In presenting the dissertation as a partial fulfillment of the requirements for an advanced degree from the Georgia Institute of Technology, I agree that the Library of the Institution shall make it available for inspection and circulation in accordance with its regulations governing materials of this type. I agree that permission to copy from, or to publish from, this dissertation may be granted by the professor under whose direction it was written, or, in his absence, by the dean of the Graduate Division when such copying or publication is solely for scholarly purposes and does not involve potential financial gain. It is understood that any copying from, or publication of, this dissertation which involves potential financial gain will not be allowed without written permission.

MEASUREMENT OF VELOCITY PROFILES

WITH A HOT-WIRE ANEMOMETER

A THESIS

Presented to

The Faculty of the Graduate Division

by

David William Crawford

In Partial Fulfillment

of the Requirements for the Degree

Master of Science in Mechanical Engineering

Georgia Institute of Technology

October, 1962

MEASUREMENT OF VELOCITY PROFILES

WITH A HOT-WIRE ANEMOMETER

Approved:

Charles W. Gorton

T. E. Sunderland

F. G. Mayer

Date Approved by Chairman: Nov. 12, 1962

ACKNOWLEDGMENTS

I express my deepest appreciation to Dr. Charles W. Gorton for suggesting this problem and for giving most generously of his time and knowledge. My gratitude is also extended to Dr. J. E. Sunderland and Dr. F. G. Mayer for their kind assistance as members of my reading committee.

Also, I extend my thanks to the personnel of the Mechanical Engineering Labs, especially Mr. Lou Cavalli, who were invaluable in helping me construct and assemble my apparatus.

Finally, I give my love and thanks to my wife, Joan, who during the course of this thesis, gave birth to our first child, typed the rough draft, and was a constant source of inspiration.

TABLE OF CONTENTS

TABLE OF CONTENTS (Continued)

LIST OF ILLUSTRATIONS

LIST OF TABLES

SUMMARY

This investigation was conducted to design and construct a relatively simple apparatus for calibrating a hot-wire anemometer at very low velocities. In addition, the feasibility of using a hot-wire anemometer to measure velocity profiles in natural-convection, laminar boundary layers was examined.

The calibration was accomplished by placing the hot-wire at the centerline of a tube in which air was in fully-developed, laminar flow. The volume flow rate of the air was measured by a wet-gas meter, and corrected to conditions at the hot-wire position. The area of the tube was determined and the centerline velocity calculated. This velocity was used as the reference for calibration.

The hot-wire was operated with a resistance ratio of 1.4 for all readings. Static pressure at the hot-wire position was measured and a graph of I^2 versus $(PV)^{1/2}$ was made and used as the calibration curve; where I is the hot-wire current in milliamperes, P is the static pressure at the hot-wire position in atmospheres, and V is the velocity of the air over the hot-wire in feet per second.

A method was devised to correct the calibration curve for temperature changes of the air. This correction accounted for the fact that at very low velocities natural convection is the predominant mode of heat transfer from the wire.

To investigate the feasibility of using a hot-wire anemometer to measure low velocities, a vertical cylinder was constructed so that mea-

surements could be made in the laminar, natural-convection boundary layer on the outer surface. The cylinder was heated with steam to keep its surface isothermal. Temperature profiles were measured with an iron-constantan thermocouple so that corrections for air temperature could be made.

By examining the results of the velocity profile obtained, it was concluded that it is feasible to measure natural-convection, velocity profiles with a hot-wire anemometer.

CHAPTER I

INTRODUCTION

The purpose of this study was twofold: to construct an apparatus for calibrating a hot-wire anemometer at very low velocities, and to investigate the possibility of using a hot-wire anemometer to measure velocity profiles in laminar, natural-convection boundary layers.

The velocities of interest ranged from zero to five feet per second. Cowdrey (1) gives a method for calibrating a hot-wire anemometer at these low velocities. His method is to use a whirling arm incorporated within a circular chamber. Hromas and Kentzer (2) use this same method, but also accounted for changes in ambient air temperature. Due to the fact that the probe is rotating, a mercury pool commutator was used. Since the currents and voltages involved are very small, the commutation process can result in appreciable error. Also, as the arm rotates, the air in the chamber is set in a circulatory motion and correction for this "swirl" must be made. Cowdrey (1) gives a method for making this correction. First, a probe is calibrated by using the whirling arm. Then it is removed and mounted in a stationary position, so that the hot-wire is about 1/16 of an inch distance from the path taken by a "dummy" probe mounted on the whirling arm. As the dummy probe is rotated the calibrated probe measures the swirl. By subtracting the swirl a new calibration is obtained. Ideally, this method is repeated indefinitely and the calibration converges to the true value. To eliminate the necessity for this repetition, Cowdrey (1) gives an approximate method for determining the swirl from the first measurement. This approximate method is based on the fact that the convergent process mentioned above can be expressed mathematically as a series. The approximation is to use only the first term of this series. This approximation will also introduce some error.

In the present work it was decided to calibrate the hot-wire by placing it at the centerline of a tube in which air was in fully-developed, laminar flow.

Ostrach (3) gives the exact solution to the boundary layer problem of a vertical flat plate in natural convection. Experimental results of this same problem have been presented by Eckert (4), who made temperature measurements by means of a Zehnder-Mach interferometer; and by Schmidt and Beckmann (5), who made velocity measurements with a quartz-filament anemometer, and temperature measurements by means of a manganese-constantan thermocouple. Also, Hama and Recesso (6), measured the natural-convection temperature field along a vertical thin cylinder. However, at present there is no experimental data on laminar, natural-convection boundary layer velocity profiles, in which the measurements were made with a hot-wire anemometer.

CHAPTER II

PART ONE

INSTRUMENTATION AND EQUIPMENT FOR HOT-WIRE CALIBRATION

General

Equipment was required to calibrate a hot-wire anemometer in steady laminar flow. This calibration was to be accomplished by measuring the velocity of air at the centerline of a circular tube. Basically, the equipment involved in the calibration apparatus was the hot-wire anemometer, a probe, a smooth copper tube, a probe aligning device, temperature measuring instruments, pressure measuring devices, and a compressor for providing the air flow. These components are considered in detail in the sections that follow.

Anemometer

The instrument used to measure velocity was a model HWB2 hot-wire anemometer, manufactured by the Flow Corporation. This is a multi-purpose precision instrument for use in measuring fluid velocities, including steady velocity, instantaneous velocity (large or small fluctuations) and turbulence intensity. However, it was only used for steady velocity measurements in this thesis.

All readings were reproduced within 0.1 milliamperes, which at the lowest velocity encountered (0.138 feet per second) corresponds to 0.07 feet per second accuracy. As the velocity increases so does the per cent accuracy.

Air Flow

A schematic diagram of the air flow is shown in Figure 1, page 25.

The air first entered a wet test meter where its volume flow rate, temperature, and pressure were measured. Next, it passed into the inlet plenum. The purpose of this plenum was to reduce the velocity of the air and dampen out any turbulence. It was constructed of 1/4 inch plate steel, and had dimensions 7x10x10 inches. The inlet section of the tube was located inside of this plenum. The hot-wire was positioned about ten inches from the tube exit. It was at this point that all measurements were made with the anemometer. Approximately 3.75 inches behind the hot-wire, a copper-constantan thermocouple was positioned to measure the air temperature.

The air exited the tube into the exhaust plenum. This plenum was also constructed of 1/4 inch plate steel, but had dimensions 12x12x12 inches, and a plexiglas access plate. A 50 inch U-tube water-filled manometer measured the pressure inside the plenum. This pressure was assumed to be the pressure at the hot-wire position.

As the air left the exhaust plenum it passed through a small 1/4 inch needle valve, used to regulate the flow, and into a dampening chamber. From this chamber the air was drawn into the intake of a reciprocating compressor and discharged to the atmosphere.

The reason for installing the compressor on the discharge side of the system was to eliminate the turbulence that would result if the air was subjected to compression before entering the tube. The purpose of the dampening chamber was to eliminate pulsations in the flow, brought about by the pumping action of the compressor.

To insure that the system was airtight, all pipe joints were coated with compound before assembling and all rubber tubing connections were wrapped with wire.

To facilitate easy assembly of the tube into the two plenums, O-ring seals were used.

Probe

A model HWP-A probe, furnished by the Flow Corporation, was used to support the hot-wire. The stem material is stainless steel with dimensions 24 inches long and 0.134 inches in diameter. Nose and insulation material is Kel-F and Teflon, and the maximum recommended stream temperature in continuous operation is 390° F.

The hot-wire was a 0.0002 inch diameter 90 per cent platinum, 10 per cent rhodium wire, 0.044 inches in length.

When assembled, the probe was positioned through the back wall of the exhaust plenum and approximately ten inches into the tube. It was assumed that this depth would eliminate any effects of the tube exit on the air flow.

Tube

The laminar velocity profile was developed in a smooth copper tube with a 1.025 inch inside diameter. Eckert (7) gives the following expression for determining the tube length necessary to obtain fully-developed, laminar flow:

$$L_t = 0.0288 \, (Re_d) \, d_t$$

where, d_t is the tube inside diameter and Re_d is the Reynolds number based on the tube inside diameter.

Using this relation, with the maximum Reynolds number anticipated (Re_d = 1200), the tube length required for fully-developed, laminar flow was determined to be 2.96 feet. To insure that the profile would be fully-developed at the point of calibration a length of 16 feet was used. The maximum Reynolds number encountered during the calibration operation was Re_d = 1172.

Upon installation the tube was leveled using adjustable supports and a spirit level. The inlet section was polished and sharp edges were rounded to give smooth inlet conditions, and thus insure laminar flow.

Probe Alignment

Some method had to be devised to align the probe tip at the centerline of the tube. A sketch of the probe aligning device is shown in Figure 2, page 26.

The probe retaining ring and the access bushing in the rear of the exhaust plenum were made of plexiglas to keep the probe from making electrical contact with the plenum wall. A small aluminum bushing was attached to the probe about 3.75 inches behind the tip. This bushing was used to insure good electrical contact between the tube wall and the probe, and to prevent excessive bending of the probe during the alignment operation.

A micrometer traversing device, with a traveling distance of roughly 0.9 inches, was used to move the probe across the diameter of the tube. The micrometer could be read to one thousandth of an inch.

Connection between the micrometer and the probe retaining ring was made by a 1/16 inch diameter steel rod. The rod was threaded on each end and the retaining ring was tapped to receive one end. The other end was locked to the traversing micrometer by two small nuts.

Vertical and horizontal alignment could be accomplished with this arrangement. When the micrometer was being used in one plane the connecting rod in the other plane was bolted to the plenum wall to allow the probe motion in only one direction.

After all connections were made, an ohm meter was attached to the probe and the plenum, to indicate when the centering bushing made contact with the tube wall.

A discussion on the alignment operation is given in the Procedure.

Temperature Measurement

A copper-constantan thermocouple was attached to the probe stem, approximately 3.25 inches behind the probe tip, in order to measure the air stream temperature near the hot-wire. A number 8686 Leeds and Northrup millivolt potentiometer was used to measure the potential difference between the hot and cold (32° F) junctions. The manufacturer's specification of the accuracy of the potentiometer is ±0.05 per cent of the reading +6 microvolts. (1/3° F for the temperatures involved.)

It was also necessary to know the temperature inside the wet-test meter, and at the barometer position. Both of these instruments were furnished with mercury-in-glass thermometers. The thermometer in the wet-test meter could be read to 1/4° F, while the thermometer at the barometer position could be read to 1° F.

Pressure Measurement

A small, water-filled U-tube manometer, furnished with the wet-test meter, was used to measure the pressure inside the wet-test meter. Also, a 50 inch U-tube manometer was used to give the pressure inside the exhaust plenum. It was assumed that the static pressure inside the exhaust plenum was equal to the pressure at the hot-wire position. The justification for this assumption lies in the fact that for the very low velocities involved, the pressure loss due to friction over the last ten inches of the smooth copper tube is negligible.

PART II

INSTRUMENTATION AND EQUIPMENT FOR VELOCITY PROFILE MEASUREMENT

General

In order to determine if it is feasible to use a hot-wire anemometer to measure low-velocity profiles, it was decided to attempt measurements in the boundary layer of an isothermal vertical cylinder in natural-convection. The measurements were made with the 0.0002 inch diameter 90 per cent platinum, 10 per cent rhodium wire previously calibrated.

The cylinder was housed in a four foot square, ten foot high structure made of 1/2 inch plywood. It had an access door and two glass windows for visual observations. The top was covered to reduce drafts.

Cylinder

A standard one inch, thick wall copper pipe, six feet long, was finely polished and used for the cylinder. Heat was supplied by low pressure steam which proved to be a very reliable method of keeping the cylinder isothermal.

The cylinder was tapped with 1/2 inch internal pipe threads, and connections were made to the steam line. A special fitting was constructed to pass the steam and condensate out the bottom of the cylinder, without heating the surroundings below the leading edge. This fitting is shown in Figure 3, page 27.

A 3/4 inch globe value admitted steam to the cylinder at the desired rate. A 1/4 inch stopcock value was installed just below the special fitting to control the pressure inside the cylinder. One-half inch copper tubing was used to pass the condensate from the stopcock valve to a bucket outside of the plywood structure.

A two foot square, 1/2 inch plywood base was cut, and a 1/2 inch hole drilled in the center. This piece fitted on to a short 1/4 inch pipe nipple connecting the special fitting and the stopcock valve. Two purposes were served by this base. First, it was used to hold the cylinder in its position, once it had been made vertical, using a spirit level. And secondly, it was used to keep the cylinder leading edge conditions free of disturbing currents, which could have been caused by convection from the hot copper tube passing the condensate from the cylinder.

All pipe joints were coated with compound to prevent leakage of steam.

Temperature Measurement

The cylinder was fitted with three iron-constantan thermocouples. One was installed three inches from each end, and one at the middle of the cylinder. Installation was accomplished by drilling a small hole in the wall, and feeding the thermocouple wire through the hole and up the length of the cylinder. Three holes were drilled in a small pipe nipple and the thermocouple wires were passed back out through these holes. A pipe union was used between this nipple and the top of the cylinder to prevent twisting of the thermocouple wires during final assembly. Devcon plastic steel was used to seal the holes and make the system free from steam leakage. A very accurate reading of cylinder wall temperature should have resulted from this arrangement.

The ambient air temperature was measured by taking the average of three iron-constantan thermocouples at random positions in the plywood structure. All of these thermocouples had radiation shields.

So that corrections for temperature could be made when measuring velocity profiles, a temperature profile was measured. This measurement was made with a very small thermocouple, 0.002 inch in diameter. The thermocouple was attached to the hot-wire shield, and the probe traversing device moved it through the boundary layer.

The same Leeds and Northrup millivolt potentiometer was used as in the calibration, and all cold junctions were at 32° F.

Probe Traversing Device

The probe traversing device is shown in Figure 4, page 28. Traversing measurement was made with the same micrometer that was used on the probe alignment device during calibration.

The probe was set at a permanent 24.5° angle with the horizontal in an attempt to prevent disturbing of the air flow until it had passed over the hot-wire.

The base of the traversing device was bolted to the wall of the housing. It was then leveled using shims and a spirit level.

Pressure Measurement

Atmospheric pressure was measured with a mercury barometer with corrections made for temperature and latitude.

CHAPTER III

PART ONE

PROCEDURE FOR HOT-WIRE CALIBRATION

Probe Insertion

The probe was inserted through the plexiglas bushing at the back wall of the exhaust plenum. A mark was made on the probe stem so that it would be known when the hot-wire, on the probe tip, was ten inches inside the calibration tube. When the probe tip was through the wall, but before it entered the tube, the probe retaining ring and the aluminum bushing were slid onto the stem, respectively. The aluminum bushing was secured to the stem about 3.75 inches behind the tip by means of a set screw. The copper-constantan thermocouple was inserted through a small hole in the bushing and taped to the stem about 3.5 inches behind the tip. Care was taken to insure that the thermocouple did not make contact with the probe stem. The probe was then inserted slowly into the tube and the thermocouple wire was taped to the stem every few inches.

When the mark on the stem indicated that the hot-wire was ten inches inside the tube, the hot-wire shield was screwed into the plexiglas bushing and tightened onto the stem to lock the probe in position.

Next, the plexiglas, probe retaining ring was positioned and the connecting rods were screwed into it. Then the retaining ring was secured to the probe stem with a set screw. The probe was visually centered in the tube and the horizontal connecting rod was secured to the plenum by two small nuts. The vertical rod was locked to the micrometer traversing device. The probe was now ready to be aligned.

Probe Alignment

Since the horizontal connecting rod was secured to the plenum wall, the probe could only move in the vertical direction. An ohm meter was connected to the plenum and the probe stem, so that when the aluminum centering bushing made contact with the tube wall, the meter would indicate a closed circuit.

The micrometer traversed the probe to the top of the tube until contact was made. The micrometer reading was recorded. Then the probe was moved to the bottom of the tube and a reading was taken in that position. These readings were checked for duplication. Half way between these two readings was considered to be the center point. The vertical connecting rod was secured to the plenum at this center position, and the micrometer was removed and attached to the horizontal connecting rod. The small nuts securing the horizontal rod to the plenum were loosened to allow the micrometer to move the probe in the horizontal direction. The probe was centered horizontally by the same procedure just described for vertical alignment.

An attempt was made to check this alignment of the hot-wire. The check was accomplished by letting the air-flow reach steady-state and then moving the probe across the tube diameter, taking readings at several positions. Readings were only taken in the vertical direction. A graph of these points is shown in Figure 6, page 30.

Calibration

The needle valve was opened and the compressor started. The valve was adjusted to give the desired flow rate and several minutes were allowed for the system to attain steady state.

One revolution of the wet-test meter represents 0.1 cubic feet of air flow at meter temperature and pressure. A stopwatch was employed to measure the time for one revolution. The measurement was accomplished by allowing the meter to turn several revolutions and then dividing the time elapsed by the number of revolutions. This method reduced the error due to starting and stopping the watch.

The flow rate was checked before and after a run to insure that the flow had been steady during the run. A small counter made the job of measuring the flow rate very easy. The counter and the watch were started and then other readings were taken while the flow rate was being measured.

After steady state was reached, the pressure and temperature in the meter and at the hot-wire position were recorded. Then the hot-wire bridge was balanced and the wire current measured and recorded. The needle valve was adjusted to give another flow rate and the calibration procedure outlined above was repeated.

In a few cases the volume flow rate required to give the desired centerline velocity exceeded the wet-test meter capacity. In these cases two meters were hooked up in parallel with each meter taking approximately half the load.

One of the meters was set for correct reading by the Atlanta Gas Company. The other meter was operated in series with this adjusted meter to obtain a calibration curve for correcting the volume flow rate. The Manufacturer's specification of the accuracy of the wet-test meters is 1/4 of a per cent.

An error analysis for the calibration is given in Appendix C.

PART TWO

PROCEDURE FOR VELOCITY PROFILE MEASUREMENT

Temperature Profile Measurement

Measurement of a temperature profile was required so that temperature corrections could be made when the velocity profile was measured. A small 0.002 inch diameter iron-constantan thermocouple was used to take the measurement.

The probe traversing device was bolted to the housing at the desired height on the cylinder. Then steam was passed through the cylinder to maintain it at a constant temperature. While the cylinder was heating, the thermocouple wire was attached to the hot-wire shield on the probe tip. The thermocouple extended 3/4 of an inch from the tip and was bent so that about 1/4 of an inch ran parallel to the cylinder. This bend was to help keep from disturbing the air flow until it passed the thermocouple, and also, to prevent heat loss from the hot junction by conduction up the thermocouple leads, and consequent error in the thermocouple reading (see Figure 5, page 29).

The probe traversing device was used to position the thermocouple in the boundary layer. The distance of the thermocouple from the leading edge of the cylinder was measured with a scale having 1/64 inch divisions.

The thermocouple was zeroed by moving it in until it almost touched the cylinder wall. Then it was sighted with a cathetometer and slowly moved in until it made contact with the cylinder wall. This zero reading was recorded. It should be noted that the cylinder was heated before the zero reading was taken. If the thermocouple was zeroed before heating the cylinder, the thermal expansion of the copper would cause the cylinder diameter to change, resulting in an incorrect zero reading. The micrometer zero was reproduced within 0.002 of an inch.

Once the cylinder was heated and the zero reading recorded, the temperature profile was measured by traversing the thermocouple through the boundary layer.

Velocity Profile Measurement

Since the temperature profile had just previously been measured, everything was ready to measure the velocity profile, except that a micrometer zero reading had to be taken for the hot-wire. Direct contact was not made with the cylinder wall, for fear of breaking the wire. Instead, the hot-wire shield cap was removed, and the shield was positioned so that the probe tip could barely be seen with the cathetometer. The probe was then moved in until the top edge of the shield touched the cylinder. The vertical distance from the top edge of the shield to the hot-wire was measured using the cathetometer. By knowing the angle of probe inclination (24.5°), the distance between the hot-wire and the cylinder wall could then be calculated. The cathetometer measures to 0.003 inch accuracy. The accuracy of the probe angle measurement is 0.5°.

Once the hot-wire was zeroed, it was traversed across the boundary-layer and anemometer current readings were taken at several positions. The accuracy of traversing was the same as for the temperature profile measurement. These readings were later corrected for temperature and converted to velocity by using the calibration curves in Figure 8, page 32.

During velocity profile measurements, slight fluctuations occurred which indicated that possibly extraneous drafts were disturbing the flow.

CHAPTER IV

DISCUSSION OF RESULTS

By examining Figure 6, page 30, it appears that the probe tip could have been off the centerline of the calibration tube by 0.050 of an inch. However, when readings were being taken across the diameter of the calibration tube, at no point did the anemometer reading exceed the reading at the presupposed centerline. Accurate determination of this deviation from the centerline cannot be made since the position of the probe tip, during traverse across the tube diameter, was calculated by assuming a linear deflection of the probe stem, and by approximating the distances from the assumed pivot point. Since the velocity profile is fairly flat at the centerline, no appreciable error should result if the hot-wire is not exactly at the center of the tube. The equation for the velocity profile in a tube for laminar flow is:

$$V = V_c \left[1 - \left(\frac{r_o}{R_o} \right)^2 \right]$$

If the probe was off the centerline of the tube by 0.050 of an inch, the velocity measured would be $v = 0.990\ V_c$, or a 1.0 per cent error would be incurred.

The graph in Figure 6, page 30, also indicates that a fully-developed profile did exist in the tube.

The experimentally determined calibration curve, (Curve I) is shown in Figure 7, page 31. Included in this figure are also the two theoretically determined curves for air temperature at 550° R. Curve II is for the wire natural and forced convections perpendicular to each other. Curve III is for these two components of convection parallel to each other. Curve II is very nearly the same as curve I. This result would seem reasonable since the hot-wire was calibrated in a position so that the natural convection from the wire was perpendicular to the forced convection over the wire. Curve III is very different from curve I at low values of $(PV)^{1/2}$. However, as $(PV)^{1/2}$ increases, curve III converges on the other two curves. The reason for this convergence is that as the velocity across the hot-wire increases, the forced convection over the wire becomes much greater than the natural convection from the wire. Since the natural convection component is now unimportant, it does not matter whether it is perpendicular or parallel to the forced convection.

Since the velocity profile was measured from a vertical cylinder, the hot-wire was in a position so that the natural and forced components of convection were parallel. Therefore, the theoretically determined equation for this type of condition was used as the calibration. A family of curves was plotted for various air temperatures and used to obtain the velocity profile. This family of curves is shown in Figure 8, page 32. Appendix B contains a complete discussion on the technique used to account for the natural convection from the hot-wire.

Hromas and Kentzer (2) obtained their calibration curve by plotting $\overline{Nu}_d$ versus $(Re_d)^{-1/2}$ (see Figure 10 of reference 2). The curve is linear, as $(Re_d)^{-1/2}$ decreases, until a value of 0.32 is reached. They indicate that the reason for this non-linearity is probably due to natural convection effects. By converting this value of $(Re_d)^{1/2}$ to a velocity for the wire used in this thesis, the value of $(PV)^{1/2} = 1.025$ is obtained. This value of $(PV)^{1/2}$ is very close to the point at which the non-linearity of the calibration curve, obtained in this thesis, becomes apparent. Therefore, these two independent results seem to support each other very well.

The value of $(PV)^{1/2}$ at which the natural and forced convections become equal in magnitude is 0.382. This value was determined by equating the Nusselt numbers for natural and forced convection found in Appendix B. Below this value the natural convection becomes more and more predominant. Hromas and Kentzer (2) indicate that their curve breaks down at a value of $(Re_d)^{1/2} = 0.1414$. That is to say, the curve becomes horizontal, and regardless of the value of $(Re_d)^{1/2}$ below this point, $\overline{Nu}_d$ remains a constant. This value of $(Re_d)^{1/2}$ corresponds to $(PV)^{1/2} = 0.420$, which is slightly above the value where the natural and forced convections are equal in magnitude.

An error analysis for this experimentally determined calibration curve is given in Appendix C.

The temperature and velocity profiles measured for the vertical cylinder are shown in Figures 9 and 10, pages 33 and 34, respectively. These profiles were put in dimensionless form and compared with Ostrach's (3) exact solutions for a vertical flat plate in natural convection. As can be seen from Figure 9, page 33, the slope of the temperature profile at the cylinder wall is greater than the slope of the temperature profile at the wall of a flat plate. According to Hama and Recesso (6) this trend is correct.

During the temperature profile measurement, fluctuations of 10° F to 12° F were noted at about 0.150 of an inch from the cylinder wall. This position is approximately where the maximum velocity occurs in the boundary layer. At other positions fluctuations of only 2° F to 4° F occurred.

The value of ξ at the point of measurement was 0.463. According to Sparrow and Gregg (8), the ratio of the average Nusselt number for the cylinder to the average Nusselt number for the vertical flat plate is 1.15 for this value of ξ. An overall heat balance was made for the cases of the flat plate and the vertical cylinder. The result of these calculations indicate that the velocity profile shows a correct trend.

The experimental measurements of this part of the thesis are not the primary result. What is important is the fact that these measurements indicate that it is feasible to use a hot-wire anemometer to measure natural-convection velocity profiles.

CHAPTER V

CONCLUSIONS

The results of the velocity profile measurement indicates that it is feasible to use a hot-wire anemometer to measure profiles in a low-velocity range. However, greater accuracy could be obtained with a smaller wire, a greater resistance ratio, and a more sensitive galvanometer for measuring the hot-wire current. However, care must be taken not to set the resistance ratio too high or the wire will burn out.

The method used to calibrate the hot-wire appears to be extremely satisfactory. This method also allows a rapid approximation of velocities. At atmospheric conditions the value of P should not change appreciably, since it is the static pressure at the hot-wire position in atmospheres. Therefore, for a given temperature a quick, but fairly accurate approximation of velocity can be obtained upon reading the hot-wire current.

The natural convection from the wire should be accounted for in very low-velocity measurements. Also, consideration should be given to whether the natural and forced components of convection are perpendicular or parallel to each other. Figure 7, page 31, shows that at very low values of $(PV)^{1/2}$ the error involved in neglecting this effect would be large.

There are no experimental results available for making a comparison with the experimentally determined velocity profile. However, as mentioned in the Discussion of Results, an overall heat balance for the cases of the flat plate and the vertical cylinder indicate that the velocity profile shows the right trend. Fluctuations of the galvanometer needle were noted during the profile measurement. These fluctuations indicate that possible drafts were disturbing the flow.

The analytically determined calibration equation for the wire, when the two components of convection are perpendicular, represents the experimentally determined curve extremely well. But, since the profile measurements were made when these components were parallel, the analytically determined equation for parallel components was used. How well this equation would represent the experimentally determined curve for this case is not known. However, since the theory represents the perpendicular components case so well, it should be representative of the case where the components are parallel.

The temperature profile appears to be good, and the method for measuring it satisfactory. But, if the hot-wire had been calibrated as a resistance thermometer, then both temperature and velocity profiles could have been measured simultaneously.

CHAPTER VI

RECOMMENDATIONS

In order to achieve increased accuracy in velocity measurements, a smaller diameter wire should be used. Also, by employing a higher resistance ratio, the hot-wire sensitivity will be increased. However, care must be taken not to set this ratio too high or the wire will burn out. Increased accuracy in velocity measurements will also result if a more sensitive galvanometer is used.

If some method of varying the air temperature in the calibration apparatus could be devised, the theoretical method for correcting for air temperature change could be checked. However, if this check could not be accomplished, then placing the hot-wire in a temperature controlled oven and taking readings of the wire at zero velocity would at least give a partial check.

Also, as mentioned previously, there is a difference in the calibration curves, if the natural and forced components of convection are perpendicular instead of parallel. The case to be encountered should be determined and the calibration accomplished accordingly. It would be interesting if a wire were calibrated for both cases at the same air temperature, and compared. In this way the theory given in Appendix B could be verified.

Care should be taken to insure that extraneous drafts do not disturb the flow along the cylinder. Hama and Recesso (6) give a method for reducing these drafts.

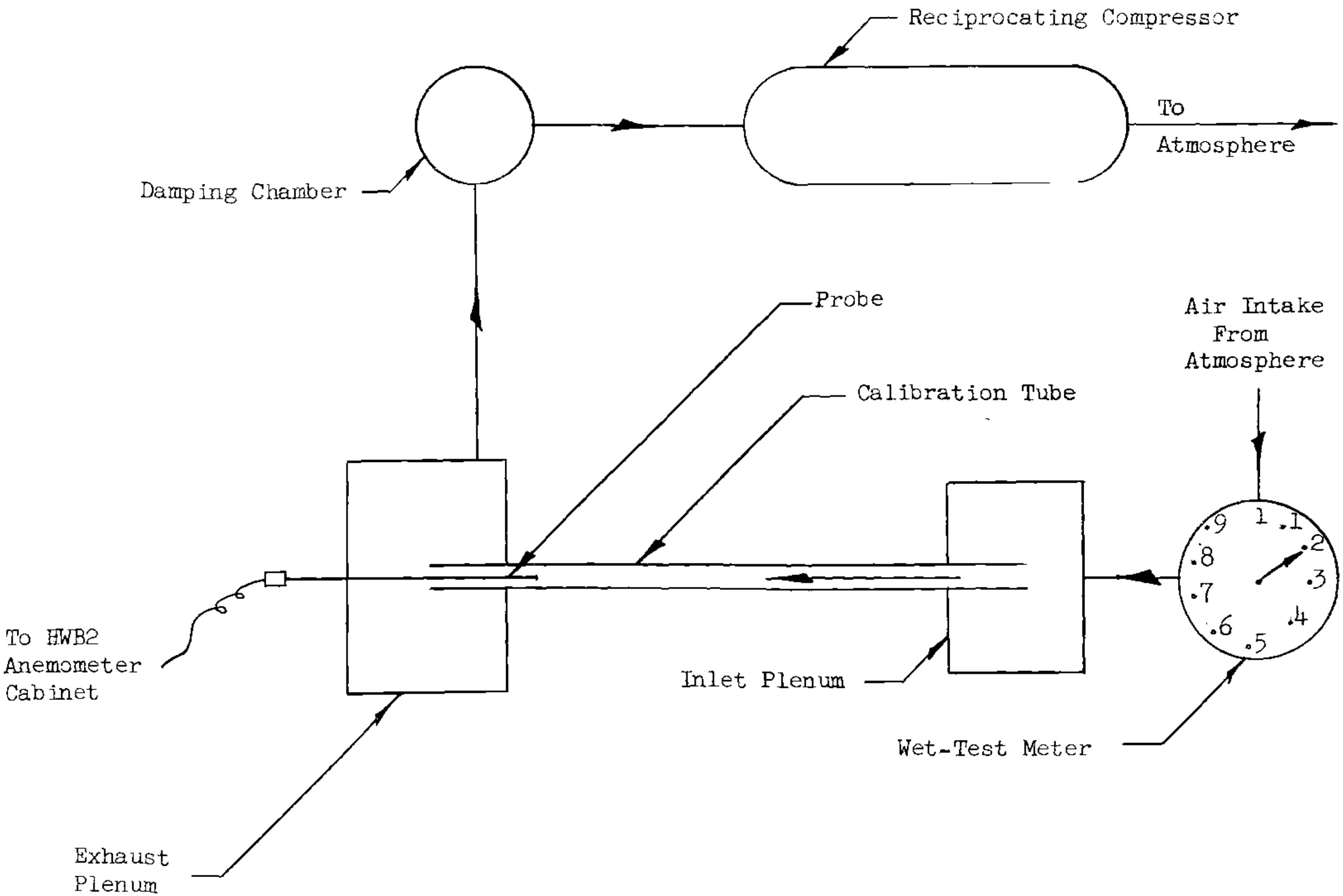


Figure 1. Air Flow Schematic for Calibration Apparatus.

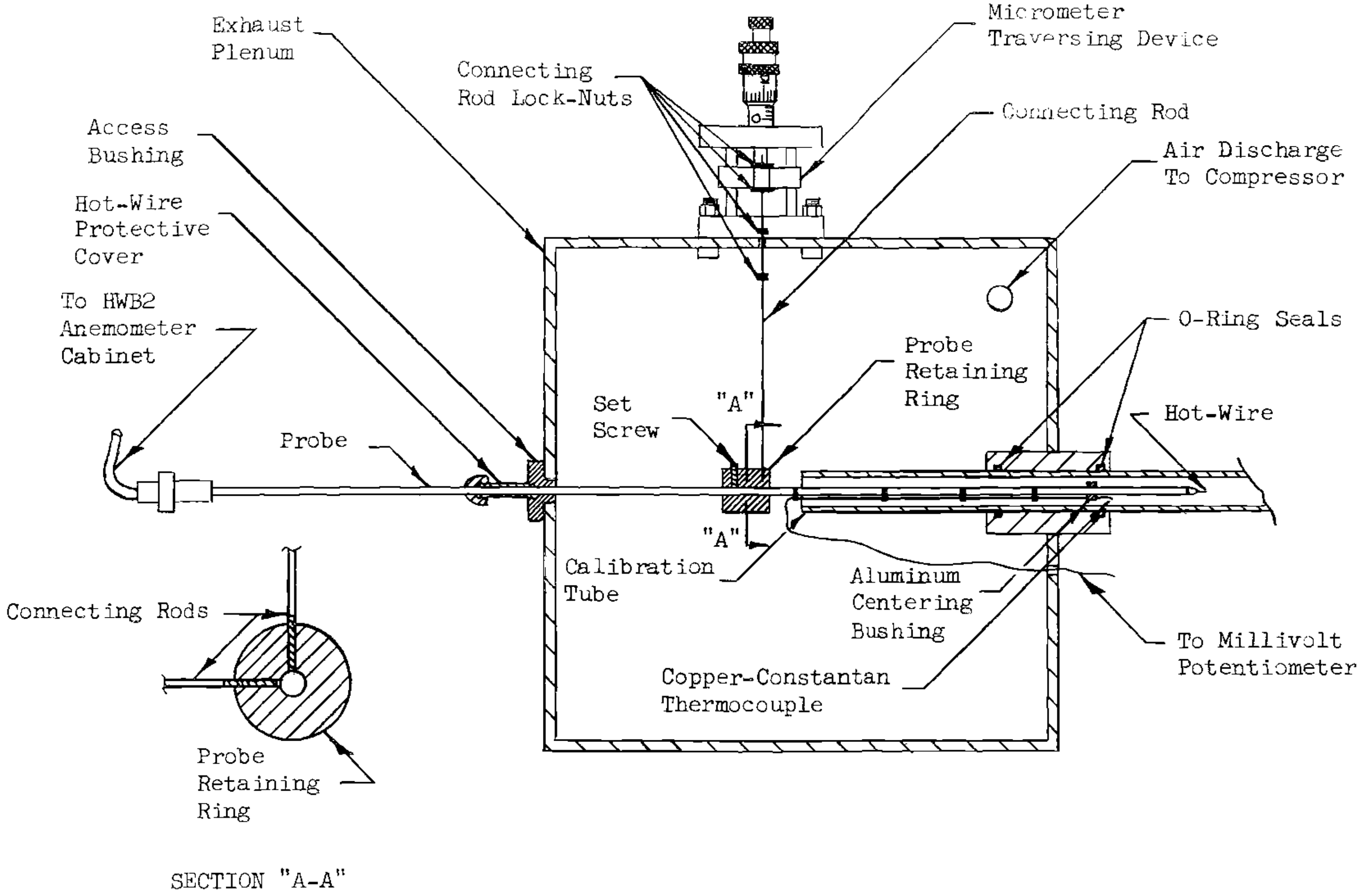


Figure 2. Sectional View of Probe in Position to be Calibrated.

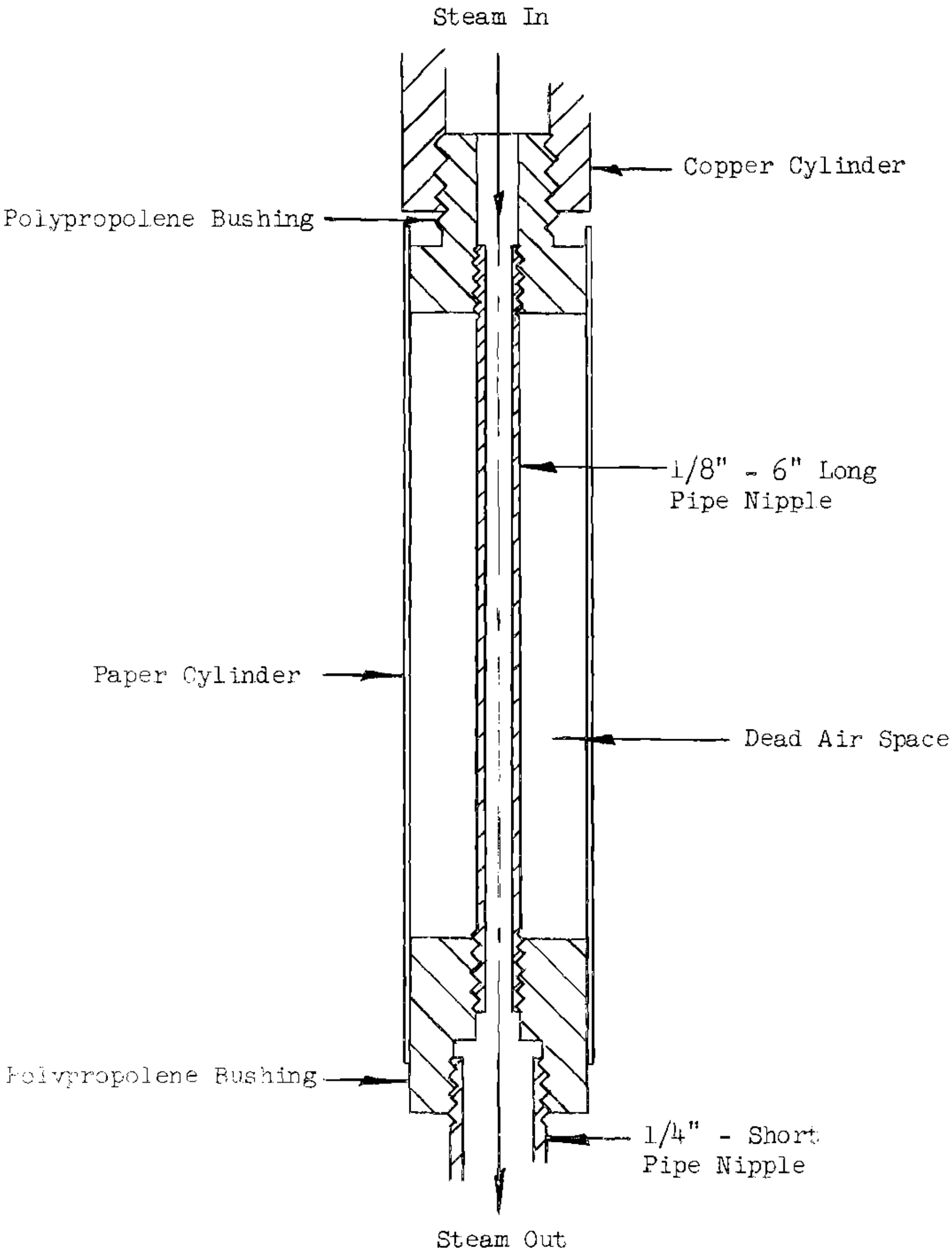


Figure 3. Special Fitting at Bottom of Cylinder for Preserving Leading Edge Conditions.

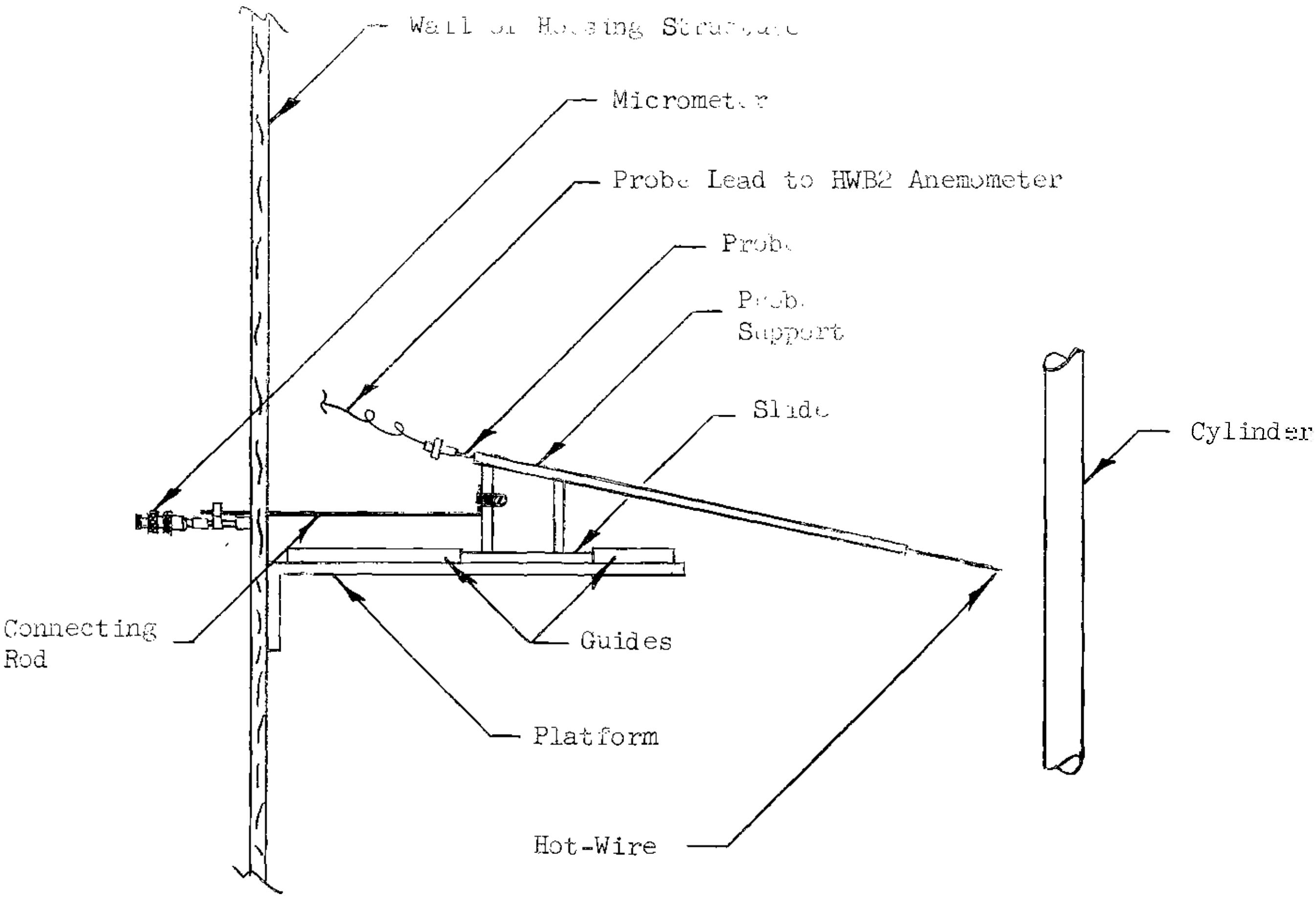


Figure 4. Probe Traversing Device.

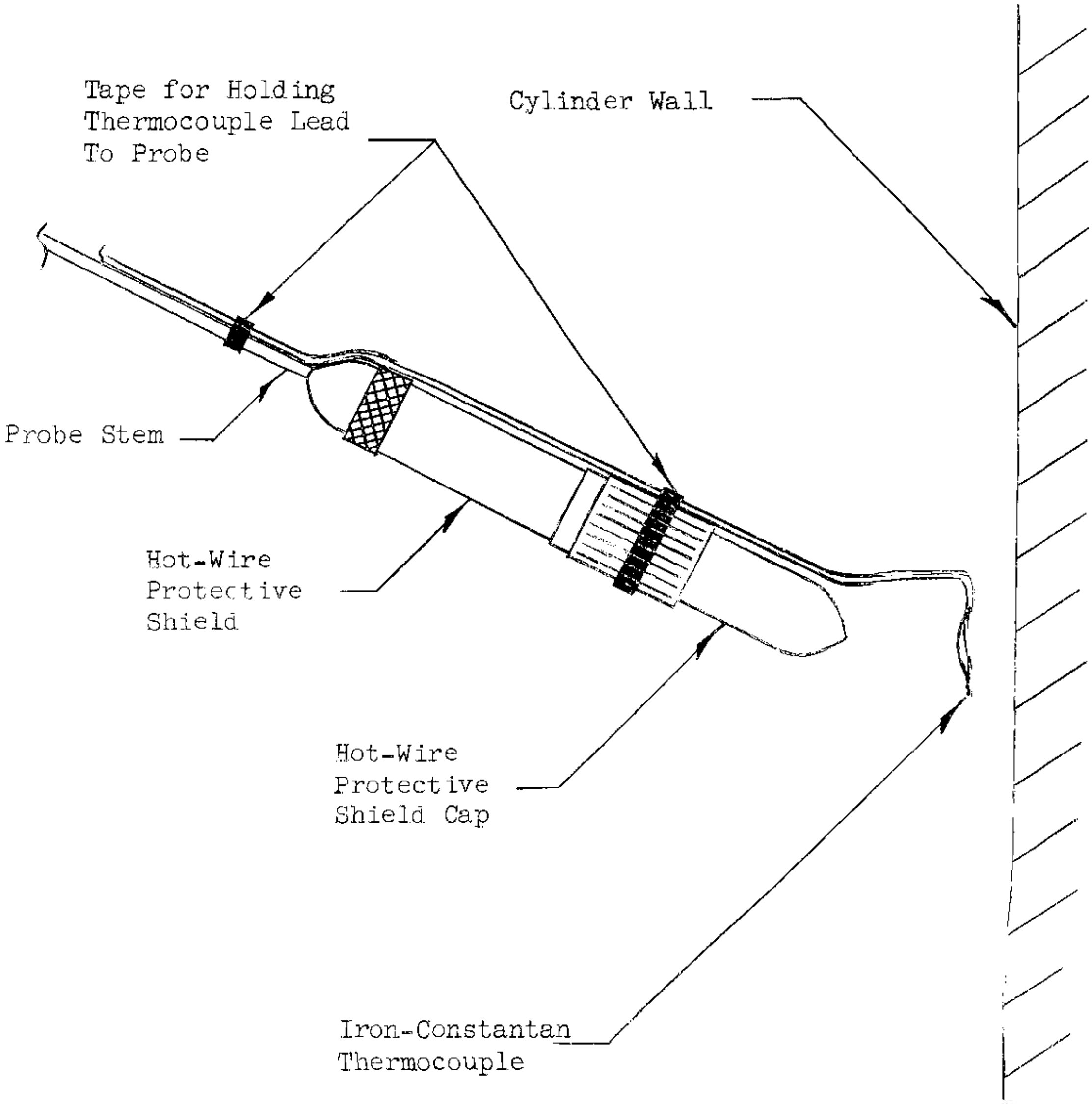


Figure 5. Thermocouple Attachment to Probe for the Purpose of Traversing the Boundary Layer.

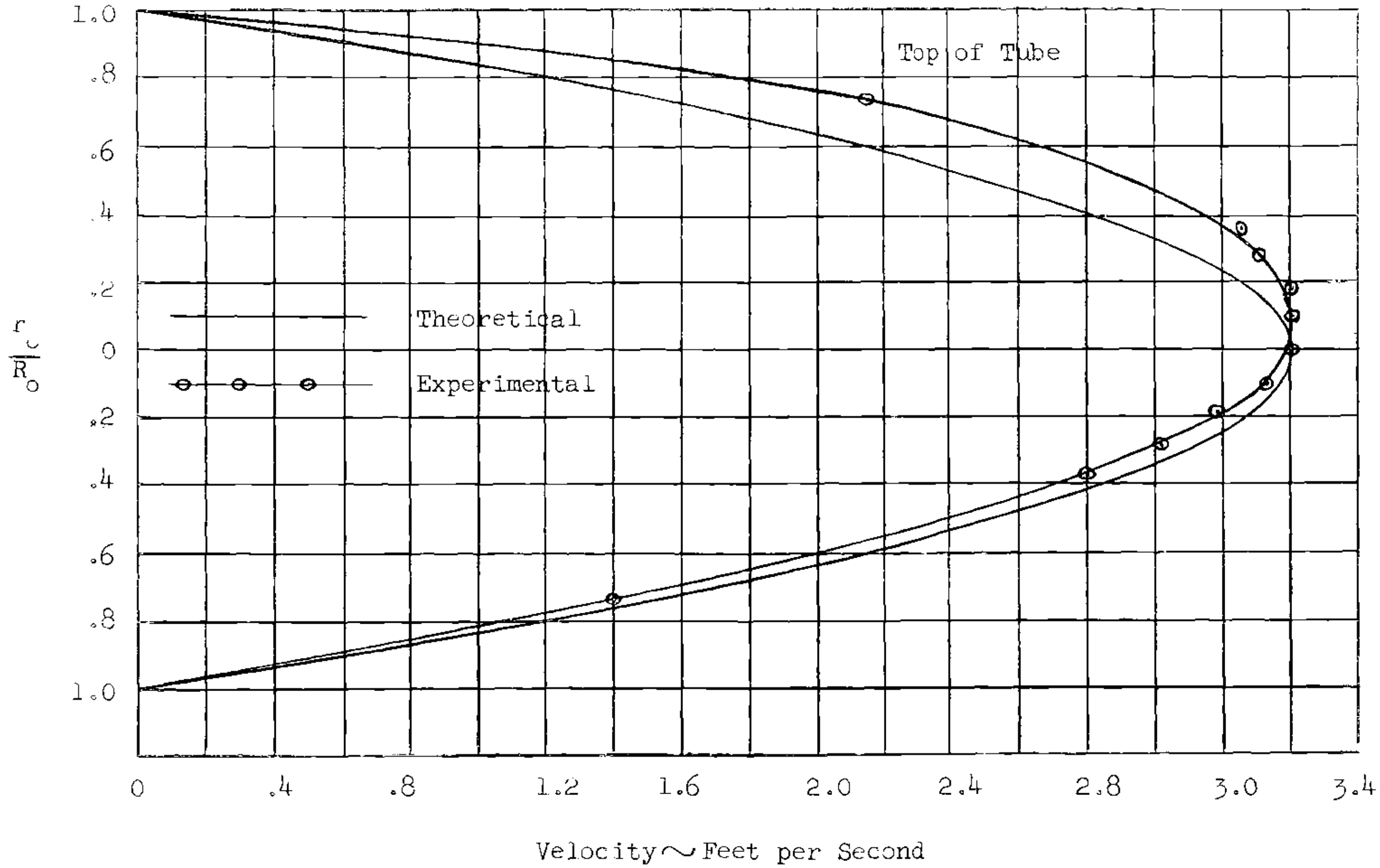


Figure 6. Parabolic Profile Measured in the Calibration Tube.

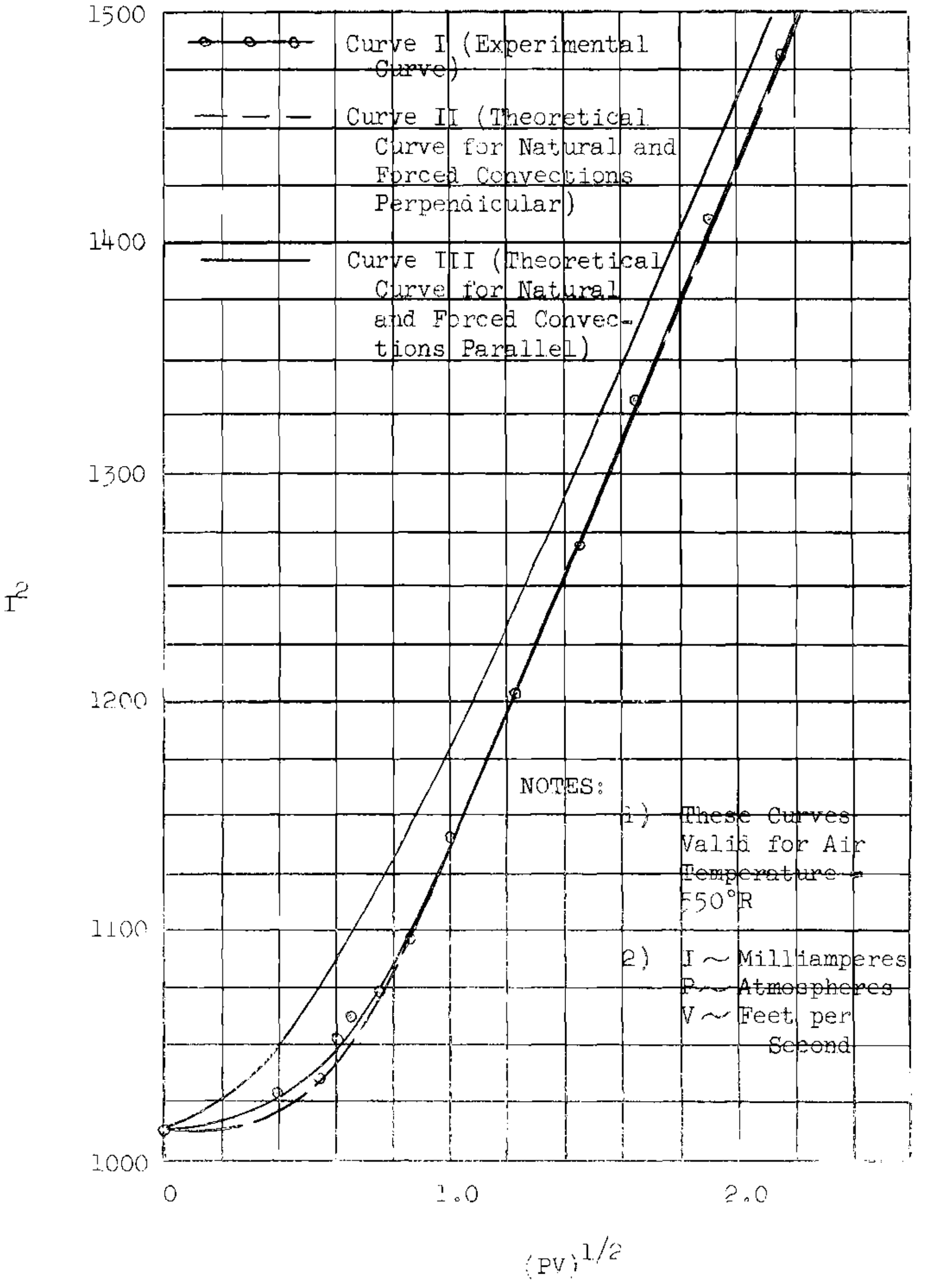


Figure 7. Experimentally Determined Calibration Curve, and Curves Drawn from Analytically Determined Equations.

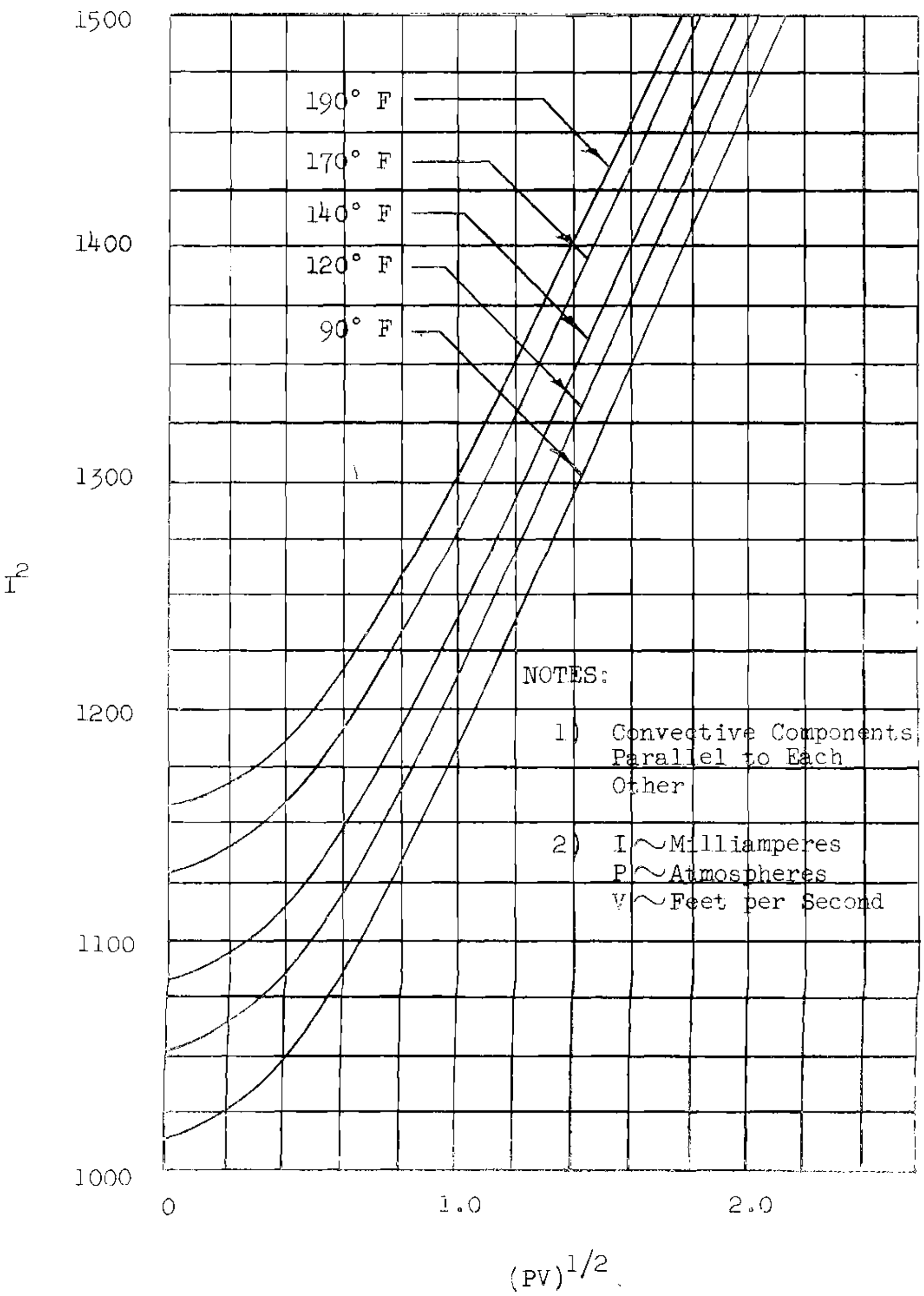


Figure 8. Family of Analytically Determined Calibration Curves.

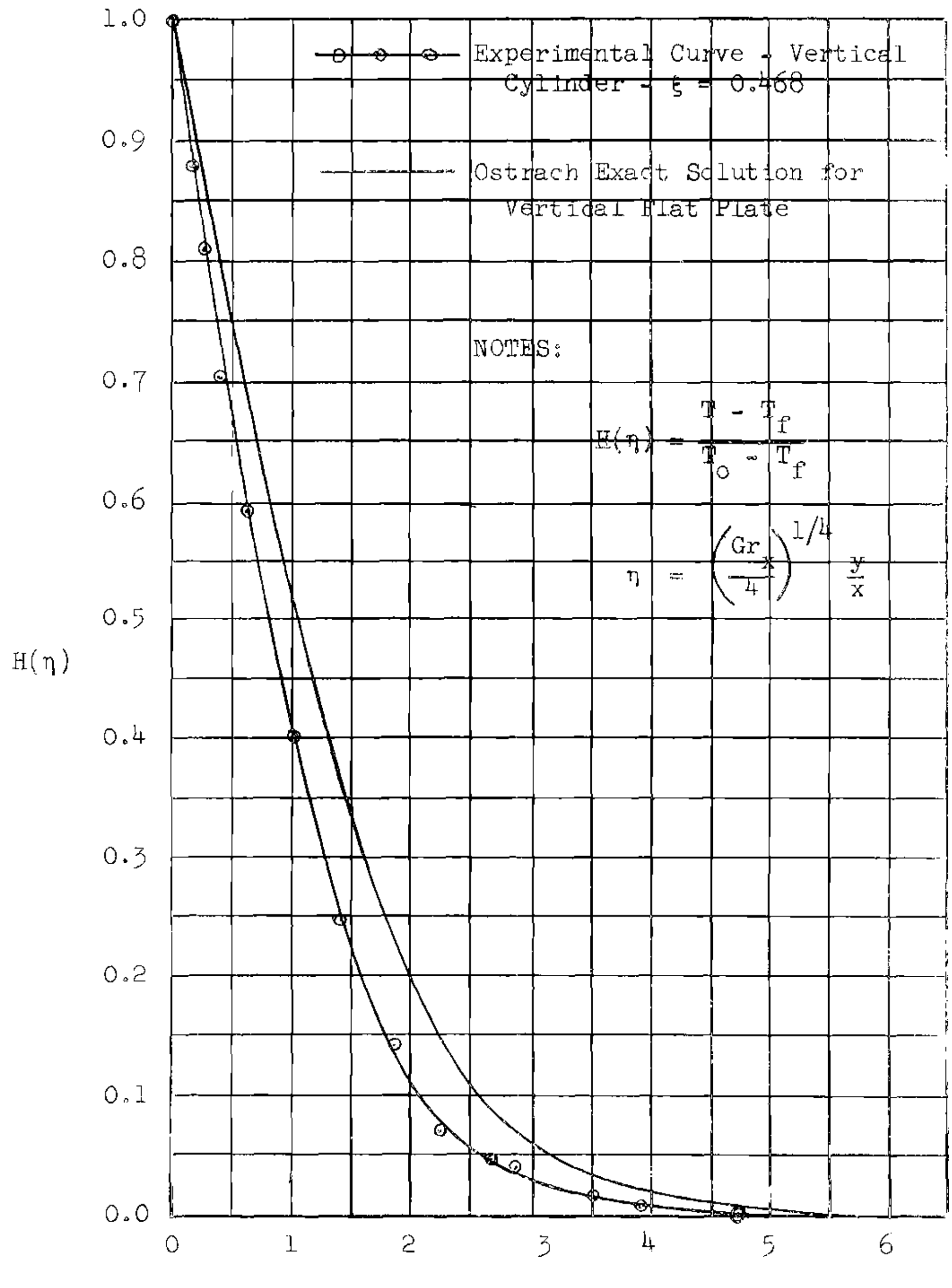


Figure 9. Dimensionless Temperature Profile.

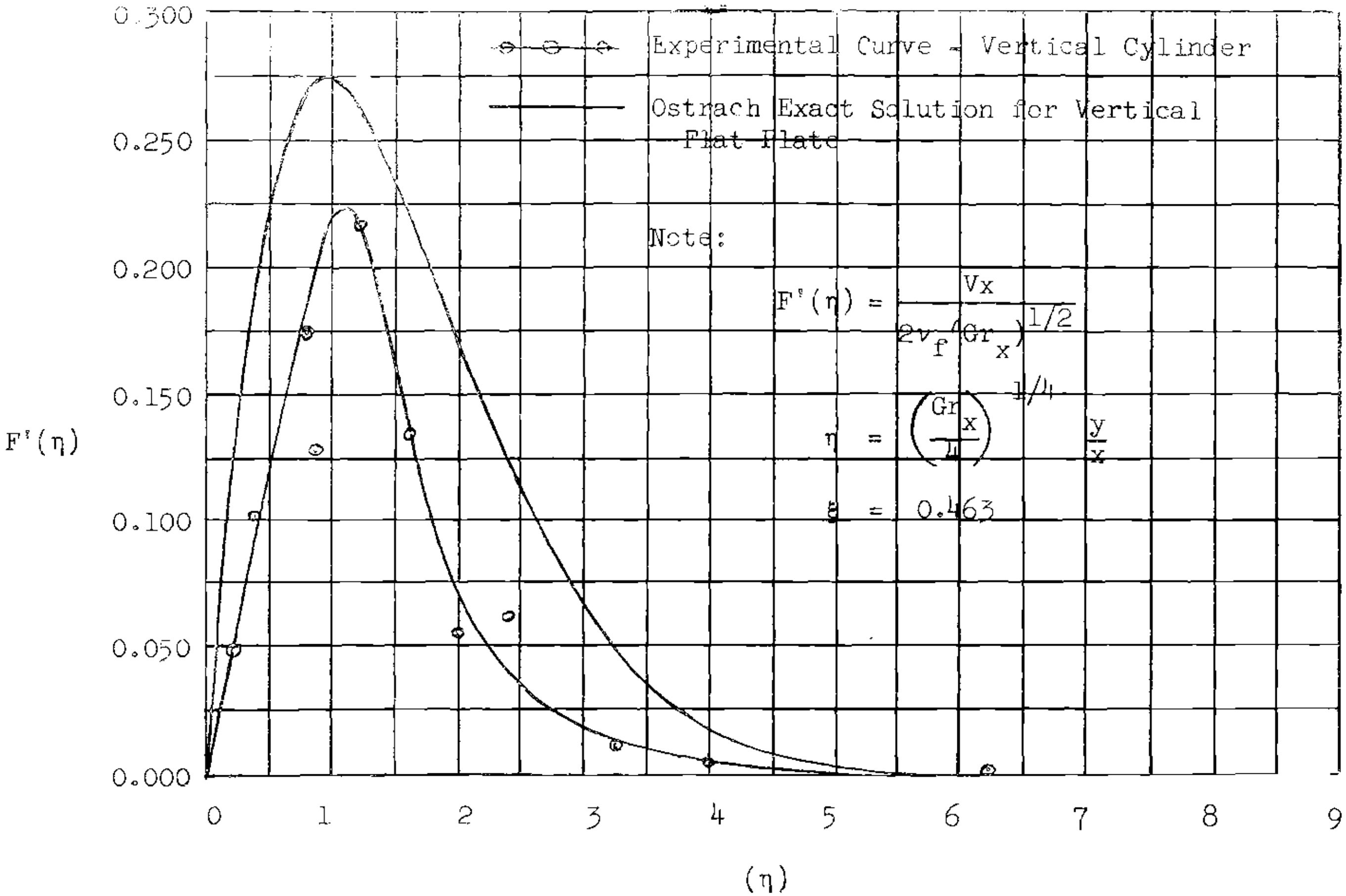


Figure 10. Dimensionless Velocity Profile.

A P P E N D I C E S

APPENDIX A

WET-TEST METER CORRECTION TO THE TEMPERATURE AND PRESSURE AT THE HOT-WIRE POSITION

For air:

$$p\dot{V} = \dot{m}RT$$

At wet-gas meter position:

$$P_{wm}\dot{V}_{wm} = \dot{m}_{wm}RT_{wm} \qquad (A)$$

At hot-wire position:

$$P_p\dot{V}_p = \dot{m}_pRT_p \qquad (B)$$

Since the flow is steady:

$$\dot{m}_{wm} = \dot{m}_p$$

Dividing (B) by (A):

$$\frac{P_p\dot{V}_p}{P_{wm}\dot{V}_{wm}} = \frac{T_p}{T_{wm}}$$

Or,

$$\dot{V}_p = \dot{V}_{wm}\frac{P_{wm}}{P_p}\frac{T_p}{T_{wm}}$$

APPENDIX B

THE EFFECT OF TEMPERATURE CHANGE ON THE CALIBRATION CURVE WHEN NATURAL CONVECTION FROM THE HOT-WIRE IS IMPORTANT

Basically, the constant resistance ratio hot-wire anemometer works on the principle that the faster a fluid flows over the wire, the more heat that must be generated by the wire to keep its temperature constant. Thus, the wire current is indicative of the fluid stream velocity. When this velocity becomes low enough, the magnitude of the heat transferred from the wire by natural and by forced convection are of the same order of magnitude. If the velocity is decreased further, the natural convection becomes the predominant mode of heat transfer from the wire.

Also, as the temperature of the fluid stream changes, the heat transfer from the wire will be affected. Therefore, some method for predicting the effect of fluid stream temperature change and natural convection from the wire at low velocities had to be devised. The Flow Corporation Bulletin No. 37B (9) gives an approximate method for correcting the calibration curve for temperature change. However, in the velocity range where the natural convection is important this correction is not sufficient.

The following analysis is an attempt to show the effect of these two phenomenon on the calibration, and to give some feeling for how the importance of the natural convection varies with velocity.

At present, there is neither theoretical nor experimental information on the effect of natural convection from a horizontal wire where forced convection over the wire is of the same order of magnitude. The approach used here is tenative. However, it has been used with some success for the case of combined laminar natural and forced convections in a horizontal tube (10).

The case in which the natural and forced components of convection from the wire are perpendicular is presented in detail. The technique used when these components are parallel is the same, and a short discussion on this phase of the problem is presented.

The technique is to convert the natural convection effect into an equivalent Reynolds number. Then combine this equivalent Reynolds number with the forced convection Reynolds number, by adding them as vectors. This vector addition will give a total Reynolds number which can be used in the forced-convection heat transfer equation.

First, it was necessary to get an expression for the heat transfer from a small horizontal wire in natural convection. Since the Grashof number is of the order $Gr_d = 10^{-7}$, it was difficult to find any such information. However, Madden and Piret (11) give the expression:

$$\overline{Nu}_n = \frac{2}{\ln \dfrac{6.82}{(Gr_d\ Pr)^{1/3}}} \qquad (1)$$

for sub-atmospheric pressures, and very low Grashof numbers.

Since it would be desirable to know how $\overline{Nu}_n$ varies with temperature change, several points in the Grashof number range of interest were calculated and a curve plotted. The points were very close to being linear. Therefore, the following expression for natural convection was established from the curve:

$$\overline{Nu}_n = 0.34 - 8.65 \times 10^{-5}\ T_f \tag{2}$$

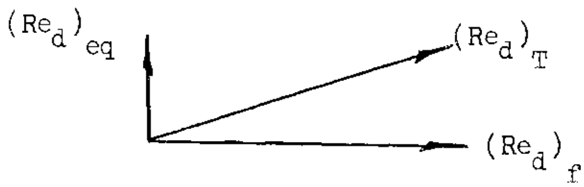
Hromas and Kentzer (2) give the following expression for forced convection:

$$\overline{Nu}_f = 0.34 + 0.53\ (Re_d)^{1/2} \tag{3}$$

By setting $\overline{Nu}_n = \overline{Nu}_f$ the equivalent Reynolds number for natural convection can be determined.

$$(Re_d)_{eq} = 2.66 \times 10^{-8}\ T_f^{\,2} \tag{4}$$

During the calibration process the hot-wire was transferring heat by natural convection vertically and by forced convection horizontally. Therefore, these components are added as vectors 90° apart.



$$(Re_d)_T = \left[(Re_d)_f^{\,2} + (Re_d)_{eq}^{\,2}\right]^{1/2} \tag{5}$$

Again, using equation (3) for forced convection:

$$\overline{Nu}_d = \frac{\bar{h} d_w}{k_f} = 0.34 + 0.53\ (Re_d)_T^{\,1/2} \tag{6}$$

Now, if the effect of heat loss from the wire by conduction to the end supports is neglected:

$$q = \bar{h}\pi d_w L_w (T_w - T_f) = I^2 R_w \tag{7}$$

Since:

$$R_w = R_f \left[1 + \alpha_f (T_w - T_f)\right] \tag{8}$$

Then:

$$T_w - T_f = \frac{R_w - R_f}{\alpha_f R_f} = \frac{r-1}{\alpha_f} \quad \text{where: } r = \frac{R_w}{R_f} \tag{9}$$

Also, since the fluid of interest is air at low pressure:

$$\rho_f = \frac{P}{RT_f} \tag{10}$$

Substituting and simplifying:

$$I^2 = \pi L_w \left(\frac{r-1}{r\alpha_f R_f}\right) \left\{ 0.34\ k_f + 0.53 \left[\left(\frac{PVdwk_f^2}{RT_f \mu_f} \right)^2 + 7.08 \times 10^{-16}\ k_f^4\ T_f^4 \right]^{1/4} \right\} \tag{11}$$

All fluid properties are evaluated at a mean temperature, $T_m = \frac{T_w + T_f}{2}$.

The temperature dependence of the combination of fluid properties is given in The Flow Corporation Bulletin No. 25 (12).

$$k_f \sim T_m^{0.86} \qquad \mu_f \sim T_m^{0.76} \qquad \rho_f \sim T_m^{-1.00}$$

Therefore:

$$\frac{k_f^{\,2}}{T_f \mu_f} \sim T_m^{\,-0.04}$$

This combination of properties will be considered as a constant.

Putting the equation in a simplified form:

$$I^2 = C_1 T_m^{\,0.86} + \left[C_2 (PV)^2 + C_3 T_m^{\,3.44}\, T_f^{\,4} \right]^{1/4} \qquad (12)$$

From equation (9), since $r = 1.4$ for all measurements, and $\alpha_f = 0.000945$ $1/°$ F for the 90 per cent platinum, 10 per cent rhodium wire:

$$T_w - T_f = \frac{r-1}{\alpha_f} = 424° \text{ F}$$

Therefore:

$$T_m = \frac{T_w - T_f + 2T_f}{2} = 212 + T_f$$

Making this substitution:

$$I^2 = C_1 (212 + T_f)^{0.86} + \left[C_2 (PV)^2 + C_3 (212 + T_f)^{3.44} T_f^{\,4} \right]^{1/4} \qquad (13)$$

Now, it is necessary to evaluate the constants. This evaluation is accomplished by setting $T_f = 550°$ R, which is the temperature that prevailed when the experimental curve was constructed. Now, using this experimental curve, Figure 7, page 31, the necessary boundary conditions for determining the constants can be chosen. These boundary conditions are:

1) When $(PV)^{1/2} = 0$ $\qquad I^2 = 1013\ MA^2$

2) As $(PV)^{1/2} \rightarrow \infty$ $\qquad \frac{d(I^2)}{d(PV)^{1/2}} = \text{constant} = 306$

3) When $(PV)^{1/2} = 0.8$ $\qquad I^2 = 1087\ MA^2$

This third boundary condition was chosen, because it was found to give the curve most nearly representing the experimentally determined curve.

Using these boundary conditions the constants are found to be:

$$C_1 = 2.73$$

$$C_2 = 87.68 \times 10^8$$

$$C_4 = 1.731 \times 10^{-12}$$

And, the resulting equation is:

$$I^2 = 2.73(212 + T_f)^{0.86} + \left[87.68 \times 10^8\ (PV)^2 + 1.731 \times 10^{-12}\ (212 + T_f)^{3.44}\ T_f^{\ 4}\right]^{1/4} \qquad (14)$$

The equation for the 550° R curve is:

$$I^2 = 823 + \left[87.68(PV)^2 + 13\right]^{1/4} \times 10^2 \qquad (15)$$

This equation fits the experimentally determined calibration curve very well (see Figure 7, page 31).

During the measurements of the velocity profiles from the isothermal vertical cylinder, the hot-wire natural and forced convections were in the same direction. In order to get calibration curves at various air temperatures, the procedure outlined above was followed, except for two changes. First the vector summation of $(Re_d)_{eq}$ and (Re_d) was a simple algebraic summation, because the vectors were parallel. And, the third boundary condition was changed. In its place the following condition was imposed: $(T_f = 550° \text{ R})$

$$3) \quad \text{When } (PV)^{1/2} \rightarrow N \qquad (Re_d) = 100(Re_d)_{eq}$$

In other words, at some value, N, of $(PV)^{1/2}$ the natural convection was small enough compared to the forced convection that it could be neglected, and I^2 could be evaluated by equation (15). It was found that $(Re_d)_{eq}$ = 0.00805, so that (Re_d) = 0.805. Therefore, $(PV)^{1/2}$ was determined and I^2 calculated as follows:

$$\text{When } (PV)^{1/2} = 3.813 \qquad I^2 = 1991 \text{ MA}^2$$

By using these boundary conditions, the equation for the 550° R curve, when the natural and forced components of convection are parallel is:

$$I^2 = 823 + \left[9.36(PV) + 3.61\right]^{1/2} \times 10^2 \qquad (16)$$

Or, in terms of T_f:

$$I^2 = 2.73(212 + T_f)^{0.86} + \left[9.36 \times 10^4(PV) + 1.316 \times 10^{-6} (212 + T_f)^{1.72} T_f^{\,2}\right]^{1/2} \qquad (17)$$

A family of curves, shown in Figure 8, page 32, was drawn from equation (17). These curves were used to obtain the velocity profile shown in Figure 10, page 34.

APPENDIX C

ERROR ANALYSIS FOR EXPERIMENTAL CALIBRATION CURVE

In order to examine the accuracy of the calibration a per cent error curve was constructed.

All ammeter readings were reproduced within 0.1 of a milliampere. Several points on the calibration curve were selected. At each point the values of hot-wire current, I, and velocity, V, were determined. The value of V was determined by setting P = 0.986, which was the value used to originally construct the calibration curve. Once the value of I was determined, 0.1 was added and subtracted to obtain new values of I. Corresponding values of V were determined and the difference between these new values and the original value of V was calculated. These calculations gave the plus and minus deviations for the velocity of interest. An average of these deviations was taken and used to determine the per cent error based on the original value of velocity, V. A graph of per cent error versus velocity is shown in Figure 11, page 46.

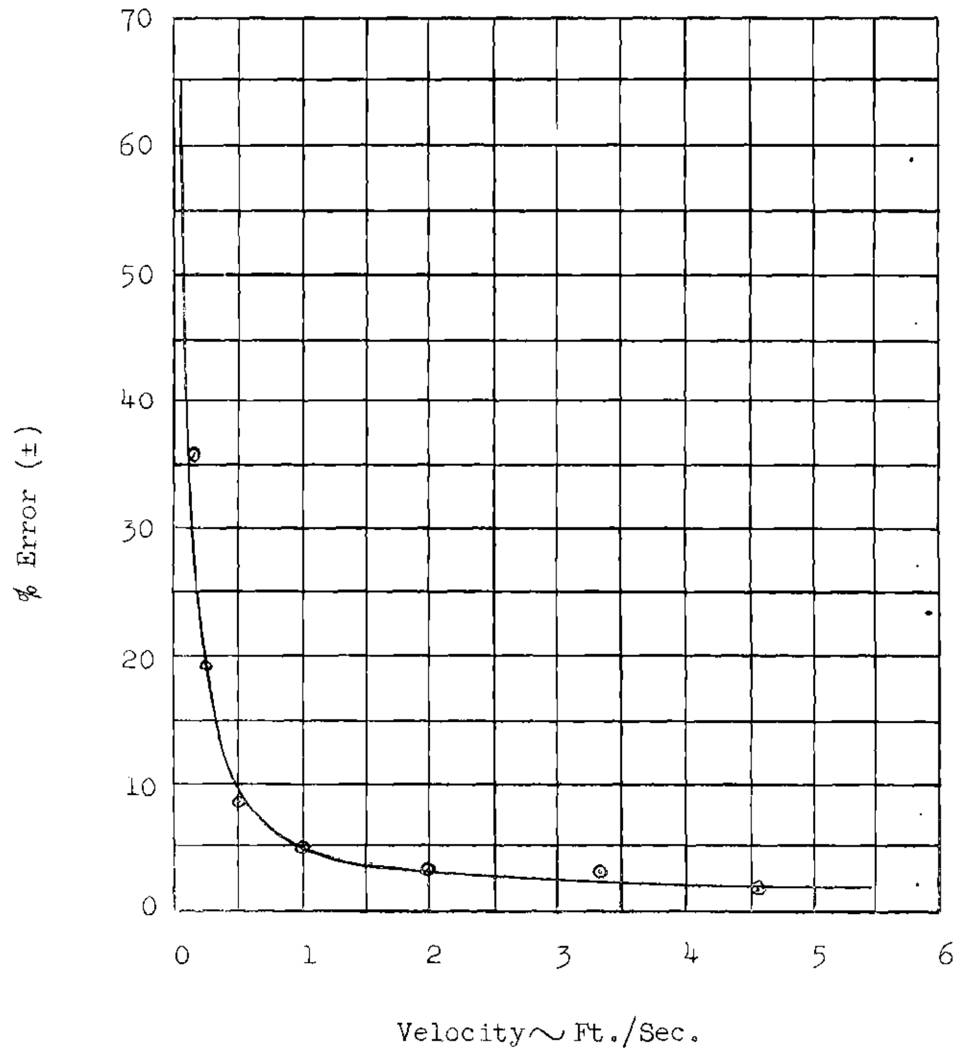


Figure 11. Error Curve Determined from Experimental Calibration Curve.

APPENDIX D

SAMPLE CALCULATIONS

Calibration:

Data for run No. 6 - pages 50 and 51:

Barometer = 394.03 in. H_2O (corrected for temperature and latitude).

Gas Meter reading = 0.564 min./rev.

$T_{wm} = 87.6° \text{ F} = 547.6° \text{ R}$

$P_{wm} = 393.64 \text{ in. } H_2O$

$T_p = 90.6° \text{ F} = 550.6° \text{ R}$

$P_p = 392.97 \text{ in. } H_2O$

$I = 33.78$ milliamperes (MA)

$$\dot{V}_{wm} = \frac{0.1 \text{ ft.}^3/\text{rev.}}{0.564 \text{ min./rev.}} = 0.177 \text{ ft.}^3/\text{min.}$$

$$\dot{V}_p = (0.177 \text{ ft.}^3/\text{min.}) \; \frac{P_{wm}}{P_p} \; \frac{T_p}{T_{wm}}$$

$$\dot{V}_p = (0.177 \text{ ft.}^3/\text{min.})\left(\frac{393.64}{392.97}\right)\left(\frac{550.6}{547.6}\right)$$

$$\dot{V}_p = 0.179 \text{ ft.}^3/\text{min.}$$

$$\overline{V}_p = \frac{\dot{V}_p}{A_t} = \frac{(0.179 \text{ ft.}^3/\text{min.})(144 \text{ in.}^2/\text{ft.}^2)}{(0.825 \text{ in.}^2)(60 \text{ sec./min.})}$$

$$\overline{V}_p = 0.520 \text{ ft./sec.}$$

$$V_c = 2\bar{V}_p = 1.040 \text{ ft./sec.}$$

$$P = \frac{392.97}{405.30} = 0.970 \text{ atmospheres}$$

where: 405.30 is one atmosphere (in. H_2O).

$$(PV)^{1/2} = 1.004 \text{ (atm.-ft./sec.)}^{1/2}$$

$$I^2 = 1141 \text{ (MA)}^2$$

Temperature Profile:

$$x = 0.443 \text{ ft.}$$

$$y = 0.015 \text{ in.}$$

$$T_o - T_f = 211° \text{ F} - 86° \text{ F} = 125° \text{ F}$$

$$\frac{\rho^2 g\beta}{\mu^2} = (1.31)(10^6) \text{ 1/ft.}^3 \text{ °F} \quad \text{(evaluated at } T_m = 150° \text{ F)}$$

$$\eta = \left[\frac{Gr_x}{4}\right]^{1/4} \left(\frac{y}{x}\right) \quad \text{(see reference No. 3)}$$

$$\eta = \left[\frac{\rho^2 g\beta(T_o - T_f)}{4\mu^2}\right]^{1/4} \left(\frac{y}{x^{1/4}}\right)$$

$$\eta = \left[\frac{(1.31)(10^6)(1/\text{ft.}^3 \text{ °F})(125° \text{ F})}{4}\right]^{1/4} \left[\frac{0.015 \text{ in.}}{(0.443 \text{ ft.})^{1/4}}\right] \left(\frac{1 \text{ ft.}}{12 \text{ in.}}\right)$$

$$\eta = 0.1224 \text{ (dimensionless)}$$

$$H(\eta) = \frac{T - T_f}{T_o - T_f} = \frac{T - 86}{211 - 86} = \frac{196 - 86}{211 - 86} = 0.880 \text{ (dimensionless)}$$

Velocity Profile:

$x = 0.443$ ft.

$y = 0.030$ in.

$T_o - T_f = 208° F - 87° F = 121° F$

$Tm = 148° F$

Therefore, assume $\frac{\rho^2 g\beta}{\mu^2} = (1.31)(10^6) 1/\text{ft.}^3\ °F$

$\eta = 0.243$ (dimensionless)

$$F'(\eta) = \frac{Vx}{2\nu_f (Gr_x)^{1/2}} = \frac{Vx}{2\nu_f \left[\frac{\rho^2 g\beta}{\mu^2}(T_o - T_f)x^3\right]^{1/2}}$$

$\nu_f = (0.173)(10^{-3})$ ft.^{2}/sec.

$$F'(\eta) = \frac{(0.443\ \text{ft.})\ V}{(0.346)(10^{-3})(\text{ft.}^2/\text{sec})\left[(1.31)(10^6)(121)(0.0870\ \text{ft.}^3\right]^{1/2}}$$

$F'(\eta) = 0.0481$ (dimensionless), since $V = 0.139$ ft./sec.

at $y = 0.030$ in.

APPENDIX E

TABULATION OF EXPERIMENTAL DATA

Table 1. Calibration - Experimental Data

Run No.	No. 1 Wet Meter Reading Min/Rev	No. 1 Wet Meter Temp. °F	No. 1 Wet Meter P in. H_2O	No. 2 Wet Meter Reading Min/Rev	No. 2 Wet Meter Temp. °F	No. 2 Wet Meter P in. H_2O	Hot-Wire P in. H_2O	Air Temp. At Hot-Wire MV	Hot-Wire Current I MA
1	0.258	85.0	0.70	0.249	87.2	0.70	6.72	1.279	38.50
2	0.320	85.4	0.52	0.306	87.2	0.52	4.53	1.284	37.55
3	0.439	86.0	0.35	0.413	87.5	0.35	2.57	1.298	36.50
4	0.271	87.6	0.91	-----	----	----	3.61	1.303	35.78
5	0.378	87.6	0.59	-----	----	----	2.01	1.307	34.70
6	0.564	87.6	0.39	-----	----	----	1.06	1.301	33.78
7	0.767	85.4	0.25	-----	----	----	0.65	1.316	33.05
8	1.056	85.4	0.25	-----	----	----	0.43	1.308	32.78
9	1.348	87.8	0.23	-----	----	----	0.38	1.298	32.60
10	1.557	87.9	0.23	-----	----	----	0.30	1.286	32.45
11	1.976	85.5	0.20	-----	----	----	0.27	1.308	32.18
12	3.660	88.2	0.16	-----	----	----	0.20	1.279	32.08
13	0.000	----	0.00	-----	----	----	0.00	1.298	31.83

NOTES:

1. One meter revolution represents 0.1 cubic feet.
2. For runs 1-3 two meters were used in parallel, because the volume flow rate was above one meter's capacity.
3. Average barometer reading = 394 in. H_2O (corrected for temperature and latitude = 33° 45').

Table 2. Calibration - Calculated Data

Run No.	$\dot{V}_{wm1}$	$\dot{V}_{wm2}$	$\dot{V}_{p1}$	$\dot{V}_{p2}$	$\dot{V}_{pt}$	V_p	V_c	P	$(PV)^{1/2}$	I^2	Air Temp.
	cubic feet per minute					feet per sec.		atm.		$(MA)^2$	°F
1	0.402	0.402	0.411	0.410	0.821	2.390	4.780	0.956	2.138	1482	89.3
2	0.324	0.312	0.330	0.317	0.647	1.881	3.762	0.962	1.902	1410	90.0
3	0.237	0.242	0.240	0.245	0.485	1.410	2.820	0.967	1.651	1332	90.5
4	0.369	-----	0.373	-----	0.373	1.086	2.172	0.964	1.447	1280	90.7
5	0.265	-----	0.267	-----	0.267	0.778	1.556	0.968	1.227	1204	91.0
6	0.177	-----	0.179	-----	0.179	0.520	1.040	0.970	1.004	1141	90.6
7	0.130	-----	0.132	-----	0.132	0.384	0.768	0.969	0.862	1092	91.3
8	0.095	-----	0.096	-----	0.096	0.278	0.556	0.969	0.735	1074	91.0
9	0.074	-----	0.075	-----	0.075	0.217	0.434	0.971	0.649	1063	90.5
10	0.064	-----	0.064	-----	0.064	0.188	0.376	0.970	0.603	1053	90.0
11	0.051	-----	0.051	-----	0.051	0.149	0.298	0.970	0.537	1035	91.0
12	0.027	-----	0.027	-----	0.027	0.080	0.160	0.970	0.393	1029	89.7
13	0.000	-----	0.000	-----	0.000	0.000	0.000	0.973	0.000	1013	90.0

Note: Meter No. 1 was set for correct measurement by the Atlanta Gas Company and meter No. 2 was calibrated by the author by running it in series with meter No. 1. The calibration equation for meter No. 2 is:

$$\dot{V}_{wm2}\ (\text{actual}) = 1.037\ \dot{V}_{wm2}\ (\text{measured})$$

The corrected reading is entered in the above table.

Table 3. Temperature Profile Data

y / in.	Temp. / MV	Temp. / °F	η	H(η)
0.015	4.78	196	0.1224	0.880
0.025	4.53	187	0.204	0.808
0.050	4.12	174	0.408	0.704
0.075	3.70	160	0.612	0.592
0.125	3.00	136	1.021	0.400
0.175	2.45	117	1.430	0.248
0.225	2.05	104	1.840	0.144
0.275	1.80	95	2.25	0.072
0.325	1.70	92	2.66	0.048
0.350	1.68	91	2.86	0.040
0.425	1.58	88	3.48	0.016
0.475	1.55	87	3.88	0.008
0.575	1.53	86	4.70	0.000

NOTES:

1) At this position on the cylinder x = 0.443 ft.

2) $\eta = \left(\frac{Gr_x}{4}\right)^{1/4} \frac{y}{x}$

3) $H(\eta) = \frac{T - T_f}{T_o - T_f}$

Table 4. Velocity Profile Data

y (in.)	I (MA)	I^2 $(MA)^2$	η	$H(\eta)$	T °F	$(PV)^{1/2}$	$V^{1/2}$	V fps	$F'(\eta)$
0.030	34.39	1182.5	0.243	0.878	193	0.370	0.373	0.139	0.0481
0.050	34.39	1182.5	0.405	0.694	171	0.540	0.543	0.295	0.102
0.115	33.95	1152.6	0.933	0.432	139	0.605	0.610	0.372	0.129
0.125	34.18	1167.9	1.013	0.400	135	0.710	0.715	0.511	0.177
0.150	34.18	1167.9	1.217	0.318	125	0.790	0.797	0.635	0.220
0.200	33.30	1108.9	1.621	0.193	110	0.620	0.624	0.390	0.135
0.250	32.50	1056.3	2.03	0.108	100	0.400	0.403	0.162	0.056
0.300	32.51	1057.0	2.43	0.059	94	0.420	0.423	0.179	0.062
0.400	31.94	1020.0	3.24	0.029	91	0.150	0.151	0.023	0.008
0.500	31.95	1020.8	4.05	0.008	88	0.140	0.141	0.020	0.007
0.700	31.90	1017.6	5.68	0.000	87	0.120	0.121	0.015	0.005

NOTES:

1) At this position x = 0.443 ft.

2) See note No. 2, Table 3 for η.

3) $$F'(\eta) = \frac{Vx}{2\nu_f (Gr_x)^{1/2}} .$$

APPENDIX F

NOMENCLATURE

The following notation is used in this thesis:

A_t = Cross-sectional area of calibration tube

C_i = Constants (i = 1,2,3,----)

d_t = Inside diameter of calibration tube

d_w = Diameter of hot-wire

$F'(\eta)$ = Dimensionless velocity function

g = Acceleration due to gravity

Gr_d = Grashof number based on diameter

Gr_x = Grashof number based on distance from leading edge of vertical cylinder

$\bar{h}$ = Average heat transfer coefficient

$H(\eta)$ = Dimensionless temperature function

I = Hot-wire current

k_f = Thermal conductivity of fluid

L_t = Length of calibration tube

L_w = Length of hot-wire

m = Mass flow rate

MA = Milliamperes

MV = Millivolts

$\overline{Nu}_d$ = Average Nusselt number for hot-wire, including natural and forced convection components

$\overline{Nu}_f$ = Average hot-wire Nusselt number for forced convection

$\overline{Nu}_n$ = Average hot-wire Nusselt number for natural convection

P = Static pressure at hot-wire position during measurements

P_p = Static pressure at hot-wire position in the calibration tube

P_{wm} = Static pressure at wet-test meter position

Pr = Prandtl number

q = Heat transfer from hot-wire

r = Resistance ratio, $r = \frac{R_w}{R_f}$

r_{co} = Outside radius of vertical cylinder

r_o = Local value of radius inside calibration tube

R = Gas constant

R_o = Inside radius of calibration tube

R_f = Resistance of hot-wire at fluid temperature

R_w = Resistance of hot-wire, heated

Re_d = Reynolds number based on diameter

$(Re_d)_{eq}$ = Equivalent Reynolds number for natural convection. Defined by equation (4), Appendix B.

$(Re_d)_T$ = Total Reynolds number. Obtained by a vector addition of Re_d and $(Re_d)_{eq}$. See Appendix B.

T_f = Temperature of fluid

T_m = Mean temperature, $T_m = \frac{T_w + T_f}{2}$

T_o = Temperature of vertical cylinder wall

T_p = Temperature at hot-wire position in calibration tube

T_w = Average temperature of hot-wire

T_{wm} = Temperature at wet-test meter position

$\dot{V}_p$ = Volume flow rate at hot-wire position

$\dot{V}_{wm}$ = Volume flow rate through wet-test meter

V = Local value of velocity

$\overline{V}$ = Average velocity

x = Distance from leading edge of vertical cylinder

y = Radial distance from vertical cylinder

α_f = Temperature coefficient of resistance of the wire

β = Coefficient of volumetric expansion, $\beta = \rho \left[\frac{\partial(1/\rho)}{\partial T} \right]_p$

η = Similarity variable,

μ_f = Absolute viscosity of the fluid

ν_f = Kinematic viscosity of the fluid

ρ_f = Density of the fluid

ξ = Dimensionless variable, $\xi = \frac{2^{3/2}}{Gr_x^{1/4}} \frac{x}{r_{co}}$

BIBLIOGRAPHY

1. Cowdrey, C. F., "A Note on the Calibration and Use of a Shield Hot-Wire Anemometer for Very Low Speeds," Journal of Scientific Instruments, Vol. 27 (1950), p. 327.

2. Hromas, L. A., and Kentzer, C. P., "Calibration of a Hot-Wire Anemometer for Low Velocities in Steady Flow with Temperature Gradients," Purdue University School of Aeronautics Report No. A-55-1 (July, 1955).

3. Ostrach, Simon, "An Analysis of Laminar Free-Convection Flow and Heat Transfer about a Flat Plate Parallel to the Direction of the Generating Body Force," NACA-TR-1111 (1953).

4. Eckert, E. R. G., and Soehngen, E. E., "Studies on Heat Transfer in Laminar Free-Convection with the Zehnder-Mach Interferometer," Technical Report No. 5747, A.T.I. No. 44580, Air Material Command, Dayton, Ohio (December 27, 1948).

5. Schmidt, Ernst, and Beckmann, Welhelm, "Das Temperature-und Geschwindigketsfeld vor einer Wärme abgebenden senkrechter Platte bei natürlicher Konvektion," Tech. Mech. u. Thermodynamik, Bd. 1, Nr. 10 (Okt. 1930) pp. 341-349; cont., Bd. 1. Nr. 11, Nov. 1930, pp. 391-406.

6. Hama, F. R. and Recesso, J. V., "The Axisymmetric Free-Convection Temperature Field Along a Vertical Thin Cylinder," Technical Note Bn-116, Maryland University, Institute for Fluid Dynamics and Applied Mechanics (January, 1958).

7. Eckert, E. R. G. and Drake, Jr., R. M., Heat and Mass Transfer, McGraw-Hill Book Co., Inc. (1959).

8. Sparrow, E. M. and Gregg, J. L., "Laminar-Free Convection Heat Transfer from the Outer Surface of a Vertical Circular Cylinder," Transactions, American Society of Mechanical Engineers (November, 1956).

9. Flow Corporation Bulletin No. 37B, "Model HWB2 Hot-Wire Anemometer Theory and Instructions" (11 Carleton Street, Cambridge 42, Massachusetts).

10. Jackson, T. W., Spurlock, J. M., and Purdy, K. R., "Combined Free and Forced Convection in a Constant Temperature Horizontal Tube," American Institute of Chemical Engineers Journal, Vol. 7 (March, 1961), pp. 38-41.

11. Madden, Jr., A. J., and Piret, E. L., "Heat Transfer from Wires to Gases at Sub-Atmospheric Pressure Under Natural Convection Conditions," Institute of Mechanical Engineers, London. Proceedings of the General Discussion on Heat Transfer (September 1951), pp. 328-333.

12. Flow Corporation Bulletin No. 25, "Selected Topics in Hot-Wire Anemometer Theory."