Simultaneous single element air temperature and velocity measurements

James E. Benjamin  
*Iowa State College*

R. W. Fahien  
*Iowa State College*

Follow this and additional works at: [http://lib.dr.iastate.edu/ameslab_iscreports](http://lib.dr.iastate.edu/ameslab_iscreports)

Part of the [Physics Commons](http://lib.dr.iastate.edu/ameslab_iscreports)

**Recommended Citation**  
[http://lib.dr.iastate.edu/ameslab_iscreports/174](http://lib.dr.iastate.edu/ameslab_iscreports/174)

This Report is brought to you for free and open access by the Ames Laboratory at Iowa State University Digital Repository. It has been accepted for inclusion in Ames Laboratory ISC Technical Reports by an authorized administrator of Iowa State University Digital Repository. For more information, please contact digirep@iastate.edu.
Simultaneous single element air temperature and velocity measurements

Abstract
Equations were derived for measuring gas velocity and temperature simultaneously using a single heated platinum wire as the sensing element. These equations contained four unknown coefficients which were considered constant. These constants were to be determined by calibrating at two known levels of temperature and velocity.

Disciplines
Physics
SIMULTANEOUS SINGLE ELEMENT AIR TEMPERATURE AND VELOCITY MEASUREMENTS

By
James E. Benjamin
R. W. Fahien

June 1957

Ames Laboratory
Iowa State College
Ames, Iowa

Technical Information Service Extension, Oak Ridge, Tenn.
F. H. Spedding, Director of Ames Laboratory.

Work performed under Contract No. W-7405-eng-82.

LEGAL NOTICE

This report was prepared as an account of Government sponsored work. Neither the United States, nor the Commission, nor any person acting on behalf of the Commission:

A. Makes any warranty or representation, express or implied, with respect to the accuracy, completeness, or usefulness of the information contained in this report, or that the use of any information, apparatus, method, or process disclosed in this report may not infringe privately owned rights; or

B. Assumes any liabilities with respect to the use of, or for damages resulting from the use of any information, apparatus, method, or process disclosed in this report.

As used in the above, "person acting on behalf of the Commission" includes any employee or contractor of the Commission to the extent that such employee or contractor prepares, handles or distributes, or provides access to, any information pursuant to his employment or contract with the Commission.

This report has been reproduced directly from the best available copy.

Printed in USA. Price $1.75. Available from the Office of Technical Services, Department of Commerce, Washington 25, D. C.
<table>
<thead>
<tr>
<th>Section</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>ABSTRACT</td>
<td>4</td>
</tr>
<tr>
<td>INTRODUCTION</td>
<td>5</td>
</tr>
<tr>
<td>LITERATURE SURVEY</td>
<td>7</td>
</tr>
<tr>
<td>THEORY</td>
<td>10</td>
</tr>
<tr>
<td>DERIVATION</td>
<td>12</td>
</tr>
<tr>
<td>EQUIPMENT</td>
<td>16</td>
</tr>
<tr>
<td>PROCEDURE</td>
<td>32</td>
</tr>
<tr>
<td>RESULTS</td>
<td>37</td>
</tr>
<tr>
<td>DISCUSSION</td>
<td>45</td>
</tr>
<tr>
<td>CONCLUSIONS AND RECOMMENDATIONS</td>
<td>51</td>
</tr>
<tr>
<td>APPENDIX</td>
<td>53</td>
</tr>
<tr>
<td>SAMPLE CALCULATION PROCEDURE</td>
<td>53</td>
</tr>
</tbody>
</table>
ABSTRACT

Equations were derived for measuring gas velocity and temperature simultaneously using a single heated platinum wire as the sensing element. These equations contained four unknown coefficients which were considered constant. These constants were to be determined by calibrating at two known levels of temperature and velocity.

The method of measuring required numerical values for the current and voltage drop in the wire and the derivative of the voltage with respect to the current. These were achieved by plotting curves of current versus voltage with an X-Y plotter and taking slopes from the resultant curves.

Calibration was attempted on an instrument consisting of concentric platinum wire loops mounted in a vertical 4-inch pipe which had heated air flowing upward through it. Equipment and procedure of the calibration are given in detail.

From the values obtained for the four calibration "constants" found at three levels of gas temperature and velocity and three levels of resistance, it was concluded that the theory was oversimplified in assuming constancy of these coefficients. However, it was felt that determination of the relationships between the four coefficients and the system parameters would make this means of measurement possible though complicated.

A vivid graphic portrayal of the degree of turbulence in "laminar" and turbulent flow was also demonstrated.

This report is based on an M. S. thesis by James E. Benjamin submitted June, 1957, to Iowa State College, Ames, Iowa. This work was done under contract with the Atomic Energy Commission.
Simultaneous Single Element Air Temperature and Velocity Measurements

James E. Benjamin and R. W. Fahien

INTRODUCTION

This project was undertaken to provide instrumentation for measuring radial temperature and velocity profiles for air flow in an empty, vertical pipe. These temperature and velocity values were to be suitable for calculating point values of thermal and momentum diffusivities as a function of radial position in a future experiment. It was intended that the instrumentation thus developed would eventually be used to make a study of heat and momentum transfer parallel to a contemporary study on mass and momentum transfer in the same system. Two such series of data on the same system with one variable in common, namely the momentum transfer, should prove of considerable value in helping prove or disprove the theorized similarity of mechanism for heat, mass and momentum transfer. The particular system chosen was also a reasonable approach to systems encountered in industrial practice such as the vertical tubular cooling section of a fluidized catalyst reaction bed.

Initially the type of instrumentation was unspecified but academic and practical considerations quickly narrowed the field. Use of such devices as thermocouples, impact tubes, etc., left little original work to be done and made the project one for a technician. These same devices also had the fault of being sensitive to only one variable. This required that the assumption of steady state in the air system must hold over the entire

---

period of measuring both a temperature and a velocity profile and that the geometric position of the two sensing elements be identical. It was known, however, that the electrical properties of a hot wire were affected by the temperature, velocity and composition of its surroundings. Therefore, a single wire looked like a worthy candidate for investigation.

Since an electrically heated wire must come to thermal equilibrium with its gaseous surroundings or melt; and since this equilibrium temperature is a function of the heat conductivity, thermal capacity, velocity and temperature of the gas, the equilibrium temperature of the wire is a function of the composition, velocity and temperature of the gas. The resistance of a wire is also a function of its temperature. Therefore, the current through and voltage drop along a wire which determine its power consumption and resistance, also determine its equilibrium temperature in a particular system. Thus, if the composition of the gas is held constant the current and voltage drop are functions of the velocity and temperature of the gas.
LITERATURE SURVEY

The literature was surveyed under the headings of hot wire anemometry and resistance wire thermometry with special interest placed on finding material concerned with doing both simultaneously. The result of this survey was only one article dealing with simultaneous anemometry and thermometry. This was the article of S. Corrsin\(^1\) titled "Extended Applications of Hot Wire anemometer". Basing his work on King's\(^2\) hot wire anemometer equation, Corrsin showed theoretical derivations for measuring local fluctuation levels of velocity, temperature or composition in binary mixing, with an extremely small hot wire anemometer. These fluctuation levels were to be statistical numbers analogous to the turbulent transport numbers first measured by Skromstad. Operation at two distinct levels of current was necessary to determine a pair of velocity and temperature fluctuation level values. This was a purely analytical article and no experimental work was reported.

In the field of simple hot wire anemometry theory, all the articles seemed to corroborate rather than elaborate on King's

---


basic work. Some articles dealt with extension of the velocity range beyond King's work but since the range of interest for this project is within that of King's work these articles are not particularly apropos. Therefore, only King's "Heat from Small Cylinders in a Stream of Fluid" will be reviewed. Using hydrodynamic theory King solved the two dimensional problem for steady state heat loss from very small cylinders in a fluid stream making the assumption of uniform heat flux across the solid fluid boundary. He also assumed the heat conductivity and thermal capacity of the fluid to be constant with temperature change. He obtained two approximate results and showed experimentally that a value of the velocity and wire diameter product discriminated which to use. Only extremely fine wires or very small velocities necessitate the use of the equation which does not contain the velocity term, in other words, the free convection equation.

The very complete and precise experimental work by King, whirling platinum wires on an arm in stagnant air to obtain an easily measured relative velocity over the wire, closely verified his derivation results. The form of this equation has been used incessantly for hot wire anemometry by successive investigators since the paper was published in 1914. As a final note in his paper King says, "In fact the hot-wire method seems capable of affording a convenient means of analysing the velocities and true temperatures of flames or of heated gases in boiler-flues, etc."

A major problem mentioned by nearly all workers in the
field of resistance thermometry or hot wire anemometry was the
anomalous behavior of the electrical properties of the wire used
under certain circumstances. In the case of platinum these non-
reproducible resistance characteristics are normally blamed on
impurities in the metal. Corrucini\(^1\) presents experimental work
and a survey of literature bearing on the effects of impur-

\(^{1}\)Corrucini, R. J. Annealing of Platinum for Resistance
Aug. 1951.
THEORY

There are three major considerations in trying to measure simultaneous temperature and velocity profiles as a function of radial position in a tube at considerably sub-sonic flow rates:

1. Are the measurements representative of all points at the same radial position?
2. Are the spatial positions reproducible?
3. Are the variables constant in time?

Two separate, diameter traversing, point sensitive probes (such as a thermocouple and pitot tube) used alternately leave all three considerations open to debate. Two joined, diameter traversing, point sensitive probes used simultaneously leave only the first and second considerations debatable. A whole series of pairs of point sensitive probes in fixed positions and used simultaneously would leave only the first or none of the considerations debatable depending on their number and arrangement. However, the mechanical complexity of such a system is rather prohibitive. Thus, it would appear that point sensitive probes are not the ideal solution.

The next logical investigation would be line sensitive probes such as fine wires. If the wire is placed along a concentric circle at the desired radial position and used as either a resistance thermometer or hot wire anemometer it will be self averaging over that position, eliminating the first consideration. If several loops are permanently fixed, that will take
care of the second consideration except for the slight expansion of the loops when going from a low ambient temperature (resistance thermometry application) to a high temperature (hot wire anemometer application). The third consideration still remains in question with this arrangement.

Initially plans were made to use such a system of fixed loops using them alternately with heating for velocity measurement and without heating for temperature measurement. The proposed circuitry for this Figure 12, Appendix, incorporated a direct current loop heating source with a recording ammeter, and an alternating current recording Wheatstone resistance bridge to measure the loop's resistance with negligible power flow. Readings taken with the heavy direct current flowing would have permitted determination of the velocity and readings with the direct current off (after a suitable wire cooling period) would have indicated temperature. However, this system incorporates an inherent time lag between the two measurements leaving the third consideration in question.

At this point it was felt that since both measurements were to be made by noting the electrical properties of the same wire at two different static conditions, there must exist some dynamic means of measuring both temperature and velocity simultaneously. On this premise the following derivation was made. Its proof and application should remove all doubt arising from the three considerations mentioned.
DERIVATION

Since hot wire anemometry and ambient temperature resistance thermometry are two extremes of usage for the same electrical properties of a wire, let us combine the equations expressing the relationships between temperature, resistance, velocity, current and voltage, into a single equation.

Defining nomenclature:

All discussion and equations are hereafter based on a unit length of a specific platinum wire.

Lower case letters refer to known or measurable values, upper case to calibration constants and barred upper case to the variables to be determined.

x = distance from pipe center (inches)
i = wire current (amps)
e = potential drop along wire (volts)
r = wire resistance (ohms) = e/i
w = power consumed and dissipated by wire (watts) = ei
s = de/di = slope of function e = f(i) at i,e(volts/amp)
d = si + e/si - e (unitless) recurrent combination reduced thus for simplicity of writing

t_{w} = wire temperature (°F)
T_{a} or t_{a} = air temperature (°F)
V or v = air velocity (ft./sec.)
R_{0} = wire resistance at t_{w} = 0° F (ohms)
A = thermal coefficient of wire resistivity (1/°F)
K = thermal conductivity of air (watts/°F)
\[ M = \text{hot wire anemometer convection constant by King's derivation} \]
\[ M = \sqrt{2} k C_v \rho D \quad \text{(watts/ft.}^2/\text{sec.}^{1/2} \text{°F)} \]

where: 
- \( k \) = thermal conductivity of air
- \( C_v \) = specific heat of air
- \( \rho \) = density of air
- \( D \) = wire diameter

Assuming that the following four first order approximation equations are adequately valid under the conditions which the experiment will involve:

1. \( r = \frac{e}{i} \)
2. \( w = i^2 r \)
3. \( r = R_0 \sqrt{l} + A(t_w - 0) \)
4. \( w = (t_w - \bar{T}_a) (K + M \sqrt{V}) \) from King

Eliminating \( t_w \) from (3) and (4) making use of (1) and (2) and rearranging:

\[ (5) \quad e_i = \frac{(K + M \sqrt{V})}{R_0 A} \left( \frac{e}{i} \right) - \frac{(\bar{T}_a A + 1)}{A} \left( K + M \sqrt{V} \right) \]

Thus we have one equation in two unknowns, \( \bar{T}_a \) and \( V \).

Under conditions of fixed \( V \) and \( \bar{T}_a \), which will approximately prevail during a measurement, the quantities \( C_1 \) and \( C_2 \) are

\[ C_1 = \frac{e_i}{\sqrt{2}} \]
\[ C_2 = \frac{K + M \sqrt{V}}{A} \]

\[ ^1 \text{King, op. cit. p381} \]
constants. Therefore, the differential of the equation will supply a second equation with only one of the unknowns.

Differentiating (5) and solving for \( \frac{de}{di} = s \):

\[
(6) \quad s = \frac{(K+M \sqrt{V} + RoAi^2) e}{(K+M \sqrt{V} - RoAi^2) i}
\]

If the function \( e = f(i) \) could be plotted and its slope \( s \), equal to \( \frac{de}{di} \), measured at the point \((i,e)\) then the equations (5) and (6) would fix \( Ta \) and \( V \) in terms of the calibration constants. Simultaneous solution of (5) and (6) gives the following forms for use when the calibration constants \( K, M, R, \) and \( A \) are known:

\[
(7) \quad V = \frac{(RoAi^2d - K)^2}{M} \quad \text{where} \quad d = \frac{si + e}{si - e}
\]

\[
(8) \quad Ta = \frac{r}{RoA} (1 - \frac{1}{d}) - \frac{1}{A} \quad \text{where} \quad r = \frac{e}{i}
\]

It will be noted from (8) that if calibration run data are available at two different known values of \( ta \) the equation can be written twice and solved for \( RoA \) thus:

\[
(9) \quad \overline{RoA} = \frac{r_1(1 - \frac{1}{d_1}) - r_2(1 - \frac{1}{d_2})}{t_{a1} - t_{a2}}
\]

where subscripts 1 and 2 designate any two different runs.

The quantity \( \frac{1}{A} \) is determined from (8) by any single known \( ta \) run after \( RoA \) is known.
\[
\frac{1}{X} = \frac{z}{R_0A} \left( 1 - \frac{1}{d} \right) - T_a
\]

Similarly from (7) and two different velocity level runs we obtain K after \( R_0A \) is known.

\[
(11) \quad K = \frac{R_0A}{\sqrt{\text{v}_2}} \left( \sqrt{\text{v}_2} \; i_1^2 \; d_1 \right) - \left( \sqrt{\text{v}_1} \; i_2^2 \; d_2 \right) \]

This permits direct solution of (7) for \( M \) with any single velocity run.

\[
(12) \quad \overline{M} = \frac{(R_0A \; i^2 \; d)}{\sqrt{v}} - K
\]

Thus it should be possible to calibrate for \( R_0, A, K, \) and \( M \) if \( e = f(i) \) can be plotted at each of two known temperature levels and each of two known velocity levels. Also if \( R_0, A, K, \) and \( M \) prove equal by several unrelated determinations they can be assumed constant and used in equations (7) and (8) for determining unknown values of \( T_a \) and \( \overline{V} \) with the same system.
EQUIPMENT

The equipment for this project, shown in Figure 1, was divided into three main divisions; namely, the physical system for producing concurrent values of velocity and temperature in an air stream, the measuring systems for determining these values, and the instrumentation system whose calibration was to be attempted. These divisions will be described separately.

The physical system was basically 21 feet of 4-inch nominal pipe standing vertically and wrapped with electric furnace resistance wire and insulation. The pipe was schedule 40 galvanized iron except for the 4-foot long machined brass test section which started 1 feet from the bottom. At the top a right angle exhaust into the room was provided to prevent foreign material from falling down the pipe. Air entered the bottom from a 3/4 inch nominal pipe through two reducers short-coupled to both sides of an elbow.

The brass test section was machined to the same inside diameter as the galvanized pipe and provided with a longitudinal 1/2 inch slot with flanges for mounting the instrumentation system sensing element loops. This slot permitted the loops to be positioned vertically at any point in the test section. The part of the slot not occupied by the sensing loop mounting block was filled with tee-shaped aluminum blocks machined to give a flush fit at the inner surface of the pipe. All sections of the physical system pipe were joined by simple interchange-
Figure 1. Overall view of equipment.
able male and female ferrules on their ends. This assembly was then made rigid by tightening two external longitudinal draw bolts across the joint.

The pipe was wound with chromel resistance wire of approximately 0.8 ohm per foot resistance with about 3-1/2 inches between turns. This wire was wound over a double wrapping of asbestos furnace paper to prevent shorting to the pipe and then covered with a triple wrapping for external insulation. Finally, the whole assembly was covered with 1-1/2 inches of fiberglass and aluminum thermal insulation. Electrical input to the resistance wire was controlled by an 8 ampere, 110 volt powerstat.

Since circular wrapping was not possible on the test section due to the instrumentation slot, three longitudinal wires were equally spaced around it to give the same effective wrapping density but a different geometry. It was felt that the high thermal conductivity of the metal would prevent large thermal gradients between the wires. These three wires were secured with water base asbestos filler cement to the under wrapping of asbestos furnace paper which in turn was cemented with boiler cement directly to the brass. The outer layers of insulation on this section were held in place by spring steel clips and temporary, wrap-around wiring.

Close to the bottom of the physical system the air passed through four baffle plates inside a 2 inch pipe which in turn was contained in a 30 ampere, 220 volt furnace supplied by an equivalent powerstat. These baffle plates each contained
twelve 1/4 inch holes in a staggered pattern. The 3/4 inch line between this furnace and the bottom of the physical system was thermally insulated with asbestos and glass wool. Air came to this furnace through a 3/4 inch pipe from a rotameter and globe valve mounted on the same floor as the test section.

The air supply came from the 90 psi building facilities via two oil traps, two pressure regulators and two conditioning beds. One of these beds (5 feet deep in 4 inch pipe) contained silica gel to remove H₂O and the other contained CaO to remove CO₂. This air supply system was constructed and used in conjunction with two other projects which could tolerate no change in the constituent gases of the air used. Oil was the only really great concern for this project as it can cause deposits on heated platinum wires changing their properties. A schematic air flow diagram is shown in Figure 2.

For a calibration velocity measuring system, the bulk flow rate was measured by the previously mentioned rotameter in conjunction with an immediately upstream pressure gauge, the controlling globe valve being located close to and downstream from the rotameter. At low flow rates this permitted calculation of velocities at any position on the assumption of a parabolic distribution of velocity. At higher flow rates the flow in the physical system was to be screen restricted immediately beneath the sensing loops, permitting calculation on the basis of a uniform velocity profile across the pipe.
Figure 2. Air flow schematic.
For a calibration temperature measuring system, an iron constantan thermocouple probe traversing a diameter immediately below the sensing loop was used. This was made from 0.020 inch wires with a small bead. About 1/4 inch of wire and bead were beyond the 2 millimeter glass tubing probe which was used. This gave fairly quick response and negligible error due to conduction along the wires, since the probe passed 2 inches through the loop mounting block which was at approximately the same temperature as the gas being measured. The EMF from this junction versus that from the junctions with the lead wires, which were sealed in paraffin and submerged in a Dewar flask of ice water, was read with a hand operated 1.6 volt Rubicon potentiometer and reflecting galvanometer, using the one hundredth scale of sensitivity.

This same potentiometer and its newly certified standard cell and three new Mallory mercury cells, was used in calibrating and checking all voltages. A single 1/2 ohm resistance built up of precision resistors was used as a standard for determining current. Thus, even if the electrical values in this paper are not absolute they are at least related in a consistent manner to two fixed standards.

The instrumentation system itself (the one to be calibrated) should be further subdivided into sensing elements, "bucking circuits", recording instrument, power supply and regulation, and overall circuitry. A look at the simplified overall circuit diagram on the following page may help to clarify
the ensuing discussion. (Figure 3)

The sensing elements are 0.006 inch platinum wire loops placed concentrically inside the pipe in a single plane. Each wire is placed in the center of one of the five equal area concentric rings into which the pipe area was arbitrarily divided. The loops are electrically and thermally isolated from the pipe. These conditions were approximated by having the wires supported by passing through mica vanes running radially from a central support which in turn is attached to the tee-shaped bakelite mounting block. The ends of the loops are held under small screws to the two halves of 1/4 inch brass rods which pass through the mounting block insulated from each other by strips of mica between the halves. Small countersunk Allen set-screws hold all the brass rods passing through the mounting block in place. On the outer surface of the mounting block each half of every brass conductor rod is connected to two female banana plugs by a short piece of heavy copper wire. (Figure 4)

Considerable difficulty was experienced in fastening the radial mica vanes to the central brass support rod extending out and down from the mounting block. Initially the vanes were held in a machined plexiglass mount with an adhesive. However, this arrangement melted at the upper calibration temperatures. Since adhesives and most plastics were thus ruled out and limited space made mechanical clamping unattractive it was decided to try casting vanes directly into the metal. Lead was considered too low melting for good service and no other
Figure 3. Simplified schematic circuit.
Figure 4. Sensing element pictures.
pure metals or alloys with melting temperatures below aluminum were found which could readily be cast in open air. At the temperature necessary to cast aluminum, however, the mica was so weakened that the work of completing the loops always resulted in breaking the vanes.

Finally, the vanes were cast successfully in an alloy or mixture of lead and aluminum not listed in the handbooks. It was approximately 85 per cent lead and 15 per cent aluminum by weight. Its melting point was about $480^\circ C$ and it had a very low casting viscosity at about $600^\circ C$. Its density was markedly less than lead and it was highly machinable. The casting was done in a graphite mold shown in Figure 5. The hole in the alloy for the brass mounting rod was drilled after casting before removed from the mold. A push fit of the alloy over the brass rod holds the assembly, which is wired in place as a safety precaution.

In order to record high voltages with good sensitivity on a paper limited in size, it is necessary to cancel out a large accurately known portion of the signal ahead of the recorder with a potential source of inverse polarity. This potential source should be easily adjustable to facilitate reading the finished record by having the coordinates evenly located on the graph paper. This is the function which the bucking circuits, shown in Figure 6 perform in this paper. There are essentially two identical circuits, each consisting of three 200 ohm and one 25 ohm helipots in series with about 20 ohms of fixed resistance all
Figure 5. Graphite mold.
Figure 6. Detailed circuit diagram showing component values.
of which is across 6 volt automotive storage batteries. Provision was made for tapping off between the base of the first helipot, and the slider of any of the three. This is a simple potential divider system. The 25 ohm helipot is used for adjustment of the current in the circuit and thereby sensitive adjustment of the voltage tapped off. Further groups of fixed resistors (approximately 630 ohm), which can be placed in series with the rest, permit use of the system up to 18 volts by simply changing external connections. Figure 6 shows the external panel of these circuits containing a series of voltmeters for rough measuring.

A 200 ohm helipot and a choice of 200 ohm fixed resistors in the tap off lines permit the resistance in the main recording circuits to be kept constant even when the bucking voltages are changed.

The actual recording instrument was a Moseley, Model 2, X-Y recorder which consists of two independent, electronically amplifying, servo-mechanism recorders operating the same pen along two perpendicular axes. This instrument was normally set on such ranges that the full X-axis represented 0.150 volts (0 millivolts/inch) and the Y-axis represented 1.0 volts (100 millivolts/inch). At these settings the X and Y input terminals of the recorder acted as fixed resistors of 20,000 ohms and 200,000 ohms respectively. Rather than calibrate the X-Y plotter separately to record true input at its own terminals (as described in the operation manual) it was calibrated as a
part of the overall circuitry of this project to indicate and record the actual voltages across the standard resistor and sensing loops as they were independently determined with the previously mentioned hand operated potentiometer.

Six-volt automotive storage batteries were used as the source of power for heating the sensing loops. Rough adjustment in supply voltage was obtained by varying the number of batteries in series and changing the settings of three 2-ohm potentiometers and two 2.5-ohm fixed resistors in series with them. For the very slow and uniform output change needed during recording, no standard potentiometer system could be procured which had the required high power rating and low resolution. Therefore, the multiple wire, mercury dip contact, variable speed mechanical drive, variable resistor, shown in Figure 7, was made. The one ohm per foot chromel wire is strung between spring loaded bakelite end pieces on a polyethylene covered brass rod. This design proved useable but was expensive to fill with mercury and required that the surface of the mercury be cleaned before each day's use.\(^1\) A Graham reversible, variable speed transmission (16 rpm maximum) with a 1-1/4 inch diameter threaded cable drum was used to raise and lower the resistance wires by a heavy cord passed over a ball-

\(^1\)It was found that keeping an acetone-benzene mixture on the surface of the mercury improved performance. A proposal for better design of this component is given in the appendix.
Figure 7. Mercury dip resistor.
bearing pulley. Two 6000 microfarad, 15 volt direct current electrolytic capacitors were placed across the rough adjusting potentiometers and three across the variable mercury dip resistor to help even out voltage irregularities due to sudden resistance changes.

In the main circuit diagram, Figure 5 or 6, it will be noted that the recorder does not connect directly across the potentials to be measured but across the capacitors which are connected across the desired potentials through fixed resistances. This is a simple time delay arrangement used to damp out overly-rapid signal oscillations of short duration. Without this damping the inertia of the recording pen system caused it to "jitter" meaninglessly rather than record the actual voltage variations. These damping factors were arrived at by trial and error, a system of three 1000 microfarad, 15 volt capacitors limited by a 50-ohm resistor on the X-signal and one 6000 microfarad, 15-volt capacitor limited by a 10-ohm resistor on the Y-signal giving stable recording with nominal time lag. Fifty microfarad, 50-volt capacitors were also placed across both the X and Y-input terminals as recommended by Moseley to damp out stray 60-cycle signal since shielded leads were not used.
PROCEDURE

The platinum loops were annealed at 2.2 amperes for 24 hours after they were mounted in the position in which they were to be used. During annealing the air flow was shut off. After this anneal the loop being used was kept on continuously at approximately 1 ampere between runs and the air flow rate of the following run. During a run the current would be varied from 0 to 2 amperes as necessary.

Calibration of the recorder was accomplished by replacing the sensing element in the circuit with a variable resistor. This permitted the two signal voltages to be set to predetermined levels approximately equal to full scale with the sensitivity ranges used, and with the bucking circuit potentials appropriately set as will be explained later. The recorder was then set to indicate these values using the origin transposition controls provided on its operating panel. Next the input signals were readjusted to approach null readings on the recorder. The recorder was then adjusted to read these values with the calibration screws found near the input terminals. The procedure was then repeated until no further change was found necessary at either extreme of the signal. Further spot checks were run occasionally during use by comparing the actual signal voltages at steady state with those the recorder indicated.  

---

1 No significant drift was found over a two month period.
For measuring potentials greater than the full scale value of 1.6 volts available on the hand potentiometer, mercury cells of approximately 1.35 volts were placed in series with the potentiometer so that their potentials would be additive. The potentials of the mercury cells were first determined with the same potentiometer. In this service the mercury cells drifted a maximum of 0.00003 volts in 24 hours since all potentials were measured on a null balance basis.

In order to make a run it was necessary to establish a known fixed value of temperature and velocity. At room temperature the rotameter was adjusted to each level and each run made with only a simple check of temperature necessary, since it was found to correspond to ambient room temperature within the accuracy of measurement. However, for elevated temperature runs it was necessary to regulate the two powerstats controlling the temperature of the physical system walls and the temperature of the bulk stream entering, so that a uniform temperature was achieved across the stream at the sensing plane. This flat profile was assumed attained when the single diameter traverse of the thermocouple indicated no more than 2° Centigrade variation wall to wall. It took approximately 8 hours for a change in heating to come to equilibrium and 3 or 4 days to flatten the profile for each run. Recording a run took only about 6 hours.

Once the conditions for a run were achieved, the recorder was temporarily connected directly across the signal voltages
(no bucking potentials) and set on less sensitive scales so that a plot of the function $e = f(i)$ could be quickly made passing through the origin and reaching the highest $e$ and $i$ values safe for the sensing elements. This plot was then used as a guide in mapping out the bucking potentials necessary to fully cover the function with a minimum of the more sensitive recordings necessary for accuracy in reading $i$, $e$, and $s$ for calculating. The plot passing through the origin also serves as an excellent qualitative demonstration of the theory.

The bucking circuits were isolated from the circuit and set to the potentials determined as described above, using the hand potentiometer and mercury cells previously mentioned. The resistance compensators between the bucking circuits and recorder were then set accordingly to keep the circuit resistance constant. Next the recorder was set on the appropriate sensitivity scales and the graph paper labeled along its axes starting with the bucking potentials at the lower left hand corner. The recording system was then ready to operate.

To actually operate, the mercury dip variable resistor was placed in its position of maximum resistance and the power supply regulated with the adjusting resistors so that the recorder pen was at the bottom or left axis with the recorder servo-motors in action. Then the pen was put down and the mercury dip resistor was slowly lowered in resistance by mechanically lowering it into the mercury. This recording was normally done at a rate requiring approximately 5 minutes for a full traverse
of the paper. Greater recording speeds tended to introduce lag as evidenced by considerable lack of retrace on the return leg of operation.

Once a set of runs was completed they were placed together according to their overlapping axes values and checked for deviations from a single curve from sheet to sheet. Then a single "best" curve was drawn through irregular recordings using ship's curves. In order to avoid trouble from the assumption of linear resistance properties for platinum, all readings for a set of calculations were taken along a straight line passing through the origin which is the locus of all points having a fixed resistance or, therefore, a fixed wire temperature. At the intersection of each curve with the line through the origin, i and e were read directly. The value of \(-1/s\) was determined at these points by using the two glass rod method of finding the normal to a curve.

In this manner runs were recorded and calculated at three levels of temperature, three levels of velocity at each temperature, and three levels of wire resistance at each temperature velocity combination.

In making the calculations it is necessary to know the radial position and length of each loop. These were determined by taking photographs of the completed sensing elements at different wire temperatures while mounted inside the test section whose diameter was known. Using a planimeter on 8 by 10 inch enlargements of these pictures gave the ratios of the area of
each loop to that of the test section. This permitted calculation of the desired radial position in terms of \( X/X_0 \) (where \( X_0 \) is the radius of the test section), and the length of each loop plus the \( 1/4 \) inch actually taken up by electrical leads. The variation of position and length with wire temperature was not found significant so an arithmetic average of the determinations was used.
RESULTS

The four quantities \( R_0, 1/A, K \) and \( M \) were calculated using Equations (9) through (11) from the derivation. The data and results are tabulated in Tables 1 and 2 and the results are plotted in Figures 8 through 11. Since the theory being tested proposes that \( R_0, A, K, \) and \( M \) are constants, and since calculations for the latter three involve values of the preceding "constants", an arithmetic mean of the values from intersections along each constant resistance line was used in successive calculations.

The values of \( R_0A \) have a wide variation within each constant resistance group and a trend to lower values as the constant resistance parameter is increased. Theories to account for this are presented in the discussion.

The values of \( 1/A \) have less spread and a marked tendency to increase with an increasing constant resistance parameter. A theory for this is also presented in the discussion.

Values of \( K \) have a very wide spread and a very strong dependence upon \( t_a \). This effect tends to make uncertain a possible increase in \( K \) with an increasing resistance parameter. This is also to be discussed in view of the physical situation prevailing during measurements.

\( M \) also has a wide spread and probably trends downward with both increasing \( t_a \) and increasing constant resistance parameters.
Table 1. Data

<table>
<thead>
<tr>
<th>Resistance group</th>
<th>Temperature group</th>
<th>$t_a$ (°F)</th>
<th>$v$ (ft/sec)</th>
<th>$i$ (amps)</th>
<th>$e$ (volts)</th>
<th>$s$ (volts/amps)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1</td>
<td>75°</td>
<td>0.2499</td>
<td>1.3022</td>
<td>0.3450</td>
<td>0.5169</td>
</tr>
<tr>
<td>1</td>
<td>2</td>
<td>75°</td>
<td>0.4077</td>
<td>1.0266</td>
<td>0.3600</td>
<td>0.5603</td>
</tr>
<tr>
<td>1</td>
<td>3</td>
<td>75°</td>
<td>0.5620</td>
<td>1.4144</td>
<td>0.3747</td>
<td>0.5243</td>
</tr>
<tr>
<td>2</td>
<td>1</td>
<td>215°</td>
<td>0.3153</td>
<td>1.0810</td>
<td>0.2865</td>
<td>0.4060</td>
</tr>
<tr>
<td>2</td>
<td>2</td>
<td>215°</td>
<td>0.5157</td>
<td>1.0810</td>
<td>0.2865</td>
<td>0.4060</td>
</tr>
<tr>
<td>2</td>
<td>3</td>
<td>215°</td>
<td>0.7100</td>
<td>1.1388</td>
<td>0.3018</td>
<td>0.4089</td>
</tr>
<tr>
<td>3</td>
<td>1</td>
<td>338°</td>
<td>0.3748</td>
<td>0.6542</td>
<td>0.1734</td>
<td>0.3129</td>
</tr>
<tr>
<td>3</td>
<td>2</td>
<td>337°</td>
<td>0.6082</td>
<td>0.6986</td>
<td>0.1851</td>
<td>0.3134</td>
</tr>
<tr>
<td>3</td>
<td>3</td>
<td>337°</td>
<td>0.8331</td>
<td>0.7300</td>
<td>0.1935</td>
<td>0.3099</td>
</tr>
<tr>
<td>2</td>
<td>1</td>
<td>75°</td>
<td>0.2491</td>
<td>1.4826</td>
<td>0.4498</td>
<td>0.6644</td>
</tr>
<tr>
<td>2</td>
<td>2</td>
<td>75°</td>
<td>0.4082</td>
<td>1.5378</td>
<td>0.4665</td>
<td>0.6782</td>
</tr>
<tr>
<td>2</td>
<td>3</td>
<td>75°</td>
<td>0.5620</td>
<td>1.5962</td>
<td>0.4841</td>
<td>0.6862</td>
</tr>
<tr>
<td>2</td>
<td>1</td>
<td>215°</td>
<td>0.3145</td>
<td>1.2714</td>
<td>0.3858</td>
<td>0.5411</td>
</tr>
<tr>
<td>2</td>
<td>2</td>
<td>215°</td>
<td>0.5138</td>
<td>1.3310</td>
<td>0.4039</td>
<td>0.5495</td>
</tr>
<tr>
<td>2</td>
<td>3</td>
<td>212°</td>
<td>0.7042</td>
<td>1.4002</td>
<td>0.4249</td>
<td>0.5594</td>
</tr>
<tr>
<td>3</td>
<td>1</td>
<td>339°</td>
<td>0.3724</td>
<td>1.0192</td>
<td>0.3093</td>
<td>0.4441</td>
</tr>
<tr>
<td>3</td>
<td>2</td>
<td>335°</td>
<td>0.6074</td>
<td>1.0920</td>
<td>0.3313</td>
<td>0.4381</td>
</tr>
<tr>
<td>3</td>
<td>3</td>
<td>340°</td>
<td>0.8362</td>
<td>1.1260</td>
<td>0.3416</td>
<td>0.4312</td>
</tr>
<tr>
<td>3</td>
<td>1</td>
<td>75°</td>
<td>0.2496</td>
<td>1.6150</td>
<td>0.5454</td>
<td>0.7946</td>
</tr>
<tr>
<td>3</td>
<td>2</td>
<td>75°</td>
<td>0.4087</td>
<td>1.6704</td>
<td>0.5642</td>
<td>0.8000</td>
</tr>
<tr>
<td>3</td>
<td>3</td>
<td>75°</td>
<td>0.5627</td>
<td>1.7292</td>
<td>0.5838</td>
<td>0.8114</td>
</tr>
<tr>
<td>3</td>
<td>1</td>
<td>215°</td>
<td>0.3161</td>
<td>1.4350</td>
<td>0.4848</td>
<td>0.6609</td>
</tr>
<tr>
<td>3</td>
<td>2</td>
<td>215°</td>
<td>0.5138</td>
<td>1.5030</td>
<td>0.5075</td>
<td>0.6758</td>
</tr>
<tr>
<td>3</td>
<td>3</td>
<td>212°</td>
<td>0.7069</td>
<td>1.5730</td>
<td>0.5313</td>
<td>0.6763</td>
</tr>
<tr>
<td>3</td>
<td>1</td>
<td>339°</td>
<td>0.3724</td>
<td>1.2346</td>
<td>0.4168</td>
<td>0.5624</td>
</tr>
<tr>
<td>3</td>
<td>2</td>
<td>335°</td>
<td>0.6080</td>
<td>1.3212</td>
<td>0.4462</td>
<td>0.5594</td>
</tr>
<tr>
<td>3</td>
<td>3</td>
<td>341°</td>
<td>0.8379</td>
<td>1.3660</td>
<td>0.4614</td>
<td>0.5758</td>
</tr>
</tbody>
</table>
### Table 2. Results

<table>
<thead>
<tr>
<th>Resist-</th>
<th>Temp-</th>
<th>Velocity</th>
<th>$R_0 A x 10^4$</th>
<th>Resist-</th>
<th>Temp-</th>
<th>Velocity</th>
<th>$1/A$</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>group</td>
<td>group</td>
<td></td>
<td>group</td>
<td>group</td>
<td>group</td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>1+2</td>
<td>1</td>
<td>2.178</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>649.5</td>
</tr>
<tr>
<td>1</td>
<td>2+3</td>
<td>1</td>
<td>2.679</td>
<td>1</td>
<td>2</td>
<td>1</td>
<td>632.5</td>
</tr>
<tr>
<td>1</td>
<td>1+3</td>
<td>1</td>
<td>2.412</td>
<td>1</td>
<td>3</td>
<td>1</td>
<td>642.5</td>
</tr>
<tr>
<td>1</td>
<td>1+2</td>
<td>2</td>
<td>2.176</td>
<td>1</td>
<td>1</td>
<td>2</td>
<td>646.5</td>
</tr>
<tr>
<td>1</td>
<td>2+3</td>
<td>2</td>
<td>2.745</td>
<td>1</td>
<td>2</td>
<td>2</td>
<td>629.4</td>
</tr>
<tr>
<td>1</td>
<td>1+3</td>
<td>2</td>
<td>2.441</td>
<td>1</td>
<td>3</td>
<td>2</td>
<td>642.5</td>
</tr>
<tr>
<td>1</td>
<td>1+2</td>
<td>3</td>
<td>2.178</td>
<td>1</td>
<td>1</td>
<td>3</td>
<td>642.6</td>
</tr>
<tr>
<td>1</td>
<td>2+3</td>
<td>3</td>
<td>2.946</td>
<td>1</td>
<td>2</td>
<td>3</td>
<td>625.7</td>
</tr>
<tr>
<td>1</td>
<td>1+3</td>
<td>3</td>
<td>2.536</td>
<td>1</td>
<td>3</td>
<td>3</td>
<td>648.7</td>
</tr>
<tr>
<td>2</td>
<td>1+2</td>
<td>1</td>
<td>1.991</td>
<td>2</td>
<td>1</td>
<td>1</td>
<td>747.2</td>
</tr>
<tr>
<td>2</td>
<td>2+3</td>
<td>1</td>
<td>2.282</td>
<td>2</td>
<td>2</td>
<td>1</td>
<td>727.8</td>
</tr>
<tr>
<td>2</td>
<td>1+3</td>
<td>1</td>
<td>2.128</td>
<td>2</td>
<td>3</td>
<td>1</td>
<td>726.0</td>
</tr>
<tr>
<td>2</td>
<td>1+2</td>
<td>2</td>
<td>2.023</td>
<td>2</td>
<td>1</td>
<td>2</td>
<td>735.9</td>
</tr>
<tr>
<td>2</td>
<td>2+3</td>
<td>2</td>
<td>2.699</td>
<td>2</td>
<td>2</td>
<td>2</td>
<td>718.4</td>
</tr>
<tr>
<td>2</td>
<td>1+3</td>
<td>2</td>
<td>2.355</td>
<td>2</td>
<td>3</td>
<td>2</td>
<td>739.0</td>
</tr>
<tr>
<td>2</td>
<td>1+2</td>
<td>3</td>
<td>2.001</td>
<td>2</td>
<td>1</td>
<td>3</td>
<td>729.3</td>
</tr>
<tr>
<td>2</td>
<td>2+3</td>
<td>3</td>
<td>2.905</td>
<td>2</td>
<td>2</td>
<td>3</td>
<td>710.9</td>
</tr>
<tr>
<td>2</td>
<td>1+3</td>
<td>3</td>
<td>2.438</td>
<td>2</td>
<td>3</td>
<td>3</td>
<td>744.0</td>
</tr>
<tr>
<td>3</td>
<td>1+2</td>
<td>1</td>
<td>1.930</td>
<td>3</td>
<td>1</td>
<td>1</td>
<td>931.0</td>
</tr>
<tr>
<td>3</td>
<td>2+3</td>
<td>1</td>
<td>2.007</td>
<td>3</td>
<td>2</td>
<td>1</td>
<td>926.0</td>
</tr>
<tr>
<td>3</td>
<td>1+3</td>
<td>1</td>
<td>1.966</td>
<td>3</td>
<td>3</td>
<td>1</td>
<td>927.0</td>
</tr>
<tr>
<td>3</td>
<td>1+2</td>
<td>2</td>
<td>1.754</td>
<td>3</td>
<td>1</td>
<td>2</td>
<td>927.0</td>
</tr>
<tr>
<td>3</td>
<td>2+3</td>
<td>2</td>
<td>2.434</td>
<td>3</td>
<td>2</td>
<td>2</td>
<td>909.0</td>
</tr>
<tr>
<td>3</td>
<td>1+3</td>
<td>2</td>
<td>2.068</td>
<td>3</td>
<td>3</td>
<td>2</td>
<td>935.0</td>
</tr>
<tr>
<td>3</td>
<td>1+2</td>
<td>3</td>
<td>1.935</td>
<td>3</td>
<td>1</td>
<td>3</td>
<td>916.4</td>
</tr>
<tr>
<td>3</td>
<td>2+3</td>
<td>3</td>
<td>1.974</td>
<td>3</td>
<td>2</td>
<td>3</td>
<td>912.0</td>
</tr>
<tr>
<td>3</td>
<td>1+3</td>
<td>3</td>
<td>1.954</td>
<td>3</td>
<td>3</td>
<td>3</td>
<td>910.0</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Resist-</th>
<th>Temp-</th>
<th>Velocity</th>
<th>$K x 10^4$</th>
<th>Resist-</th>
<th>Temp-</th>
<th>Velocity</th>
<th>$M x 10^4$</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>group</td>
<td>group</td>
<td></td>
<td>group</td>
<td>group</td>
<td>group</td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>1</td>
<td>1+2</td>
<td>9.311</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>11.27</td>
</tr>
<tr>
<td>1</td>
<td>1</td>
<td>2+3</td>
<td>8.264</td>
<td>1</td>
<td>1</td>
<td>2</td>
<td>9.90</td>
</tr>
<tr>
<td>1</td>
<td>1</td>
<td>1+3</td>
<td>8.944</td>
<td>1</td>
<td>1</td>
<td>3</td>
<td>9.65</td>
</tr>
</tbody>
</table>
Table 2. (Continued)

<table>
<thead>
<tr>
<th>Resistance group</th>
<th>Temperature pair</th>
<th>Kx10^4</th>
<th>Resistance group</th>
<th>Temperature group</th>
<th>Mx10^4</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>2</td>
<td>1+2</td>
<td>10.550</td>
<td>1</td>
<td>2</td>
</tr>
<tr>
<td>1</td>
<td>2</td>
<td>2+3</td>
<td>2.368</td>
<td>1</td>
<td>2</td>
</tr>
<tr>
<td>1</td>
<td>2</td>
<td>1+3</td>
<td>7.719</td>
<td>1</td>
<td>2</td>
</tr>
<tr>
<td>1</td>
<td>3</td>
<td>1+2</td>
<td>6.824</td>
<td>1</td>
<td>3</td>
</tr>
<tr>
<td>1</td>
<td>3</td>
<td>2+3</td>
<td>-0.261</td>
<td>1</td>
<td>3</td>
</tr>
<tr>
<td>1</td>
<td>3</td>
<td>1+3</td>
<td>4.369</td>
<td>1</td>
<td>3</td>
</tr>
<tr>
<td>2</td>
<td>1</td>
<td>1+2</td>
<td>11.090</td>
<td>2</td>
<td>1</td>
</tr>
<tr>
<td>2</td>
<td>1</td>
<td>2+3</td>
<td>9.073</td>
<td>2</td>
<td>1</td>
</tr>
<tr>
<td>2</td>
<td>1</td>
<td>1+3</td>
<td>10.400</td>
<td>2</td>
<td>1</td>
</tr>
<tr>
<td>2</td>
<td>2</td>
<td>1+2</td>
<td>9.985</td>
<td>2</td>
<td>2</td>
</tr>
<tr>
<td>2</td>
<td>2</td>
<td>2+3</td>
<td>7.854</td>
<td>2</td>
<td>2</td>
</tr>
<tr>
<td>2</td>
<td>2</td>
<td>1+3</td>
<td>9.247</td>
<td>2</td>
<td>2</td>
</tr>
<tr>
<td>2</td>
<td>3</td>
<td>1+2</td>
<td>4.098</td>
<td>2</td>
<td>3</td>
</tr>
<tr>
<td>2</td>
<td>3</td>
<td>2+3</td>
<td>5.512</td>
<td>2</td>
<td>3</td>
</tr>
<tr>
<td>2</td>
<td>3</td>
<td>1+3</td>
<td>4.581</td>
<td>2</td>
<td>3</td>
</tr>
<tr>
<td>3</td>
<td>1</td>
<td>1+2</td>
<td>10.130</td>
<td>3</td>
<td>1</td>
</tr>
<tr>
<td>3</td>
<td>1</td>
<td>2+3</td>
<td>9.305</td>
<td>3</td>
<td>1</td>
</tr>
<tr>
<td>3</td>
<td>1</td>
<td>1+3</td>
<td>9.856</td>
<td>3</td>
<td>1</td>
</tr>
<tr>
<td>3</td>
<td>2</td>
<td>1+2</td>
<td>9.777</td>
<td>3</td>
<td>2</td>
</tr>
<tr>
<td>3</td>
<td>2</td>
<td>2+3</td>
<td>6.135</td>
<td>3</td>
<td>2</td>
</tr>
<tr>
<td>3</td>
<td>2</td>
<td>1+3</td>
<td>8.508</td>
<td>3</td>
<td>2</td>
</tr>
<tr>
<td>3</td>
<td>3</td>
<td>1+2</td>
<td>5.291</td>
<td>3</td>
<td>3</td>
</tr>
<tr>
<td>3</td>
<td>3</td>
<td>2+3</td>
<td>12.330</td>
<td>3</td>
<td>3</td>
</tr>
<tr>
<td>3</td>
<td>3</td>
<td>1+3</td>
<td>7.740</td>
<td>3</td>
<td>3</td>
</tr>
</tbody>
</table>
Figure 8. R_0A Results.
RESISTANCE \( r \), ohms

\[ r_1 = 0.2650 \]
\[ r_2 = 0.3034 \]
\[ r_3 = 0.3377 \]

CALCULATION FOR \( t_a = 75^\circ F \)

CALCULATION FOR \( t_a = 215^\circ F \)

CALCULATION FOR \( t_a = 338^\circ F \)

ARITHMETIC MEAN OF ALL POINTS FOR RESPECTIVE "r"

Figure 9. 1/A Results.
Figure 10. K Results.
RESISTANCE, $r$, ohms

$r_1 = 0.2650$
$r_2 = 0.3034$
$r_3 = 0.3377$

Figure 11. M Results.
DISCUSSION

Figure 14 in the appendix shows the reduced sensitivity plot of the curves extended from the origin. A typical full sensitivity curve section sheet with added "best curve" lines and constant resistance lines, with their intersections labeled is shown in Figure 15. Figure 16 is a picture of the curve sections fitted together and extrapolated to the origin for purposes of demonstrating their qualitative adherence to the form of the reduced sensitivity curves and the form predicted by the basic equations. In the limit it will be noted that with little or no current flowing, the sensing element is essentially an ambient temperature resistance thermometer with the slope of the straight lines near the origin indicating wire resistances and therefore gas temperatures. At the other extreme, the sensing element tends to become a conventional hot wire anemometer with the temperature difference so great that a change in gas temperature has little effect on the wire temperature or resistance. Hence the separation of the curves is mainly a function of gas velocity. Accordingly data for this combined application were read from the curves at an intermediate region where both variables are important in determining the condition of the wire.

When the curve section sheets were fitted together, they were found to agree well in the overlapping parts in all but about three places. However, all the curves had too much
"wiggle" to permit single point value reading directly. Therefore "best" curves were visually placed through the X - Y plotter results with ship's curves and these smooth curves were used for the actual calculation of data.

A sample calculation procedure is shown in the appendix.

Data for use in calculation of \( R_0 \), \( A \), \( K \), and \( M \) were taken at points of constant resistance. As indicated in Figures 14 and 15, these equal resistance points were obtained at intersections of the experimental curves with straight lines through the origin. This was done in order to permit evaluation of the importance of non-linear resistance characteristics of the sensing element wire used. If the resistance of the sensing element were linear with respect to its temperature \( t_w \), values of \( R_0 \) and \( A \) would be truly constant despite the level of resistance at which they were determined, since they are the constants in the linear resistance equation

\[
(3) \quad r = R_0 \left[ 1 + A(t_w - 0) \right]
\]

However, if the temperature-resistance relationship of the wire is non-linear these values must be pseudo-constants varying with the level of \( r \) for which they are determined. None-the-less at a particular value of \( r \) these pseudo-constants should exist and would change only when \( r \) changed.

The dependence of \( R_0 \) and \( A \) upon the level of resistance indicates the non-linearity of resistance for the platinum wire used which was also indicated in three other ways.
1. Independent measurement of $r$ versus $t_w$ with the wire in a controlled furnace gave a curved relationship which could not be reproduced if the sequence and rate of heating and cooling were not also duplicated.

2. Strong overheating of the wire in the instrument for a period of 24 hours gave a decided drift from the original curve which could only be remedied by a further 24-hour annealing period at the lower temperature appropriate to that region of the curve.

3. Spectrographic analysis of the wire used indicated the presence of 1 per cent to 5 per cent rhodium. Corrucini\(^1\) in an article for the Bureau of Standards indicates that traces of metallic impurities alter the resistance properties of pure platinum wire markedly.

Variations of the pseudo-constants within a fixed resistance-determination group however can be accounted for only by experimental error or a very serious non-applicability of the equations (7) and (8) used in their calculation.

It was noted in the data taken that shifting the measured intermediate temperature of approximately 215°F to a fictitious

\(^1\)Corrucini, op.cit. pp. 94-103
value of 200°F and leaving the extremes as before at approximately 75° and 335°F, decreased the spread of the $R_0A$ data very considerably without changing its trend with the parameter of $r$. Thus it would appear that the wide spread of the $R_0A$ values might be attributed to inaccuracies in determining $t_a$. Since $t_a$ was determined from a thermocouple traverse across one fixed diameter, this appears to be a valid possibility.

No explanation has been offered for a possible tendency of $R_0A$ to vary with $v$ other than unsuitability of the equation used to determine this quantity for the actual mechanism involved. If the theorized equations and measurements of $t_a$ and $s$ were correct, $R_0$ and $A$ would have to be fixed psuedo-constants within each constant $r$ group determination for the reasons previously stated.

Values of $K$, which according to King\(^1\) correspond to the thermal conductivity of the gas involved, might logically be expected to vary with the temperature of the gas. Random variation of $K$ at a fixed $t_a$ could be attributed to experimental inaccuracies in the determination of $s$ which figures prominently in determining $\dot{d} = \frac{\dot{s}i + \dot{e}}{\dot{s}i - \dot{e}}$ in Equation (9). Successive attempts to determine $s$ at a fixed intersection gave values frequently varying by as much as 10 per cent on the particular curves taken in this experiment. A more accurate method of finding slopes is needed than that used.

\(^1\)King, op. cit. p.401
It is assumed that the values of v used were accurate since they were found in the conventional manner of working in the laminar region of flow and assuming a parabolic flow distribution. The bulk rate of flow is known from a rotameter and the pressure and temperature of the flow are known permitting application of the perfect gas law.

It is of interest to note qualitatively the curves of Figures 17 through 21 in the appendix, where each curve represents one setting of the rotameter with the flow rates decreasing as their alphabetic designation rises. The alphabetic designation refers to the same bulk flow rate in each figure. The approximately straight line intersecting the curves is the result of changing the velocity across full scale, while the electrical components of the system were untouched. Therefore, fluctuations from a smooth curve in the direction of these intersecting lines indicates a corresponding velocity fluctuation. In truly laminar flow no such fluctuations exist. It will be noted that the bulk flow rate at which these fluctuations achieve noticeable proportions decreases as the location of the sensing element approaches the center. This is as would be expected. Therefore, the three levels of flow for this experiment were chosen below the rate at which these fluctuations become appreciable, even though this is very considerably below the commonly used Reynolds Number criteria of 2100. This incipient turbulence at low Reynolds Numbers can be accounted for by the rough walls of the commercial pipe used, and the inadequate
calming section. This effect is predictable by an equation from Rouse.  

\begin{equation}
\frac{X}{D} = 0.07 \frac{VD}{\mu}
\end{equation}

where

- \( X \) = pipe length to establish steady state
- \( D \) = pipe diameter
- \( V \) = velocity of fluid
- \( \mu \) = viscosity of fluid

Values of \( M \) could logically be expected to vary with both wire and gas temperature since \( M \) is really a form of convection coefficient. Normally convection coefficients are considered to be dependent on some "effective" properties of the gas. These effective values are commonly arrived at by looking up properties of the gas as some average between the temperatures of the heating and cooling medium. Therefore, a variation of \( M \) with both \( t_a \) and \( r \) would not be unreasonable in view of the physical situation. In addition, calculated values of \( M \) accumulate all errors involved in the determination of the previous constants as Equation (10) indicates.

---

CONCLUSIONS AND RECOMMENDATIONS

In light of the results, it is concluded that the simple theory and equations proposed do not describe the behavior of the system of instrumentation adequately to permit quantitative determinations of simultaneous temperature and velocity values over the range covered in this project. It is further concluded that the inconsistencies of the results with regard to the theory are largely due to inaccurate determinations of \( t_a \) and \( s \) and variations of the actual mechanism of measurement from the simplified assumptions of the derivation.

Therefore, if further work is to be done on this theory of instrumentation, it is imperative that means be found to more accurately determine \( t_a \) and \( s \) and that calibration attempts be made at considerably more than three levels of both temperature and velocity. This would be necessary to determine the true relationships of \( K \) and \( M \) to \( t_a \). If these relationships can be accurately determined at a fixed \( r \) value, it should be possible to measure \( \overline{T}_a \) and \( \overline{V} \) using the equations of this thesis repetitively, with the values of \( K \) and \( M \) changed in each successive calculation to agree with the preceding calculation results for \( t_a \) and \( v \). Such repetitive calculations would be continued until the values of \( t_a \) and \( v \) ceased to change appreciably in successive calculations.
SAMPLE CALCULATION PROCEDURE

Values of $E_e$ and $E_i$ and the slope of the geometric normals to the curves are read at points of intersection with a constant resistance line. These are tabulated with the corresponding values of $t_a$ and rotameter and pressure gauge readings. Points $^0_{\text{XVIII}}$ and $^0_{\text{XVII}}$ can be found in Figure 15. The right hand superscript, subscript and left hand subscript in that order designate the respective levels of resistance, temperature and velocity.

<table>
<thead>
<tr>
<th>Intersection designation</th>
<th>Constant resistance</th>
<th>$t_a$ from Rotameter couple reading</th>
<th>Rotameter pressure</th>
<th>$E_e$</th>
<th>$E_i$</th>
<th>$\frac{\Delta E_e}{\Delta E_i}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$^0_{\text{XVIII}}$</td>
<td>0.2649</td>
<td>75°F 6.00</td>
<td>23.8 3.484</td>
<td>0.6511</td>
<td>-1.000</td>
<td>0.1044</td>
</tr>
<tr>
<td>$^0_{\text{XVII}}$</td>
<td>0.2649</td>
<td>75°F 10.00</td>
<td>23.2 3.636</td>
<td>0.6793</td>
<td>-1.000</td>
<td>0.1051</td>
</tr>
<tr>
<td>$^1_{\text{XXV}}$</td>
<td>0.2649</td>
<td>215°F 6.00</td>
<td>23.8 2.747</td>
<td>0.5133</td>
<td>-1.000</td>
<td>0.0815</td>
</tr>
<tr>
<td>$^1_{\text{V2}}$</td>
<td>0.2649</td>
<td>215°F 10.00</td>
<td>23.5 2.894</td>
<td>0.5405</td>
<td>-1.000</td>
<td>0.820</td>
</tr>
</tbody>
</table>

$E_e$ as read from the curve is converted to $e$ by dividing by the loop length of 10.100 inches. $E_i$ is converted to $i$ by dividing by 0.500, the value of the standard resistor used to convert the current to a voltage signal. The negative reciprocals of $\frac{\Delta E_e}{\Delta E_i}$ for the normal slopes are multiplied by $10^2$ to give $\frac{\Delta E_e}{\Delta E_i}$. 


for the slopes of the tangents to the curves. This is necessary due to the factor of 10 between the two scale axes. Then the previously mentioned conversions from $E_e$ and $E_i$ are applied to give the slopes of the tangents to the curves in terms of $e$ and $i$. These new slope ratios are $de/di$ at the point $i,e$ and are designated $s$. From these values of $i,e$ and $s$ the other necessary combinations were computed in the tabulated order.

<table>
<thead>
<tr>
<th>Intersection designation</th>
<th>$i$</th>
<th>$e$</th>
<th>$s$</th>
<th>$r = \frac{e}{i}$</th>
<th>$\frac{1}{d} = \frac{s - e}{i + e}$</th>
<th>$1 - \frac{1}{d}$</th>
<th>$i^2d$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$0$ XVIII $1$</td>
<td>1.3022</td>
<td>0.3450</td>
<td>0.5169</td>
<td>0.2649</td>
<td>0.3223</td>
<td>0.6777</td>
<td>5.261</td>
</tr>
<tr>
<td>$0$ XVII $1$</td>
<td>1.3586</td>
<td>0.3600</td>
<td>0.5203</td>
<td>0.2650</td>
<td>0.3251</td>
<td>0.6749</td>
<td>5.678</td>
</tr>
<tr>
<td>$1$ XXV $1$</td>
<td>1.0266</td>
<td>0.2720</td>
<td>0.4035</td>
<td>0.2650</td>
<td>0.2072</td>
<td>0.7928</td>
<td>5.086</td>
</tr>
<tr>
<td>$1$ $1$ $2$V $2$</td>
<td>1.0810</td>
<td>0.2865</td>
<td>0.4060</td>
<td>0.2650</td>
<td>0.2101</td>
<td>0.7899</td>
<td>5.316</td>
</tr>
</tbody>
</table>

The bulk flow rate was determined from the rotameter and pressure readings using the calibration curve and pressure correction factor chart supplied with the rotameter. This value is in terms of cubic feet per minute at 70°F. and 14.7 psia. This was converted to average velocity by multiplying by the ratio of absolute temperatures and dividing by the cross sectional area of the 4.05 inch diameter test section. Conversion of average velocity in ft./min. to ft./sec. at the radial position of interest was accomplished by multiplying by $\frac{2\sqrt{1 - \left(\frac{x}{x_0}\right)^2}}{60}$
where \( \left( \frac{\chi}{\chi_0} \right)^2 \), the reduced radial position squared, had a value of 0.6610 for the loop used.

<table>
<thead>
<tr>
<th>Intersection designation</th>
<th>Rotameter chart reading</th>
<th>Pressure correction multiplier</th>
<th>( t_a ) absolute temperature ( {}^\circ ) Rankine</th>
<th>( v(\text{ft/sec}) ) at ( \sqrt{v} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>0\text{XVIII} \text{1}</td>
<td>1.220</td>
<td>1.61</td>
<td>535°</td>
<td>0.2499, 0.4999</td>
</tr>
<tr>
<td>0\text{XVII} \text{1}</td>
<td>2.003</td>
<td>1.60</td>
<td>535°</td>
<td>0.4077, 0.6385</td>
</tr>
<tr>
<td>1\text{XXV} \text{2}</td>
<td>1.220</td>
<td>1.61</td>
<td>675°</td>
<td>0.3153, 0.5615</td>
</tr>
<tr>
<td>2\text{V} \text{2}</td>
<td>2.003</td>
<td>1.60</td>
<td>675°</td>
<td>0.5157, 0.7181</td>
</tr>
</tbody>
</table>

Using the values of these preliminary tabulations substitution was made in Equations (7) through (10) thus:

\[
(7) \quad R_0A = \frac{r\sqrt{1 - \frac{1}{d_1}}p\left(1 - \frac{1}{d_2}\right)}{t_{a_1} - t_{a_2}} = \frac{0.2649(0.4999)(5.678) - 0.6385(5.261)}{0.4997 - 0.6385}.
\]

\[
= 0.0002178.
\]

\[
(8) \quad \frac{1}{A} = \frac{r}{R_0A} (1 - \frac{1}{d}) - t_a = \frac{0.2649}{0.0002477} (0.6777) - 75 = 649.5
\]

The value of \( R_0A \) used is the arithmetic average of all values calculated for it from data at \( r = 0.2649 \).

\[
(9) \quad K = \frac{R_0A\sqrt{V_1}(i^2d_1) - (v_2)(i^2d_2)}{\sqrt{v_1} - \sqrt{v_2}}.
\]

\[
= \frac{0.0002477(0.4999)(5.678) - (0.6385)(5.261)}{0.4997 - 0.6385}.
\]
\[ M = \frac{R_0A(i^3d) - K}{\sqrt{v}} = \frac{(0.0002477)(5.261) - 0.0006454}{0.4999} = 0.001316 \]

Where the value of \( K \) used is the arithmetic average of all values found for it at \( r = 0.2649 \).
Figure 12. Proposed circuit for using a single sensing element alternately as a hot wire anemometer or an ambient resistance thermometer.
Figure 13. Proposed improved design to supersede the mercury dip resistor used.
Figure 14. Reduced sensitivity plot including origin.
Figure 16. Assembled curve section sheets.
Figure 17. Loop 1 results for changing velocity at room temperature
Figure 18. Loop 2 results for changing velocity at room temperature.
Figure 20. Loop 4 results for changing velocity at room temperature.
Figure 21. Loop 5 results for changing velocity at room temperature.