUN NUMBER 1

DIMENSIONLESS PARAMETERS

REYNOLDS NUMBER	53906
RALEIGH NUMBER	2171
PECLET NUMBER	1297.
PRANDTL NUMBER	0.02406
NUSSELT NUMBER	10.9
FRICTION FACTOR	0.00510
YANTOVSKII CRITERION	9.7
Z CRITERION	0.00749
L/D	83.59

TEMPERATURES (DEG.F.)

TEST SECTION INLET	64.21
TEST SECTION OUTLET	77.53
INSIDE INSULATION	132.51
OUTSIDE INSULATION	99.80
CENTRE LINE	73.33
WALL (EXTRAPOLATED)	81.11
TMEAN (BY INTEGRATION)	76.59
ARITHMETIC MEAN TEMPERATURE	76.81
TMEAN (BY INTERPOLATION)	76.73

VELOCITIES (FT/SEC.)

U _{MEAN} (BY INTEGRATION)	0.399
FROM ORIFICE METER	0.400
FROM HEAT BALANCE	0.421

HEAT INPUT

KWH	3.55
PERCENTAGE HEAT LOSS	1.22
NETT WALL HEAT FLUX(BTU/HR.SQ.FT)	1591

y/R	v	y*	u*	u/u _c	U	T-T _c	Φ	T*	T/T _m
1.00	0.4348	1395.6	21.6	1.000	1.091	0.00	1.00	10.23	0.957
0.90	0.4371	1256.7	21.7	1.005	1.097	0.11	0.98	10.08	0.959
0.80	0.4412	1117.9	21.9	1.015	1.107	0.36	0.95	9.75	0.962
0.70	0.4418	979.0	21.9	1.016	1.109	0.69	0.91	9.32	0.966
0.60	0.4404	840.1	21.9	1.013	1.105	0.92	0.88	9.02	0.969
0.50	0.4371	701.3	21.7	1.005	1.097	1.78	0.77	7.89	0.981
0.40	0.4322	562.4	21.5	0.994	1.084	2.39	0.69	7.08	0.989
0.30	0.4161	423.5	20.7	0.957	1.044	3.40	0.56	5.75	1.002
0.20	0.3984	284.7	19.8	0.916	1.000	4.36	0.43	4.49	1.014
0.18	0.3893	256.9	19.3	0.895	0.977	4.65	0.40	4.11	1.018
0.16	0.3823	229.1	19.0	0.879	0.959	4.84	0.37	3.86	1.021
0.14	0.3752	201.4	18.6	0.863	0.941	5.03	0.35	3.61	1.023
0.12	0.3679	173.6	18.3	0.846	0.923	5.37	0.30	3.16	1.028
0.10	0.3605	145.8	17.9	0.829	0.905	5.70	0.26	2.73	1.032
0.08	0.3504	118.0	17.4	0.806	0.879	5.93	0.23	2.43	1.035
0.06	0.3399	90.3	16.9	0.782	0.853	6.22	0.20	2.05	1.039
0.04	0.3605	62.5	17.9	0.829	0.905	6.56	0.15	1.60	1.043
0.02	0.3065	34.7	15.2	0.705	0.769	7.13	0.08	0.85	1.051

TABLE E.1 (Continued)

VELOCITY AND TEMPERATURE PROFILE MEASUREMENTS.

 RUN NUMBER 2

DIMENSIONLESS PARAMETERS

TEMPERATURES (DEG.F.)

REYNOLDS NUMBER	54053	TEST SECTION INLET	66.30
RALEIGH NUMBER	2808	TEST SECTION OUTLET	83.52
PECLET NUMBER	1274.	INSIDE INSULATION	154.96
PRANDTL NUMBER	0.02358	OUTSIDE INSULATION	111.66
NUSSELT NUMBER	9.6	CENTRE LINE	77.60
FRICTION FACTOR	0.00508	WALL (EXTRAPOLATED)	88.80
YANTOVSKII CRITERION	14.1	TMEAN (BY INTEGRATION)	82.22
Z CRITERION	0.00958	ARITHMETIC MEAN TEMPERATURE	82.41
L/D	83.59	TMEAN (BY INTERPOLATION)	82.48

VELOCITIES (FT/SEC.)

HEAT INPUT

UMEAN (BY INTEGRATION)	0.395	KWH	4.61
FROM ORIFICE METER	0.398	PERCENTAGE HEAT LOSS	1.27
FROM HEAT BALANCE	0.423	NETT WALL HEAT FLUX(BTU/HR.SQ.FT)	2064

y/R	v	y*	u*	u/u _c	U	T-T _c	Φ	T'	T/T _m
1.00	0.3865	1405.4	19.4	1.000	0.977	0.00	1.00	11.32	0.944
0.90	0.3879	1265.6	19.4	1.004	0.981	0.10	0.99	11.22	0.945
0.80	0.3909	1125.7	19.6	1.012	0.989	0.29	0.97	11.03	0.947
0.70	0.3984	985.9	20.0	1.031	1.008	0.68	0.94	10.64	0.952
0.60	0.4091	846.1	20.5	1.059	1.035	1.35	0.87	9.95	0.960
0.50	0.4183	706.2	21.0	1.082	1.058	2.07	0.81	9.23	0.969
0.40	0.4268	566.4	21.4	1.105	1.079	3.09	0.72	8.19	0.981
0.30	0.4247	426.5	21.3	1.099	1.074	4.35	0.61	6.92	0.997
0.20	0.4075	286.7	20.4	1.054	1.031	6.08	0.45	5.17	1.018
0.18	0.4030	258.7	20.2	1.043	1.019	6.46	0.42	4.78	1.022
0.14	0.3931	202.8	19.7	1.017	0.994	7.14	0.36	4.10	1.031
0.12	0.3862	174.8	19.3	0.999	0.977	7.91	0.29	3.33	1.040
0.10	0.3789	146.8	19.0	0.980	0.958	8.45	0.24	2.78	1.047
0.08	0.3705	118.9	18.6	0.959	0.937	8.77	0.21	2.45	1.051
0.06	0.3531	90.9	17.7	0.914	0.893	8.97	0.19	2.26	1.053
0.04	0.3374	62.9	16.9	0.873	0.853	9.64	0.13	1.58	1.061
0.02	0.3182	35.0	15.9	0.823	0.805	10.31	0.07	0.89	1.069

TABLE E.1 (Continued)

VELOCITY AND TEMPERATURE PROFILE MEASUREMENTS.

RUN NUMBER 3

DIMENSIONLESS PARAMETERS		TEMPERATURES (DEG.F.)	
REYNOLDS NUMBER	55062	TEST SECTION INLET	66.06
RALEIGH NUMBER	3809	TEST SECTION OUTLET	89.41
PECLET NUMBER	1273.	INSIDE INSULATION	185.02
PRANDTL NUMBER	0.02312	OUTSIDE INSULATION	127.53
NUSSELT NUMBER	10.2	CENTRE LINE	82.25
FRICITION FACTOR	0.00507	WALL (EXTRAPOLATED)	96.08
YANTOVSKII CRITERION	17.5	TMEAN (BY INTEGRATION)	87.79
Z CRITERION	0.01293	ARITHMETIC MEAN TEMPERATURE	87.93
L/D	83.59	TMEAN (BY INTERPOLATION)	88.01

VELOCITIES (FT/SEC.)		HEAT INPUT	
UMEAN (BY INTEGRATION)	0.399	KWH	6.17
FROM ORIFICE METER	0.399	PERCENTAGE HEAT LOSS	1.30
FROM HEAT BALANCE	0.418	NETT WALL HEAT FLUX(BTU/HR.SQ.FT)	2762

y/R	v	y*	u*	u/u _c	U	T-T _c	φ	T*	T/T _m
1.00	0.3769	1416.6	18.7	1.000	0.945	0.00	1.00	10.38	0.937
0.90	0.3781	1275.6	18.8	1.003	0.948	0.07	0.99	10.33	0.938
0.80	0.3847	1134.7	19.1	1.021	0.965	0.15	0.98	10.27	0.939
0.70	0.3940	993.7	19.6	1.045	0.988	0.47	0.96	10.02	0.942
0.60	0.4008	852.8	19.9	1.063	1.005	1.13	0.91	9.53	0.950
0.50	0.4128	711.8	20.5	1.095	1.035	1.79	0.87	9.04	0.957
0.40	0.4206	570.9	20.9	1.116	1.054	3.42	0.75	7.82	0.976
0.30	0.4256	429.9	21.2	1.132	1.070	5.23	0.62	6.45	0.996
0.25	0.4252	359.4	21.2	1.131	1.068	5.96	0.56	5.91	1.005
0.20	0.4202	289.0	20.9	1.115	1.054	7.23	0.47	4.96	1.019
0.16	0.4098	232.6	20.4	1.087	1.028	8.17	0.40	4.25	1.030
0.14	0.4043	204.4	20.1	1.073	1.014	8.86	0.35	3.73	1.038
0.10	0.3895	148.0	19.4	1.034	0.977	9.95	0.28	2.91	1.050
0.08	0.3814	119.8	19.0	1.012	0.956	10.53	0.23	2.48	1.057
0.06	0.3706	91.6	18.4	0.983	0.929	11.22	0.18	1.96	1.065
0.04	0.3506	63.4	17.4	0.930	0.879	12.13	0.12	1.28	1.075
0.02	0.3349	35.2	16.7	0.889	0.840	12.86	0.07	0.74	1.083

TABLE E.1 (Continued)

VELOCITY AND TEMPERATURE PROFILE MEASUREMENTS.

 RUN NUMBER 4

DIMENSIONLESS PARAMETERS		TEMPERATURES (DEG.F.)	
-----		-----	
REYNOLDS NUMBER	36592	TEST SECTION INLET	69.53
RALEIGH NUMBER	8254	TEST SECTION OUTLET	119.94
PECLET NUMBER	768.	INSIDE INSULATION	243.53
PRANDTL NUMBER	0.02100	OUTSIDE INSULATION	163.86
NUSSELT NUMBER	12.5	CENTRE LINE	109.98
FRICTION FACTOR	0.00556	WALL (EXTRAPOLATED)	124.04
YANTOVSKII CRITERION	40.5	TMEAN (BY INTEGRATION)	115.16
Z CRITERION	0.04207	ARITHMETIC MEAN TEMPERATURE	114.92
L/D	83.59	TMEAN (BY INTERPOLATION)	116.92

VELOCITIES (FT/SEC.)		HEAT INPUT	
-----		-----	
U _{MEAN} (BY INTEGRATION)	0.252	KWH	8.55
FROM ORIFICE METER	0.249	PERCENTAGE HEAT LOSS	1.39
FROM HEAT BALANCE	0.269	NETT WALL HEAT FLUX(BTU/HR.SQ.FT)	3824

y/R	v	y ⁺	u ⁺	u/u _c	U	T-T _c	φ	T ⁺	T/T _w
1.00	0.2068	987.1	15.5	1.000	0.820	0.00	1.00	5.02	0.955
0.80	0.2100	790.6	15.8	1.016	0.833	0.27	0.98	4.93	0.957
0.70	0.2170	692.4	16.3	1.050	0.861	0.61	0.95	4.81	0.960
0.60	0.2212	594.2	16.6	1.070	0.877	0.94	0.93	4.69	0.963
0.50	0.2344	496.0	17.6	1.133	0.930	1.62	0.88	4.45	0.969
0.40	0.2469	397.8	18.6	1.194	0.979	2.63	0.81	4.09	0.978
0.25	0.2724	250.5	20.5	1.317	1.080	4.82	0.65	3.30	0.997
0.20	0.2768	201.3	20.8	1.339	1.098	6.00	0.57	2.88	1.007
0.16	0.2832	162.1	21.3	1.370	1.124	6.93	0.50	2.55	1.015
0.14	0.2875	142.4	21.6	1.390	1.140	7.41	0.47	2.38	1.019
0.12	0.2902	122.8	21.8	1.403	1.151	8.38	0.40	2.03	1.028
0.10	0.2917	103.1	21.9	1.410	1.157	8.72	0.38	1.91	1.031
0.08	0.2869	83.5	21.6	1.387	1.138	9.66	0.31	1.57	1.039
0.06	0.2760	63.8	20.7	1.335	1.095	10.40	0.26	1.31	1.045
0.04	0.2669	44.2	20.1	1.291	1.059	11.74	0.16	0.83	1.057
0.02	0.2421	24.6	18.2	1.171	0.960	12.72	0.09	0.48	1.065

1
E
1
5
1

TABLE E.1 (Continued)

VELOCITY AND TEMPERATURE PROFILE MEASUREMENTS.

 RUN NUMBER 5

DIMENSIONLESS PARAMETERS		TEMPERATURES (DEG.F.)	
REYNOLDS NUMBER	35836	TEST SECTION INLET	76.72
RALEIGH NUMBER	8705	TEST SECTION OUTLET	116.15
PECLET NUMBER	759.	INSIDE INSULATION	244.00
PRANDTL NUMBER	0.02119	OUTSIDE INSULATION	173.12
NUSSELT NUMBER	13.1	CENTRE LINE	106.98
FRICTION FACTOR	0.00562	WALL (EXTRAPOLATED)	121.23
YANTOVSKII CRITERION	43.6	TMEAN (BY INTEGRATION)	112.56
Z CRITERION	0.06438	ARITHMETIC MEAN TEMPERATURE	112.17
L/D	60.59	TMEAN (BY INTERPOLATION)	112.96

VELOCITIES (FT/SEC.)		HEAT INPUT	
U _{MEAN} (BY INTEGRATION)	0.248	KWH	6.35
FROM ORIFICE METER	0.239	PERCENTAGE HEAT LOSS	1.24
FROM HEAT BALANCE	0.256	NETT WALL HEAT FLUX (BTU/HR.SQ.FT)	3836

y/R	v	y'	u'	u/u _c	U	T-T _c	φ	T'	T/T _w
1.00	0.1974	952.1	15.0	1.000	0.796	0.00	1.00	4.88	0.950
0.80	0.2023	762.7	15.4	1.025	0.815	0.19	0.98	4.81	0.952
0.70	0.2107	667.9	16.0	1.068	0.849	0.67	0.95	4.65	0.956
0.50	0.2308	478.4	17.5	1.170	0.930	1.92	0.86	4.22	0.967
0.30	0.2542	289.0	19.3	1.288	1.025	4.28	0.69	3.41	0.988
0.20	0.2720	194.2	20.7	1.379	1.096	5.96	0.58	2.84	1.003
0.18	0.2774	175.3	21.1	1.406	1.118	6.33	0.55	2.71	1.007
0.16	0.2789	156.3	21.2	1.413	1.124	7.26	0.49	2.39	1.015
0.14	0.2792	137.4	21.2	1.415	1.125	7.74	0.45	2.23	1.019
0.12	0.2794	118.4	21.2	1.416	1.126	8.19	0.42	2.07	1.023
0.10	0.2784	99.5	21.2	1.411	1.122	8.94	0.37	1.82	1.030
0.08	0.2775	80.5	21.1	1.406	1.118	9.98	0.29	1.46	1.039
0.06	0.2739	61.6	20.8	1.388	1.104	10.84	0.23	1.17	1.047
0.04	0.2703	42.6	20.6	1.370	1.089	11.86	0.16	0.82	1.056
0.02	0.2562	23.7	19.5	1.299	1.033	13.14	0.07	0.38	1.067

TABLE E.1 (Continued)

VELOCITY AND TEMPERATURE PROFILE MEASUREMENTS.

RUN NUMBER 6

DIMENSIONLESS PARAMETERS					TEMPERATURES (DEG.F.)				
REYNOLDS NUMBER	35157	TEST SECTION INLET	75.83						
RALEIGH NUMBER	8758	TEST SECTION OUTLET	100.50						
PECLET NUMBER	788.	INSIDE INSULATION	212.56						
PRANDTL NUMBER	0.02241	OUTSIDE INSULATION	161.92						
NUSSELT NUMBER	13.4	CENTRE LINE	91.73						
FRICTION FACTOR	0.00567	WALL (EXTRAPOLATED)	105.51						
YANTOVSKII CRITERION	42.1	TMEAN (BY INTEGRATION)	96.77						
Z CRITERION	0.11453	ARITHMETIC MEAN TEMPERATURE	96.42						
L/D	35.57	TMEAN (BY INTERPOLATION)	97.29						

VELOCITIES (FT/SEC.)				HEAT INPUT	
UMEAN (BY INTEGRATION)	0.251	KWH	3.94		
FROM ORIFICE METER	0.237	PERCENTAGE HEAT LOSS	0.97		
FROM HEAT BALANCE	0.253	NETT WALL HEAT FLUX (BTU/HR.SQ.FT)	3842		

y/R	v	y*	u*	u/u _c	U	T-T _c	Φ	T*	T/T _m
1.00	0.1958	926.3	14.7	1.000	0.781	0.00	1.00	4.71	0.948
0.90	0.1978	834.2	14.8	1.011	0.790	0.04	0.99	4.70	0.948
0.80	0.2066	742.0	15.5	1.056	0.825	0.18	0.98	4.65	0.950
0.70	0.2139	649.8	16.0	1.093	0.854	0.36	0.97	4.59	0.952
0.50	0.2343	465.5	17.6	1.197	0.935	1.45	0.89	4.21	0.963
0.30	0.2571	281.1	19.3	1.314	1.026	3.63	0.73	3.47	0.985
0.20	0.2706	189.0	20.3	1.383	1.080	5.74	0.58	2.75	1.007
0.18	0.2762	170.5	20.7	1.411	1.102	6.21	0.54	2.59	1.012
0.16	0.2826	152.1	21.2	1.444	1.128	6.54	0.52	2.48	1.016
0.14	0.2844	133.7	21.3	1.453	1.135	7.15	0.48	2.26	1.022
0.12	0.2849	115.2	21.4	1.456	1.137	7.63	0.44	2.10	1.027
0.10	0.2852	96.8	21.4	1.457	1.138	8.50	0.38	1.81	1.036
0.08	0.2842	78.3	21.3	1.452	1.134	9.20	0.33	1.56	1.043
0.06	0.2814	59.9	21.1	1.438	1.123	10.02	0.27	1.29	1.051
0.04	0.2735	41.5	20.5	1.397	1.091	11.28	0.18	0.85	1.065
0.02	0.2562	23.0	19.2	1.309	1.023	12.44	0.09	0.46	1.077

- E - 7 -

TABLE E.1 (Continued)

VELOCITY AND TEMPERATURE PROFILE MEASUREMENTS.

 RUN NUMBER 7.

DIMENSIONLESS PARAMETERS		TEMPERATURES (DEG.F.)	
-----		-----	
REYNOLDS NUMBER	32101	TEST SECTION INLET	60.75
RALEIGH NUMBER	3734	TEST SECTION OUTLET	83.65
PECLET NUMBER	757.	INSIDE INSULATION	135.02
PRANDTL NUMBER	0.02360	OUTSIDE INSULATION	101.62
NUSSELT NUMBER	10.2	CENTRE LINE	78.83
FRICTION FACTOR	0.00575	WALL (EXTRAPOLATED)	86.82
YANTOVSKII CRITERION	25.9	TMEAN (BY INTEGRATION)	82.00
Z CRITERION	0.02190	ARITHMETIC MEAN TEMPERATURE	82.02
L/D	83.59	TMEAN (BY INTERPOLATION)	82.28

VELOCITIES (FT/SEC.)		HEAT INPUT	
-----		-----	
UMEAN (BY INTEGRATION)	0.235	KWH	3.56
FROM ORIFICE METER	0.232	PERCENTAGE HEAT LOSS	1.24
FROM HEAT BALANCE	0.246	NETT WALL HEAT FLUX(BTU/HR.SQ.FT)	1595

y/R	v	y*	u*	u/u _c	U	T-T _c	Φ	T*	T/T _w
1.00	0.2144	875.0	17.0	1.000	0.913	0.00	1.00	6.47	0.961
0.90	0.2155	787.9	17.1	1.005	0.917	0.03	0.99	6.44	0.962
0.80	0.2177	700.9	17.3	1.015	0.927	0.09	0.98	6.40	0.962
0.70	0.2209	613.8	17.5	1.031	0.940	0.26	0.96	6.25	0.965
0.60	0.2272	526.7	18.0	1.060	0.967	0.51	0.93	6.05	0.968
0.40	0.2432	352.6	19.3	1.135	1.035	1.74	0.78	5.06	0.983
0.30	0.2490	265.5	19.8	1.162	1.060	2.78	0.65	4.21	0.995
0.25	0.2527	222.0	20.1	1.179	1.076	3.42	0.57	3.69	1.003
0.20	0.2546	173.5	20.2	1.188	1.084	4.14	0.48	3.11	1.012
0.18	0.2546	161.1	20.2	1.188	1.084	4.49	0.43	2.83	1.016
0.16	0.2528	143.7	20.1	1.179	1.076	4.65	0.41	2.70	1.018
0.14	0.2499	126.2	19.8	1.166	1.064	4.92	0.38	2.48	1.021
0.12	0.2471	108.8	19.6	1.153	1.052	5.37	0.32	2.12	1.027
0.08	0.2374	74.0	18.8	1.108	1.011	6.18	0.22	1.46	1.037
0.06	0.2314	56.6	18.4	1.079	0.985	6.37	0.20	1.31	1.039
0.04	0.2216	39.2	17.6	1.034	0.943	6.95	0.13	0.84	1.046
0.02	0.1990	21.8	15.8	0.928	0.847	7.55	0.05	0.35	1.053

1
m
1
0
1

TABLE E.1 (Continued)

VELOCITY AND TEMPERATURE PROFILE MEASUREMENTS.

 RUN NUMBER 8

DIMENSIONLESS PARAMETERS		TEMPERATURES (DEG.F.)	
-----		-----	
REYNOLDS NUMBER	33721	TEST SECTION INLET	71.30
RALEIGH NUMBER	3611	TEST SECTION OUTLET	87.71
PECLET NUMBER	784.	INSIDE INSULATION	140.65
PRANDTL NUMBER	0.02326	OUTSIDE INSULATION	110.08
NUSSELT NUMBER	10.1	CENTRE LINE	82.99
FRICTION FACTOR	0.00570	WALL (EXTRAPOLATED)	91.01
YANTOVSKII CRITERION	24.6	TMEAN (BY INTEGRATION)	86.16
Z CRITERION	0.02823	ARITHMETIC MEAN TEMPERATURE	86.14
L/D	60.59	TMEAN (BY INTERPOLATION)	86.39

VELOCITIES (FT/SEC.)		HEAT INPUT	
-----		-----	
UMEAN (BY INTEGRATION)	0.245	KWH	2.63
FROM ORIFICE METER	0.237	PERCENTAGE HEAT LOSS	1.15
FROM HEAT BALANCE	0.254	NETT WALL HEAT FLUX (BTU/HR.SQ.FT)	1590

y/R	v	y ⁺	u ⁺	u/u _c	U	T-T _c	Φ	T ⁺	T/T _w
1.00	0.2201	906.1	16.8	1.000	0.899	0.00	1.00	6.66	0.963
0.90	0.2205	815.9	16.9	1.002	0.900	0.09	0.98	6.59	0.964
0.80	0.2212	725.8	16.9	1.005	0.903	0.33	0.95	6.39	0.967
0.60	0.2311	545.4	17.7	1.050	0.944	0.81	0.89	5.99	0.973
0.40	0.2493	365.1	19.1	1.133	1.018	1.66	0.79	5.28	0.983
0.30	0.2613	275.0	20.0	1.187	1.067	2.36	0.70	4.70	0.991
0.25	0.2658	229.9	20.3	1.208	1.085	3.08	0.61	4.10	0.999
0.20	0.2694	184.8	20.6	1.224	1.100	3.82	0.52	3.49	1.008
0.18	0.2687	166.8	20.5	1.221	1.097	4.21	0.47	3.16	1.012
0.16	0.2667	148.8	20.4	1.212	1.089	4.60	0.42	2.84	1.017
0.12	0.2623	112.7	20.0	1.192	1.071	5.28	0.34	2.28	1.025
0.10	0.2568	94.7	19.6	1.167	1.048	5.76	0.28	1.87	1.030
0.08	0.2522	76.6	19.3	1.146	1.030	6.09	0.24	1.60	1.034
0.06	0.2436	58.6	18.6	1.107	0.995	6.44	0.19	1.31	1.038
0.04	0.2255	40.6	17.2	1.025	0.921	7.16	0.10	0.71	1.046
0.02	0.2148	22.5	16.4	0.976	0.877	7.77	0.03	0.21	1.053

TABLE E.1 (Continued)

VELOCITY AND TEMPERATURE PROFILE MEASUREMENTS.

 RUN NUMBER 9

DIMENSIONLESS PARAMETERS		TEMPERATURES (DEG.F.)	
-----		-----	
REYNOLDS NUMBER	33993	TEST SECTION INLET	70.45
RALEIGH NUMBER	3754	TEST SECTION OUTLET	81.04
PECLET NUMBER	809.	INSIDE INSULATION	134.82
PRANDTL NUMBER	0.02381	OUTSIDE INSULATION	104.99
NUSSELT NUMBER	10.3	CENTRE LINE	76.02
FRICTION FACTOR	0.00576	WALL (EXTRAPOLATED)	84.36
YANTOVSKII CRITERION	26.1	TMEAN (BY INTEGRATION)	79.45
Z CRITERION	0.05198	ARITHMETIC MEAN TEMPERATURE	79.39
L/D	35.57	TMEAN (BY INTERPOLATION)	79.66

VELOCITIES (FT/SEC.)		HEAT INPUT	
-----		-----	
U _{MEAN} (BY INTEGRATION)	0.250	KWH	1.61
FROM ORIFICE METER	0.237	PERCENTAGE HEAT LOSS	1.13
FROM HEAT BALANCE	0.240	NETT WALL HEAT FLUX(BTU/HR.SQ.FT)	1569

y/R	v	y ⁺	u ⁺	u/u _c	U	T-T _c	Φ	T ⁺	T/T _w
1.00	0.2033	887.6	15.2	1.000	0.814	0.00	1.00	6.88	0.957
0.80	0.2107	711.0	15.7	1.037	0.843	0.17	0.97	6.74	0.959
0.70	0.2190	622.6	16.4	1.077	0.876	0.38	0.95	6.56	0.962
0.50	0.2450	446.0	18.3	1.205	0.980	1.25	0.85	5.85	0.972
0.40	0.2578	357.7	19.3	1.268	1.032	2.01	0.75	5.22	0.982
0.30	0.2692	269.4	20.1	1.324	1.077	2.78	0.66	4.59	0.992
0.25	0.2736	225.2	20.4	1.346	1.095	3.45	0.58	4.04	1.000
0.20	0.2752	181.1	20.6	1.354	1.101	4.12	0.50	3.48	1.009
0.18	0.2746	163.4	20.5	1.351	1.099	4.41	0.47	3.24	1.012
0.16	0.2728	145.7	20.4	1.342	1.092	4.83	0.42	2.90	1.018
0.14	0.2703	128.1	20.2	1.330	1.082	4.99	0.40	2.77	1.020
0.10	0.2640	92.7	19.7	1.299	1.056	5.95	0.28	1.98	1.032
0.08	0.2576	75.1	19.3	1.267	1.031	6.43	0.23	1.59	1.038
0.06	0.2521	57.4	18.8	1.240	1.009	6.90	0.17	1.19	1.044
0.04	0.2426	39.7	18.1	1.193	0.971	7.25	0.13	0.91	1.048
0.02	0.2275	22.1	17.0	1.119	0.910	7.66	0.08	0.57	1.053

E 10

TABLE E.1 (Continued)

VELOCITY AND TEMPERATURE PROFILE MEASUREMENTS.

 RUN NUMBER 10

DIMENSIONLESS PARAMETERS		TEMPERATURES (DEG.F.)	
-----		-----	
REYNOLDS NUMBER	32469	TEST SECTION INLET	69.09
RALEIGH NUMBER	3919	TEST SECTION OUTLET	75.08
PECLET NUMBER	790.	INSIDE INSULATION	134.82
PRANDTL NUMBER	0.02433	OUTSIDE INSULATION	104.99
NUSSELT NUMBER	11.8	CENTRE LINE	70.58
FRICTION FACTOR	0.00575	WALL (EXTRAPOLATED)	78.17
YANTOVSKII CRITERION	23.4	TMEAN (BY INTEGRATION)	73.64
Z CRITERION	0.11455	ARITHMETIC MEAN TEMPERATURE	73.67
L/D	16.77	TMEAN (BY INTERPOLATION)	73.64

VELOCITIES (FT/SEC.)		HEAT INPUT	
-----		-----	
UMEAN (BY INTEGRATION)	0.241	KWH	0.95
FROM ORIFICE METER	0.237	PERCENTAGE HEAT LOSS	1.04
FROM HEAT BALANCE	0.249	NETT WALL HEAT FLUX(BTU/HR.SQ.FT)	1703

y/R	v	y ⁺	u ⁺	u/u _c	U	T-T _c	Φ	T ⁺	T/T _m
1.00	0.2274	878.2	17.6	1.000	0.942	0.00	1.00	5.78	0.960
0.80	0.2304	703.4	17.8	1.014	0.955	0.04	0.99	5.75	0.960
0.60	0.2365	528.6	18.3	1.040	0.980	0.59	0.92	5.33	0.968
0.50	0.2434	441.3	18.8	1.071	1.008	0.97	0.87	5.03	0.973
0.40	0.2491	353.9	19.2	1.096	1.032	1.82	0.75	4.37	0.985
0.30	0.2548	266.5	19.7	1.121	1.055	2.77	0.62	3.64	0.997
0.25	0.2575	222.8	19.9	1.133	1.067	3.25	0.56	3.27	1.004
0.20	0.2583	179.1	19.9	1.136	1.070	3.82	0.49	2.83	1.012
0.18	0.2570	161.6	19.9	1.131	1.065	4.10	0.45	2.61	1.016
0.16	0.2553	144.2	19.7	1.123	1.057	4.33	0.42	2.44	1.019
0.14	0.2529	126.7	19.5	1.113	1.048	4.48	0.40	2.32	1.021
0.10	0.2463	91.7	19.0	1.084	1.020	5.15	0.31	1.81	1.030
0.08	0.2395	74.3	18.5	1.054	0.992	5.53	0.26	1.51	1.035
0.06	0.2305	56.8	17.8	1.014	0.955	5.81	0.22	1.29	1.039
0.04	0.2232	39.3	17.2	0.982	0.925	6.38	0.14	0.85	1.046
0.02	0.2091	21.8	16.1	0.920	0.856	6.95	0.07	0.41	1.054

TABLE E.1 (Continued)

VELOCITY AND TEMPERATURE PROFILE MEASUREMENTS.

RUN NUMBER 11

DIMENSIONLESS PARAMETERS		TEMPERATURES (DEG.F.)	
REYNOLDS NUMBER	31525	TEST SECTION INLET	74.25
RALEIGH NUMBER	1595	TEST SECTION OUTLET	84.03
PECTLET NUMBER	740.	INSIDE INSULATION	103.45
PRANDTL NUMBER	0.02348	OUTSIDE INSULATION	80.03
NUSSELT NUMBER	8.1	CENTRE LINE	81.37
FRICTION FACTOR	0.00576	WALL (EXTRAPOLATED)	85.94
YANTOVSKII CRITERION	15.2	TMEAN (BY INTEGRATION)	83.39
Z CRITERION	0.00941	ARITHMETIC MEAN TEMPERATURE	83.47
L/D	83.59	TMEAN (BY INTERPOLATION)	83.45

VELOCITIES (FT/SEC.)		HEAT INPUT	
UMEAN (BY INTEGRATION)	0.230	KWH	1.50
FROM ORIFICE METER	0.232	PERCENTAGE HEAT LOSS	1.98
FROM HEAT BALANCE	0.241	NETT WALL HEAT FLUX(BTU/HR.SQ.FT)	669

y/R	v	y*	u*	u/u _c	U	T-T _c	ϕ	T*	T/T _b
1.00	0.2205	867.6	17.8	1.000	0.958	0.00	1.00	8.76	0.976
0.80	0.2254	695.0	18.2	1.022	0.980	0.16	0.96	8.45	0.978
0.70	0.2314	608.6	18.7	1.050	1.006	0.29	0.93	8.20	0.979
0.60	0.2382	522.3	19.3	1.080	1.035	0.64	0.86	7.53	0.983
0.50	0.2452	436.0	19.8	1.112	1.066	1.05	0.77	6.74	0.988
0.45	0.2501	392.8	20.2	1.134	1.087	1.24	0.72	6.37	0.991
0.40	0.2540	349.6	20.5	1.152	1.104	1.40	0.69	6.06	0.993
0.35	0.2540	306.5	20.5	1.152	1.104	1.76	0.61	5.39	0.997
0.30	0.2529	263.3	20.4	1.147	1.099	2.04	0.55	4.84	1.000
0.25	0.2463	220.1	19.9	1.117	1.070	2.25	0.50	4.44	1.003
0.20	0.2384	177.0	19.3	1.081	1.036	2.60	0.43	3.77	1.007
0.15	0.2303	133.8	18.6	1.044	1.001	3.01	0.34	2.98	1.012
0.10	0.2193	90.5	17.7	0.995	0.953	3.62	0.20	1.82	1.019
0.05	0.2054	56.1	16.7	0.936	0.897	3.91	0.14	1.27	1.023
0.05	0.1997	47.5	16.1	0.906	0.868	3.97	0.13	1.16	1.023
0.03	0.1822	30.2	14.7	0.827	0.792	4.21	0.07	0.68	1.026
0.02	0.1652	21.6	13.4	0.749	0.718	4.35	0.04	0.45	1.028

TABLE E.1 (Continued)

VELOCITY AND TEMPERATURE PROFILE MEASUREMENTS.

RUN NUMBER 12

DIMENSIONLESS PARAMETERS		TEMPERATURES (DEG.F.)	
REYNOLDS NUMBER	30719	TEST SECTION INLET	72.92
RALEIGH NUMBER	1637	TEST SECTION OUTLET	80.36
PECLET NUMBER	732.	INSIDE INSULATION	99.98
PRANDTL NUMBER	0.02384	OUTSIDE INSULATION	77.92
NUSSELT NUMBER	8.3	CENTRE LINE	77.25
FRICTION FACTOR	0.00578	WALL (EXTRAPOLATED)	81.71
YANTOVSKII CRITERION	15.0	TMEAN (BY INTEGRATION)	79.15
Z CRITERION	0.01349	ARITHMETIC MEAN TEMPERATURE	79.24
L/D	60.59	TMEAN (BY INTERPOLATION)	79.76

VELOCITIES (FT/SEC.)		HEAT INPUT	
UMEAN (BY INTEGRATION)	0.226	KWH	1.14
FROM ORIFICE METER	0.232	PERCENTAGE HEAT LOSS	1.82
FROM HEAT BALANCE	0.239	NETT WALL HEAT FLUX (BTU/HR.SQ.FT)	682

y/R	v	y ⁺	u ⁺	u/u _c	U	T-T _c	Φ	T ⁺	T/T _m
1.00	0.2159	855.1	17.7	1.000	0.955	0.00	1.00	8.37	0.976
0.80	0.2206	684.9	18.1	1.022	0.977	0.14	0.96	8.11	0.978
0.60	0.2320	514.7	19.1	1.075	1.027	0.54	0.88	7.36	0.983
0.50	0.2394	429.7	19.7	1.109	1.060	0.83	0.81	6.82	0.986
0.45	0.2440	387.1	20.1	1.130	1.080	0.96	0.78	6.57	0.988
0.40	0.2480	344.6	20.4	1.149	1.097	1.24	0.72	6.04	0.992
0.35	0.2497	302.0	20.5	1.157	1.105	1.58	0.64	5.40	0.996
0.30	0.2492	259.5	20.5	1.155	1.103	1.92	0.56	4.76	1.000
0.25	0.2464	217.0	20.3	1.142	1.091	2.21	0.50	4.23	1.004
0.20	0.2399	174.4	19.7	1.112	1.062	2.49	0.44	3.70	1.007
0.15	0.2292	131.9	18.8	1.062	1.014	2.94	0.34	2.85	1.013
0.10	0.2128	89.3	17.5	0.986	0.942	3.39	0.23	2.00	1.019
0.08	0.2046	72.3	16.8	0.948	0.906	3.59	0.19	1.63	1.021
0.06	0.1949	55.3	16.0	0.903	0.862	3.85	0.13	1.15	1.025
0.04	0.1830	38.3	15.0	0.848	0.810	3.96	0.11	0.94	1.026
0.02	0.1684	21.3	13.8	0.780	0.745	4.21	0.05	0.46	1.029

TABLE E.1 (Continued)

VELOCITY AND TEMPERATURE PROFILE MEASUREMENTS.

RUN NUMBER 13

DIMENSIONLESS PARAMETERS		TEMPERATURES (DEG. F.)	
REYNOLDS NUMBER	30629	TEST SECTION INLET	74.09
RALEIGH NUMBER	1644	TEST SECTION OUTLET	78.73
PECLET NUMBER	734.	INSIDE INSULATION	99.68
PRANDTL NUMBER	0.02396	OUTSIDE INSULATION	81.03
NUSSELT NUMBER	8.0	CENTRE LINE	75.75
FRICTION FACTOR	0.00580	WALL (EXTRAPOLATED)	80.42
YANTOVSKII CRITERION	16.0	TMEAN (BY INTEGRATION)	77.77
Z CRITERION	0.02344	ARITHMETIC MEAN TEMPERATURE	77.89
L/D	35.57	TMEAN (BY INTERPOLATION)	78.12

VELOCITIES (FT/SEC.)		HEAT INPUT	
UMEAN (BY INTEGRATION)	0.226	KWH	0.70
FROM ORIFICE METER	0.230	PERCENTAGE HEAT LOSS	1.57
FROM HEAT BALANCE	0.236	NETT WALL HEAT FLUX (BTU/HR.SQ.FT)	675

y/R	v	y ⁺	u ⁺	u/u _c	U	T-T _c	Φ	T ⁺	T/T _m
1.00	0.2258	846.5	18.5	1.000	0.999	0.00	1.00	8.77	0.974
0.80	0.2291	678.1	18.3	1.015	1.014	0.22	0.95	8.35	0.977
0.60	0.2385	509.6	19.6	1.057	1.056	0.62	0.86	7.62	0.982
0.50	0.2419	425.4	19.9	1.072	1.071	0.95	0.79	6.98	0.986
0.45	0.2451	383.2	20.1	1.086	1.085	1.15	0.75	6.62	0.989
0.40	0.2460	341.1	20.2	1.090	1.089	1.29	0.72	6.35	0.991
0.35	0.2475	299.0	20.3	1.097	1.096	1.68	0.64	5.62	0.996
0.30	0.2453	256.9	20.1	1.087	1.086	1.94	0.58	5.14	0.999
0.25	0.2408	214.8	19.8	1.067	1.066	2.41	0.48	4.25	1.005
0.20	0.2362	172.7	19.4	1.047	1.046	2.69	0.42	3.72	1.009
0.15	0.2256	130.6	18.5	0.999	0.998	3.17	0.32	2.83	1.015
0.10	0.2169	88.4	17.8	0.961	0.960	3.53	0.24	2.14	1.019
0.08	0.2092	71.6	17.2	0.927	0.926	3.81	0.18	1.62	1.023
0.05	0.1934	54.7	15.9	0.857	0.856	4.09	0.12	1.09	1.027
0.04	0.1871	37.9	15.4	0.829	0.828	4.21	0.10	0.88	1.028
0.02	0.1586	21.1	13.0	0.703	0.702	4.41	0.05	0.50	1.031

E-14

TABLE E.1. (Continued)

VELOCITY AND TEMPERATURE PROFILE MEASUREMENTS.

 RUN NUMBER 14

DIMENSIONLESS PARAMETERS		TEMPERATURES (DEG.F.)	
-----		-----	
REYNOLDS NUMBER	31128	TEST SECTION INLET	73.49
RALEIGH NUMBER	1747	TEST SECTION OUTLET	76.16
PECLET NUMBER	755.	INSIDE INSULATION	96.51
PRANDTL NUMBER	0.02424	OUTSIDE INSULATION-	77.99
NUSSELT NUMBER	9.5	CENTRE LINE	73.45
FRICTION FACTOR	0.00580	WALL (EXTRAPOLATED)	77.04
YANTOVSKII CRITERION	12.0	TMEAN (BY INTEGRATION)	74.64
Z CRITERION	0.05269	ARITHMETIC MEAN TEMPERATURE	74.75
L/D	16.77	TMEAN (BY INTERPOLATION)	75.51

VELOCITIES (FT/SEC.)		HEAT INPUT	
-----		-----	
UMEAN (BY INTEGRATION)	0.231	KWH	0.40
FROM ORIFICE METER	0.232	PERCENTAGE HEAT LOSS	1.45
FROM HEAT BALANCE	0.237	NETT WALL HEAT FLUX(BTU/HR.SQ.FT)	723

y/R	v	y ⁺	u ⁺	u/u _c	U	T-T _c	Φ	T ⁺	T/T _m
1.00	0.2560	851.9	20.6	1.000	1.108	0.00	1.00	6.35	0.984
0.90	0.2556	767.1	20.5	0.999	1.106	0.04	0.98	6.28	0.985
0.80	0.2549	682.3	20.5	0.996	1.104	0.11	0.96	6.16	0.986
0.70	0.2547	597.6	20.5	0.995	1.103	0.20	0.94	6.00	0.987
0.60	0.2539	512.8	20.4	0.992	1.099	0.33	0.90	5.77	0.989
0.50	0.2517	428.0	20.2	0.983	1.090	0.49	0.86	5.48	0.991
0.40	0.2484	343.3	20.0	0.971	1.075	0.77	0.78	4.99	0.994
0.30	0.2429	258.5	19.5	0.949	1.051	1.10	0.69	4.41	0.999
0.20	0.2325	173.8	18.7	0.908	1.007	1.48	0.58	3.73	1.004
0.15	0.2266	131.4	18.2	0.885	0.981	1.81	0.49	3.15	1.008
0.10	0.2154	89.0	17.3	0.842	0.933	2.20	0.38	2.47	1.014
0.08	0.2100	72.0	16.9	0.821	0.909	2.39	0.33	2.13	1.016
0.06	0.2010	55.1	16.2	0.785	0.870	2.64	0.26	1.70	1.019
0.04	0.1898	38.1	15.3	0.742	0.822	3.02	0.16	1.02	1.025
0.02	0.1584	21.2	12.7	0.619	0.686	3.35	0.06	0.44	1.029

TABLE E.2

ISOTHERMAL VELOCITY PROFILE 1 - 1

Reynolds number = 52 240
Friction factor = 0.00518
 u^* = 0.0205 ft/sec.
Integrated mean velocity = 0.402 ft/sec.
Orifice meter mean velocity = 0.402 ft/sec.
Mercury temperature = 56.54^oF

y/R	v	U	u/u_c	y^+	u^+
1.0	0.488	1.21	1.0	1354	23.80
0.9	0.487	1.21	0.998	1218	23.76
0.8	0.484	1.20	0.992	1083	23.61
0.7	0.476	1.18	0.975	948	23.22
0.6	0.458	1.24	0.994	812	22.34
0.5	0.446	1.11	0.914	677	21.76
0.4	0.429	1.07	0.879	541	20.93
0.3	0.411	1.02	0.842	406	20.05
0.2	0.388	0.965	0.795	271	18.93
0.18	0.380	0.945	0.779	244	18.54
0.16	0.376	0.935	0.770	217	18.34
0.14	0.365	0.908	0.748	190	17.80
0.12	0.360	0.896	0.738	162	17.56
0.10	0.351	0.873	0.719	135	17.12
0.08	0.341	0.848	0.699	108	16.63
0.06	0.329	0.818	0.674	81.2	16.05
0.04	0.311	0.774	0.637	54.1	15.17
0.02	0.286	0.711	0.586	27.1	13.95

TABLE E.2 (continued)

ISOTHERMAL VELOCITY PROFILE 1 - 2

Reynolds number = 31 320
Friction factor = 0.00582
 u^* = 0.0129 ft/sec.
Integrated mean velocity = 0.240 ft/sec.
Orifice meter mean velocity = 0.240 ft/sec.
Mercury temperature = 59°F

y/R	v	U	u/u_c	y^+	u^+
1.0	0.295	1.23	1.00	857	22.87
0.9	0.294	1.23	0.997	771	22.79
0.8	0.290	1.21	0.983	686	22.48
0.7	0.285	1.19	0.966	600	22.09
0.6	0.278	1.16	0.942	514	21.55
0.5	0.269	1.12	0.912	428	20.85
0.4	0.258	1.08	0.875	343	20.00
0.3	0.245	1.02	0.831	257	18.99
0.2	0.229	0.954	0.776	171	17.75
0.18	0.226	0.942	0.766	154	17.52
0.16	0.223	0.929	0.756	137	17.29
0.14	0.218	0.908	0.739	120	16.90
0.12	0.215	0.896	0.729	103	16.67
0.10	0.209	0.871	0.708	85.7	16.20
0.08	0.200	0.833	0.678	68.6	15.50
0.06	0.192	0.800	0.651	51.4	14.88
0.04	0.185	0.771	0.627	34.3	14.34
0.02	0.173	0.721	0.586	17.1	13.41