A METHOD OF MEASURING PROPERTIES OF A FLUID

Thesis for the Degree of M. S.

MICHIGAN STATE COLLEGE

Edward Archie Daly

1951

A METHOD OF MEASURING PROPERTIES OF A FLUID

BY

Edward Archie Daly

A THESIS

Submitted to the School of Graduate Studies of Michigan State College of Agriculture and Applied Science in partial fulfillment of the requirements for the degree of

Master of Science

Department of Mechanical Engineering

1951

A C K N O W L E D G M E N T

I would like to express my appreciation to Mr. R. M. Rotty of the Mechanical Engineering Department from whom I received advice and suggestions; Professor Charles Pesterfield of the Mechanical Engineering Department, my Major Professor; Dr. R. J. Jeffries of the Electrical Engineering Department from whom I obtained an extensive bibliography on this subject; and the Mechanical Engineering, Electrical Engineering and Physics Departments from which I borrowed the equipment for the experimental portion of this thesis.

TABLE OF CONTENTS

HISTORY AND DEVELOPMENT OF THE HOT-WIRE ANEMOMETER

The Hot-Wire Anemometer in its simplest form is a device for measuring the velocity of a moving fluid by measurin the heat loss of a small, electrically heated, wire placed in the fluid path. This is at present handled in either of two ways. First, by maintaining a constant wire resistance and, therefore, a constant wire temperature; second, by maintaining a constant current flow through the wire.

A small metallic wire - nickel, platinum or tungsten is generally used - is suspended in the moving fluid. This wire is then heated, by an electric current, to some temperature above the ambient temperature of the fluid. The resulting heat loss can then be measured by measuring the power dissipated. Now, since the fluid is moving, that around the wire will constantly be being replaced. The rate at which this fluid around the wire is replaced is the mass flow of the fluid. Therefore, the heat loss is a function of the mass flow of the fluid as well as the existing temperature difference. There are other factors and complications involved, some of which will be discussed later on.

The first article I could find on, or pertaining to, this subject was published by three Americans, A. E. Kennelly,

C. A. Wright and J. S. Van Bylevelt (1). These men conducted experiments and worked out some theory on the heat loss from small copper wires. In 1912, two Englishmen, Mac Gregorond and Morris (2), constructed a hot-wire anemometer and determined an equation relation of the heat loss and velocity from experiments with this instrument. About this same time an Italian, U. Bordoni (3), carried out some work along this line; I did not obtain translations of his article, and, therefore, am not sure if he did his work experimentally or theoretically. Bordoni's work was mentioned in several articles, but chiefly in an article by Carlo Ferrari (4).

The most detailed and important theoretical work, and the one on which most all of the present development is based, was done by an Englishman, L. V. King (5), and the equation

---

1. Kennelly, A. E., Wright, C. A. and Van Bylevelt, J.S. "The Convection of Heat from Small Copper Wires", The Transactions Of The American Institute of Electrical Engineers, Vol. 9, Part 1, 1910, pp. 363-397.

2. Mac Gregorond and Morris, J. T., "The Electrical Measurement of Wind Velocity", Engineering, Vol. 94, No. 26, Dec. 27, 1912, pp. 892-894.

3. Bordoni, U., Electrician, Vol. 70, Nov. 22, 1912, p. 278.

4. Ferrari, Carlo, "Electrical Equipment for The Experimental Study of The Dynamics of Fluids", N.A.C.A. Tech Memo, No. 1006, 1942.

5. King, L. V., "On The Convection of Heat From Small Cylinders in a Stream of Fluid: Determination of The Convection Constants Of Small Platinum Wires With Application To Hot-Wire Anemometer", Phil. Trans. Roy. Soc. (London), Sec. A, Vol. 214, Nov. 1914, pp. 373-432.

relating the properties of a moving fluid and the heat loss of a heated wire bears his name. King carried out an extensive theoretical development from which he developed two equations;

For small velocities

$$H = 2k\theta_0 / [\ln(b/a)] \qquad (1)$$

For large velocities

$$H = k\theta_0 + 2\sqrt{\pi ksd}\,(\rho v)^{\frac{1}{2}}\,\theta_0 \qquad (2)$$

where

H is the heat loss per unit time per unit length of the wire.

k is the thermal conductivity of the fluid.

θ_0 is the temperature difference between the fluid and the wire.

s is the specific heat of the fluid.

d is the diameter of the wire.

ρ is the density of the fluid.

v is the velocity of the fluid.

Only the second equation is of much general interest and of any interest in this report.

King developed this equation on a number of rather limiting assumptions and the equation, in this form, is only of passing interest.

Since King developed his equation there has been extensive development of this type of instrument. Among the other important articles are reports by H. L. Dryden and Kuethe (6) in 1929; three reports by J. R. Weske (7, 8 and 9) in 1943 and 1949; and one by Stanley Corrsin (10) in 1949.

The article by Dryden and Kuethe is the bases of much of the work using the constant current method of measuring velocity fluctuations. They did their work on the assumption that the equation depended only on the instantaneous values of its terms and not on their rate of change; that is, that the equation would hold under varying conditions provided the instrument was capable of reacting to these changes. The results they and others have obtained has shown this assumption to be valid.

J. R. Weske did some work on extending the useful range of the instrument in to the subsonic range of velocities. He also experimented with the effects of different wire materials and dimensions.

Corrsin's work was chiefly theoretical, he advanced theory on the extended use of this type of instrument in the

---

6. Dryden, H. L. and Kuethe, A. M., "The Measurement of Fluctuations of Air Speed by the Hot-Wire Anemometer", N.A.C.A. Rep. No. 320, 1929.

7. Weske, J. R., "Method of Measurement of High Air Velocities by The Hot-Wire Method", N.A.C.A. Tech Note, No. 880, 1943.

8. Weske, J. R., "A Hot-Wire Cirduit With Very Small Time Lag", N.A.C.A. Tech Note, No. 881, 1943.

9. Weske, J. R., "Measurement of Arithmetic Mean Velocity of Pulsating Flow of High Velocities By Hot-Wire Method", N.A.C.A. Tech Note, No. 990, April, 1949.

10. Corrsin, Stanley, "Extended Applications Of The Hot-Wire Anemometer", N.A.C.A. Tech Note, No. 1864, April 1949.

study of turbulent flow and the mixing of gases.

Many other articles have been written on the directional characteristics of the Hot-Wire Anemometer and on instrumentation for its many varied uses. A list of some of these articles can be found in "Appendix C" under "General References".

KING'S EQUATION

Since this report will only be concerned with an instrument for measuring constant, or relatively constant, values, the discussion here will be of that type of instrument.

The assumptions that King (5) made in developing his equation are briefly these; that

1. The temperature difference between the wire and the fluid remain constant,
2. The properties of the fluid - thermal conductivity, specific heat and density - remain constant,
3. There be laminar flow over the wire,
4. The wire be normal to the direction of fluid flow,
5. The wire temperature be uniform over the length of the wire,
6. The losses of radiation from the wire and viscosity of the fluid are negligible.

Many of these conditions either can not be met or it is impractical to satisfy them in practices. Also, the equations

given are only approximate forms of the more detailed equation he developed. The approximate forms were necessary to simplify the equation for this type of application.

The first, second and third assumptions can be satisfied in practice, but it is impractical to do so as this would limit the usefulness of the instrument. And, within limits, it is not necessary to satisfy these assumptions if a system that is not sensitive to small fluctuations is used. This can be accomplished by using a galvanometer with a period necessary to damp out small fluctuations or by using a wire with a heat inertia that will prevent it from reacting to small changes. Since a very small wire is desirable, the first method would seem to be preferable.

The fourth assumption can be satisfied within reasonable limits by adjusting the wire in the fluid stream to the position of greatest heat loss (11). While there will be some small variations under even good conditions, these will be taken up by the inertia used to approximate the first three assumptions. For conditions which have variations of any magnitude, it is necessary to use the directional characteristics of the Hot-Wire. This is covered in some of the references listed under "General References".

---

11. Simmons, L. F. G. and Bailey, A., "An Instrument for Measuring Speed and Direction of Air Flow", Phil. Mag., Vol. 3, 1927, pp. 81-96.

The fifth and sixth assumptions are probably the most difficult to meet in practice. Since the wire must be supported, there will be end losses and the wire temperature will, therefore, not be uniform over its length. Also the wire must be very small, the order of thousands of an inch, and its characteristics will be difficult to determine with any degree of accuracy. Even if these characteristics could be accurately determined, it is more convenient to handle it in another way.

The seventh assumption may, or may not, be approached in practice. I did not find any convincing proof either way in the many articles on this type of instrument. Since this loss will be very small, most of these who worked with this type instrument have assumed that they will be merely additive. There are several noteworthy cases of disagreement with this assumption (10 and 12), but results have justified it to a large extent. This idea is further brought out by others (12) who have compared experimental results with the expected results from King's more exact form of his equation. Here it was found that the curve of experimental data and the theoretical curve were nearly parallel over a rather large range.

It can be seen, from the fact that some of these assumptions cannot be completely met in practices, that there must

12. McAdams, W. H., Heat Transmission, New York and London: McGraw - Hill Book Co. 1933.

be some method used to compensate for those conditions that have not been considered in the development.

In developing the equation relating the properties of a moving fluid and the heat loss of a heated wire suspended in it, King used only a unit length of a wire of infinite length. He did not consider the losses by radiation or those resulting from the viscosity of the fluid. Further, in using a unit length, he neglected any losses to the supports by assuming a constant wire temperature over the length used. These, therefore, are the conditions which make it necessary to use a somewhat different form of this equation.

In constructing a practical instrument along the lines of his theory, King changed his equation (5) from the theoretical form

$$H = \left[k + 2\sqrt{\pi k s d}\ (\rho v)^{\frac{1}{2}}\right](T - T_a), \qquad (2)$$

where θ_0 has been replaced by the difference between the wire temperature (T) and the fluid temperature (T_a) at some distance from the wire,

to a form similar to this

$$i^2R = A + B\sqrt{v}\ (T - T_a). \qquad (3)$$

In this form the constant

$A = a(Lk/J)$

L is the length of the wire.

J is a conversion factor between watt-hours and BTU's.

a is a constant which corrects for errors caused by losses not taken into account in the theoretical development,

and

$$B = (2L/J)\ \sqrt{\pi k s d \rho}\,(b),$$

where

b is a constant similar to a.

King went ahead and showed that, within the limits of his work this equation could be used with some degree of accuracy.

A number of those who have worked on this type of instrument have taken the density term (ρ) out of the "constant" and made their instruments measure mass-flow. This is a logical development as the density term would not be constant over any large range of velocities, pressures or temperatures. This rewritten form of King's equation,

$$i^2R = \left[A + B\ (\rho v)^{\frac{1}{2}}\right]\ (T - T_a), \tag{4}$$

has been used with a high degree of success in work with these instruments.

The end losses are one of the most troublesome factors in calibration of the Hot-Wire Anemometer. The wire must be mounted in such a manner that the mounts will interfere as little as possible with the flow of the fluid over the wire and therefore must be small. Keeping these mounts small necessitates using a material which will conduct electricity and such material will also conduct heat. Although the mounts can be of such size that the current passing through them will not heat them much, there is the probability that it may conduct heat from the wire and disperse it as a

function of the temperature difference between it and the fluid stream. This would then cause the calibration constants to be a function of the temperature difference existing.

This possibility does not seem to have received much written consideration. The only article that I found which discussed this possibility or ways of overcoming it was written by Alfred H. Davis (13). Davis was doing some work on heat transfer by free and forced convection and using a Hot-Wire Anemometer to study the convection currents. He has calibrated his instrument for a certain temperature difference. Then, using the instrument as a resistance thermometer, he determines the temperature of the fluid stream to be studied and sets the wire temperature the set amount above the ambient temperature. This offers somewhat of a refinement, but would require that the fluid temperature remain very nearly constant over the period the fluid was being studied.

In this report the calibration constants have been changed some from those generally used. The terms of thermal conductivity and specific heat have been removed in a hope of getting these constants more exact. The revised form used here will be

$$i^2R = \left[\beta k + \delta\sqrt{ks}\ (\rho v)^{\frac{1}{2}}\right](T - T_a) \qquad (5)$$

---

13. Davis, Alfred H., "An Instrument For Use In Measuring Convected Heat", Physical Society of London - Proceedings, Vol. 33, 1920 - 21, pp. 152-163.

where

$\beta = (L/J)a$

and

$\delta = (2L/J)\sqrt{\pi d'}\,(b)$

The proposed instrument based on this will be somewhat more complicated to calibrate, but it is hoped that this and other refinements will make frequent calibration less necessary than with the present instruments.

The advantage expected to be gained by this change is not too evident with the equation as it stands, though it can be seen that with any large change in the fluid temperature, the value given to k will have some effect.

In the usual method of calibration, the temperature terms, T and T_a are replaced by their values of resistance from the equation (14)

$$R = R_o\left[1 + \alpha(T - T_o).\right] \qquad (6)$$

In doing this, it must be assumed that the ambient fluid temperature will remain very nearly constant. If a great enough difference can be maintained between the ambient fluid temperature and the wire temperature, small variations of the fluid temperature will have little or negligible effect. Since these instruments are used mostly in experiments with forced fluid flow, it is questionable if any large range

14. Marks, L. S. (Edited by), Mechanical Engineer's Hand Book, New York and London, McGraw - Hill Book Co., 1941, p. 1966.

of velocities could be accurately investigated. This follows because a change in velocities would necessitate a change in the energy input to the moving fluid and a resulting change in fluid temperature. This was one of the complications mentioned in one of the articles by J. R. Weske (7).

Since it is impractical to have laminar flow in practical problems, the type of instrument being discussed here must necessarily have some limit in the variations to which it will respond. This limit is best set by the response of the galvanometer. The galvanometer used in obtaining data for this report had a period of from 2 to 4 seconds and this was found to work out quite well. The result here is that an average value of the heat loss is obtained. That is, that very small changes in velocity, temperature or density did not effect the amperage reading, thus giving only the average effect of these.

There are instruments which will react to very small changes and many good articles can be found on the many phases of instrumentation and calibration of these velocity fluctuation measuring devices.

While the method of handling the calibration and use of these instruments which is now used has served well and is in wide use, it seems that it has many short-comings that might be corrected. It is recognized that many of these practices which seem to introduce inaccuracies are used to simplify the instrument and the simplifications have added more in making the instrument useful than they have done to make it inaccurate. With a growing need for greater accuracy and the use of the instruments in new fields, it would seem some improvements could be made. Although this is not the primary purpose of this thesis, it is hoped that some progress along these lines will be a by-product of it.

SYSTEMS OF SEVERAL WIRES

Since the time King developed his mathematical analysis of the Hot-Wire and demonstrated its possibilities, there has been much work and thought put into making it a velocity measuring device. The Hot-Wire instrument has founds its greatest field in measuring velocity fluctuations. From time to time attempts have been made to make use of its other possibilities such as its directional characteristics and its ability to measure other statistical data needed in turbulent and boundary layer research.

Examination of the equation in the form used in this report,

$$i^2R = \left[\beta k + \delta\sqrt{ks'}\ (\rho v)^{\frac{1}{2}}\right]\ (T - T_a), \tag{5}$$

shows that the equation has two independent variables. These are the velocity and ambient temperature of the fluid. Besides these, it also has three other variables - the thermal conductivity, the specific heat and the density of the fluid - which are, for all practical purposes, independent of the velocity, but are dependent on the ambient temperature and the fluid being studied.

Since the heat loss is dependent on two independent variables, the determination of one will depend on the accuracy with which the other is known. Since the Hot-Wire instrument has been chiefly used to measure velocity, an ability to make an accurate measurement of the ambient temperature is very necessary if the resulting velocity measurements are to be accurate. At low velocities the normal temperature measuring devices will serve quite well, but as the velocity increases it has been found that the temperature measurements become more and more inaccurate (7). This brings up the question of whether or not the dependence on temperature could be eliminated or minimized.

In looking over the terms of King's equation, it is seen that it depends on the temperature difference between the fluid and the properties of the wire. The diameter enters in only the second term of the equation and, therefore, if a different diameter were used, a different equation would result. The length enters in each term of the equation and, therefore, changing it would probably only give a constant times the same equation. Also the temperature enters the equation in each term, but since it is the temperature

---

7. Weske, J. R., "A Method of Measurement of High Air Velocities by The Hot-Wire Method", N.A.C.A. Tech Note, No. 880, 1943.

difference, changing the wire temperature would again result in a constant times the right hand side of the equation; but due to the complex relationship between wire temperature and wire resistance, changing the wire temperature might make a further difference in the equation that can be used.

These considerations show that it will be possible to use a system of two and three equations to evaluate the variables.

Taking up the thermal conductivity first, proper manipulation of three equations, obtained in the manner described, will give an equation for thermal conductivity as just a function of the power dissipated through the hot-wire and the constants of the hot-wire. This would be in the form of a quadratic equation and would take a complicated electronic circuit to solve it, but could be a very useful device in combustion research where there was reasonably constant flow.

The ambient fluid temperature is the second quantity that could be determined with this type of instrument. Again it would take three equations to eliminate all the other variables, but, as with the thermal conductivity, they can all be eliminated and the ambient temperature obtained as a function of the power dissipated and the equation constants.

The velocity is the third quantity that this type of instrument might be used to measure. Although this is the only one that the hot-wire instruments are presently used to measure, it is the one that, theoretically, this arrangement of the instrument would be least capable of measuring. As can be seen by examining the equation, the velocity, unlike the other two, cannot be found as a function of just the power dissipated and the constants of the instrument with any number of simultaneous equations. By using two equations the ambient temperature can be eliminated, but the thermal conductivity and specific heat will still remain. The one consolation is that these quantities do not vary much over a fairly large temperature range.

One trouble with the method just described is that the equations become very long and complicated. But if electrical circuits can be made to handle them, they should be quite useful in many types of research.

This method depends on the assumption that the terms β and δ of the equations will remain reasonably constant over a large range of velocities and temperature differences. This is assuming that the loss of radiation to and viscosity of the fluid will be small and nearly constant. Another factor that could affect the values of β and δ is the possible end losses. In an article by Weske (7) it is suggested that if the ratio of the length of the wire to its diameter is kept over 250 that the end losses will be negligible.

A report through the Bureau of Standards by G. B. Schubauer (15) has shown that changes of humidity have little

---

15. Schubauer, G. B., "Effects of Humidity In Hot-Wire Anemometer", U.S. Bureau of Standards - Journal of Research, (RP 850) p. 576-578.

effect on these constants over a normal range of humidities. Earlier two other men, A. E. Kennelly and H. S. Sanborn (16), investigated this and found a 2 percent change in heat loss per degree rise in temperature for a change in relative humidity from 25 to 70 percent for temperatures around 25 degrees centigrade. For most types of work this would have little effect.

The limitations of this instrument would be velocity limitations and the same as those of the standard instruments. First, it is assumed that the product of velocity and diameter of the wire is over 0.0187 (the velocity in cm./sec. and the diameter in cm.) (5). Essentially, this requires that the velocity be large enough to overcome the effects of any induced convection and to make the effect of any heat film which might form over the wire negligible.

Since the thermal conductivity and the specific heat of a fluid vary very little over a rather large temperature range and are generally known functions of temperature, these terms can be retained in the equation without seriously complicating it. This will make it possible to use a combination of two wires to obtain separate equations for mass-flow (ρv) and ambient fluid temperature (T_a) as functions of the

---

16. Kennelly, A. E. and Sanborn, H. S., "The Influence Of Atmospheric Pressure Upon the Forced Thermal Convection From Small Electrically Heated Wires", Proc. Am. Phil. Soc., Vol. 52, 1914, p. 55.

wire constants, thermal conductivity and specific heat. These equations are obtained in this manner:

Setting up two equations, one for each of the two wires to be used, and assuming that they are both evaluating the same fluid properties under the same conditions,

$$i_1^2R_1 = [\beta_1 k + \delta_1 \sqrt{ks} \; (\rho v)^{\frac{1}{2}}] \; (T_1 - T_a) \tag{7}$$

$$i_2^2R_2 = [\beta_2 k + \delta_2 \sqrt{ks} \; (\rho v)^{\frac{1}{2}}] \; (T_2 - T_a) \tag{8}$$

and putting in

$$T = [R_o(\alpha T_o - 1) + R] / (\alpha R_o) \tag{6'}$$

for the value of T in each equation, using the proper subscripts, and solving the two resulting equations simultaneously, first for (ρv) and then for T_a, these equations are obtained:

$$(\rho v) + (\rho v)^{\frac{1}{2}}C + D = 0 \tag{9}$$

or

$$(\rho v) = \left[(-C \pm \sqrt{C^2 - 4D}) / 2\right]^2, \tag{9'}$$

where

$$C = (f\sqrt{k/s}) + (m/\sqrt{ks}) \; \left[(i_2^2R_2d - i_1^2R_1)/(R_1 - R_2e)\right] \tag{9a}$$

$$D = (gk/s) + (n/s) \; \left[(i_2^2R_2q - i_1^2R_1)/(R_1 - R_2e)\right] , \tag{9b}$$

and

$$T_a^2 + T_aE + F = 0 \tag{10}$$

or

$$T_a = (-E \pm \sqrt{E^2 - 4F})/2, \tag{10'}$$

where

$$E = (h/k) \; (i_2^2R_2d - i_1^2R_1) - j(R_1 - R_2e) - 2p \tag{10a}$$

$$r = (np/k)(i_1^2R_1 - i_2^2R_2d) + (R_1R_2jh/k)\ (i_1^2s - i_2^2d + pj(R_1 - R_2s) + rR_1R_2 + p^2 \qquad (10b)$$

This gives two equations, the data for which can be taken from the same instrument. Equation 9 gives the product of (ρv) with only slight dependence on a knowledge of the fluid temperature. Since the value of thermal conductivity varies very little over temperatures of 15 to 20 degrees, this would be roughly the accuracy necessary to obtain reasonably good results. Equation 10 gives a method of obtaining the temperature (T_a) of a moving fluid that, theoretically at least, gives promise of being accurate at very high velocities. The small wire used would not present the friction problem nor would it distort the fluid flow in obtaining its measurements.

These equations are long and complicated and their solution would be troublesome in this form. There are several ways in which this might be overcome. One would be to always operate each wire at a set resistance, thus making every term constant, except k, s and $i_{2\ \&\ 1}$. A second method would be to operate each wire at the same resistance. The first method would cut down the number of operations needed in solution, while the only improvement of the second over the first is that it would simplify the needed operations. Neither of these simplifications, changes the original conditions assumed in setting up the two-wire equations as the wires are still of different diameters and operated at different temperatures.

There is a third possible simplification which involves operating both wires at the same temperature difference and relying on just the difference in diameters to produce the two separate equations. This would be to cut two wires of different diameters into lengths having equal zero resistances. Now, it can be seen from the temperature-resistance equation

$$R = R_0 \left[1 + \alpha(T - T_0)\right] \tag{6}$$

that, if the two wires are of the same material and have equal zero resistances, these two wires operated at equal resistances will be at equal temperatures. The two equations 9 and 10 then become

$$(\rho v)^{\frac{1}{2}} = w\sqrt{k/s}\left[(i_2^2 q - i_1^2)/(i_1^2 - i_2^2 d)\right] \tag{9''}$$

and

$$T_a = R\left[j - (u/k)(i_2^2 d - i_1^2)\right] + p. \tag{10''}$$

Any notation that has not been explained can be found in Appendix A.

Both forms of equations 9 and 10 would depend on the accuracy with which the constants β and δ could be determined as ratios of each of these terms for the two wires appear in the equations. Also there could be no variation of these terms over the range of operation.

CONSTRUCTION OF THE INSTRUMENT AND DATA TAKING

The Hot-Wire Instrument used for obtaining data for this experiment was of the constant resistance type used for measuring constant velocities. It consisted of a Wheatstone Bridge for measuring the resistance of the wire, an ammeter in the wire arm for measuring the amperage flow in the wire, a voltage divider for varying the voltage on the wire and two small wires so mounted that they could be placed in a moving air stream.

The resistances of the Wheatstone Bridge, a wiring diagram of which is shown in Figure 1 of Appendix B, were commercial, wire-wound resistances of 10 percent accuracies and rated to be used at ten watts or less. The accuracy of the resistances had no bearing on the accuracy of the bridge as the bridge was calibrated after construction. This was necessary because the resistance of the lead wires and soldered joints could not be balanced or controlled.

One arm on the bridge contained a variable resistance of three ohms, marked R_v on the diagram, which was used to obtain a balance when different values of current were used.

The calibration of the bridge was accomplished by calibrating a three ohm variable resistance of approximately linear taper, and then placing this in the instrument bridge in place of the hot-wire and using this to calibrate the variable resistance of the bridge. A current of about 0.3 amps was used to assure approximately the same galvanometer sensitivity as when the bridge was in use.

The variable resistance used for calibrating the bridge was calibrated from standard resistances in this manner:

First a one ohm standard resistance was placed in the arm of a commercial Wheatstone Bridge and balance was obtained using a sensitive wall-galvanometer. Then the standard was replaced by the variable resistance and this was varied until the balance was again obtained. This point was marked on the face of the variable resistance.

This was repeated with a one-tenth ohm standard, two one-tenth ohm standards, the one ohm standard and a one-tenth ohm standard and the one ohm standard with both one-tenth ohm standards.

Care was taken to use the same leads to connect in the variable resistance as were used for the standard or combination of standards. The resistance of the leads, which were soldered to the variable resistance was included as part of the resistance of this rheostat.

The five calibration marks which were obtained in this manner showed no deviation from a linear taper. Direct interpolation between these points was used to establish a complete set of graduations.

Since it was necessary to have points beyond the 1.4 ohm mark found in this manner, a box variable-resistance was

adjusted to one-tenth and two-tenths ohms by adjusting it to balance the bridge set for balance at these points. Then this was used in combination with the standards to obtain other combinations on the variable resistance.

Platinum was selected as the wire material because of its high resistance, its high temperature coefficient of resistance and its ease of handling. The wire dimensions and characteristics were:

Length (approximately) - - - - - - - - - - - - - -	0.5 inches
Diameters -	0.002 inches
- -	0.0015 inches
Temperature Coefficient of Resistance - - - -	$0.00204/^{\circ}F$

The Sigmund Cohn Corporation supplied the wire and gave its properties as being approximately 99.999 percent pure platinum with a coefficient of resistance of $0.00392/^{\circ}C$ ($0 - 100^{\circ}C$). The wire was supplied unannealed and was annealed by passing a current through it, which caused a visible glow, and keeping it heated for approximately one hour.

Since it is not necessary to know the exact length of the wire, no great care was taken in adjusting the length except to be sure that the wires were long enough so the ratio of the length to the diameter was over 250.

A drawing of the mountings of the wires is shown in Figure 3 of Appendix B. The wires were mounted on Number 7 needles which were in turn supported by carved, hard wood bases. The wire end was placed in the eye of the needle and

the eye filled with a soft solder. Lead wires going back to the instrument were soldered to the lower end of the needles and supported by the wood mountings. The wood mountings were held in the air stream by copper tubes which were attached to a plate that could be revolved in a horizontal plane about its vertical axis. The plate was supported on a 3/4 in. diameter pipe, the plate could be rotated about the horizontal axis of the pipe. So arranged, the wires could be adjusted in any direction to bring it into a position normal to the air stream.

A tube 14 inches in diameter, fed from a squirrel-cage fan, was used for calibration tests on the instrument. Some approximation of laminer flow was obtained by running the tests at a point some 30 ft. down the tube from the fan. Between this point and the fan, the tube contained a set of "straighteners" which tended to brake up the turbulent flow from the fan.

A static-pitot tube was used to measure the velocity in the wind tube. The wire mounts and the pitot tube were so mounted as to take three positions approximately equal distance apart and approximately equal distance from the center of the tube. This was done to have each measuring as near equal velocities as possible.

There was a gate arrangement on the wind tube, near the fan, which was used to vary the velocities in the tube.

The reference resistance of the wire was found first.

To do this, the resistance of each wire was measured at several air temperatures and the reference resistance (R_0) computed from equation 6.

The measurable properties of the air were obtained by placing a thermometer in the wind tube, near the test section, to obtain the ambient air temperature, two manometers connected to the pitot tube, one to read static head and the other to read the difference in static and total head, and the barometric pressure was taken from a barometer in the room.

Since it is necessary to find the variation in the constants with variation of both velocity and temperature difference, it was necessary to take two sets of data for each wire. One set of data was taken with constant velocity and varying temperature differences, the other with constant temperature difference with varying velocity. In the first set, the velocity was held constant, near the maximum for this experiment, and the temperature difference was varied by varying the voltage impressed on the instrument bridge. In the second set, the velocity was varied by closing the control gate by degrees and the temperature difference was held constant by varying the voltage impressed on the bridge to keep the bridge in balance at a set resistance. The temperature difference was not kept constant as the air temperature varied a little.

Since the variation of the constants with varying temperature difference was considered likely to be the most important, two sets of data were taken on this for each wire.

DISCUSSION OF EXPERIMENTAL RESULTS

Although it would seem logical to compute the constants for each point since the variation in the constants was to be checked, for several reasons this was not done. First, computing these would be a very long and tedious job; second, if this were done, it would involve only average values between sets of adjacent points; third, it would involve ratios of the differences in numbers which are very nearly equal and thus increasing the error many times; fourth, the instrument used in obtaining this data was not sufficiently accurate to warrant attempting this method; and last, there is a simpler and more direct way.

If equation 5 is rearranged in the following manner,

$$\beta = \left[i^2R/(\Delta T)(k)\right] - \delta \sqrt{s/k}\,(\rho v)^{\frac{1}{2}} \qquad (5')$$

and it is assumed that   and   are constants, this equation can be compared to the equation of a straight line,

$$\beta = y - \delta x \qquad (5a)$$

where

$y = i^2R/(\Delta T)(k)$

$x = \sqrt{s/k}\ \ (\rho v)^{\frac{1}{2}}$

If, as assumed, β and δ are constants, it can be seen that for a set value of x there is a set value of y. Further, if the

values of x and y are known, these can be plotted and the curve of equation 5' will result. This can be done with no knowledge of the values of either β or δ. Now, if the assumption made here is not correct, a curved line and not a straight line will result when x is plotted against y. This does not assume that any of the variables of the equation have been held constant.

This curve will then serve two purposes. It can serve as a check on the extent to which these "constants" are constant and also as a calibration curve for the wire. The equation here is the slope-intercept equation of a straight line where β is the intercept and δ is the slope.

The first set of values, the tabulation and graphs of which can be found in Appendix C, were taken with a constant wire temperature and varying velocity. The hope, in holding the wire temperature constant, was to get a curve at constant temperature difference, but variation in the ambient air temperature prevented this. The velocity was varied from approximately 5 to 27 ft. per sec. The temperature difference shows a variation of around 6°F. Straight lines could be drawn through most of the points for both wires. This had not been expected and it is quite possible that, if a greater range of velocities were used and greater accuracies were obtained, the curves would show some variation from a straight line. Some of the points on these curves are out of line and these can probably be attributed to errors in making the test

readings. This is shown by the fact that in some of the cases a second reading under the same condition has fallen on the line.

The second two sets of values taken for each wire are at constant velocity and variable temperature differences. This presents a slightly different problem as now the term x in equation 5' is a constant, or reasonably so. If x, β and δ are all constants then y also must be constant and the curve here would be a single point. This would not serve to show the extent of any variation in the constants.

This has been overcome by observing that if y is a constant, then if $(k)(\Delta T)$ is plotted against i^2R, this should give a straight line. Any deviation from a straight line would indicate that the constants varied with the temperature difference. This, of course, would not give an indication of which constant varied or, if both varied, the extent of variation of each. But, if a variation were found here, constant temperature difference curves could be run for a number of different temperature differences and the place and extent of the variation evaluated.

The tabulation of data and plotted curves for this are shown in Appendix C. A straight line could be drawn through most of the points except those from zero to 60 degrees temperature differences. The data taken was not accurate enough to give this portion of the curve any meaning. Again a few of the points are out of line of the curve, beyond those in this erratic portion of the curve. These points can probably be attributed to errors in data taking as there is little uniformity with the way they deviate from the line. The temperature differences used ranged from zero to around 100°F, this end point differed with each set of data.

The results from this show that, within the accuracy of the work and the limit of temperature differences used, the constants did not vary any appreciable amount.

The problem of determining the value of a reference, wire resistance is a very important one, because upon how well this is determined will depend the accuracy of the measurements of the fluid properties with the instrument. This is a problem because of the size of the wire. Since the resistance is very small, a current of the value used in most standard resistance measuring devices will tend to heat the wire and the value determined will be too large.

Three ways of determining this will be listed here. The first two were used in obtaining the data for this thesis, the first as a check on the second. This instrument was not considered accurate enough to use the third method.

1. A piece of the wire about 4 inches long was connected in series with a larger known resistance and an ammeter, the wire was placed in oil and heated to 400°F. The circuit had been tested before-hand under a certain impressed voltage and the current recorded. The wire was then included and the same impressed voltage used. The current was kept well below that

which would heat the wire at these temperatures. All the leads used were included in both tests so they would not add to the resistance. The resistance of this piece of wire was computed from the difference in amperage reading before and after adding in the heated wire. Then, from the measured dimensions of the wire and this resistance and temperature, the characteristics of the material were computed.

This method was not considered much of a success as the resistance of the wire was not large enough to make much change in the current flow.

2. The wire was placed in the calibrated bridge of the instrument and a small voltage impressed on the bridge. The bridge was balanced and the resistance read from it. This was repeated at a number of air temperatures as a manner of check. The reference resistance was then computed from equation 6.

The drawback with this method is that a very small voltage must be used to keep from heating the wire. The galvanometers that are used in this type of instrument cannot be the type that will measure as small a voltage variation as would be required here.

The reference resistances obtained by this method are given on the data sheets in Appendix C.

3. This method requires a very accurately calibrated instrument bridge and an ammeter that can be read to as many places as are required in the resistance accuracy.

As was stated in the discussion of the terms of equation $5'$ for constant velocity-varying temperature difference, if β, x and δ are constant then all the terms of the equation are constant for each point. Therefore, the y terms of any two points can be set equal,

$$y_1 = y_2$$

or

$$i_1^2 R_1/(k)(\Delta T_1) = i_2^2 R_2/(k)(\Delta T_2)$$

Cancelling the k from each side of the equation and substituting in

$$\Delta T = (R/\alpha R_0) \left[(T_0 - 1/\alpha) - T_a\right]$$

for each ΔT and solving for R_0 this equation is obtained,

$$R_0 = \left[R_1 R_2 (i_1^2 - i_2^2)\right] / \left[\alpha(T_0 - T_a) - 1\right] (i_2^2 R_2 - i_1^2 R_1) \qquad (11)$$

This gives an equation for R_0 that eliminates the troubles found in the other two methods. Also, if the instruments are constructed for use of the two-wire equations developed in this thesis, this method will not require any more accuracy than is needed for working with these equations.

DISCUSSION OF POINTS OF POSSIBLE ERROR

The method of calibrating the instrument left room for some error. Since only one and one-tenth ohm standards were used, it was necessary to assume a linear taper between these points to mark the variable resistance off in one-hundredth ohm division. A further error may have been introduced by calibrating a commercial variable resistance and then using it to calibrate the bridge. This was necessary as the bridge was changed a number of times and a method of speedy calibration was needed. The resistance readings used are given to the third place beyond the decimal point, but they are probably not accurate to more than $\pm$ 3 in this place.

The readings of the ammeter are given to the third place. These are not accurate to more than $\pm$ 2 in this third place.

The ambient air temperature is another place of possible error. The temperature here was continually changing while the tests were being made. In general, it was climbing, but at times it would drop as much as 2 degrees in a period of a few minutes. It is possible that the mercury thermometer used did not always react to these changes as fast as they occurred. The temperature readings are given to the third place with a probable reading accuracy of $\pm$ 2 in this third place.

The velocity and static pressure were measured with a static-pitot tube and it was assumed that the readings of this tube were correct over the complete range. The static head and difference in static and total head readings did not show the fluctuations that the temperature did. It is hard to believe that the velocity did not fluctuate while the temperature did and it is possible that the manometers were too slow to record these fluctuations. The static head readings were taken to three places and were accurate to this place. The difference in heads was read to the third place with an accuracy of ± 2 in this place.

There is also a possibility of error due to turbulent flow which would affect the Hot-Wire, but not the pitot tube readings.

In general, control was not considered good enough to attempt to obtain any experimental evidence on the use of the two-wire equations.

GENERAL CONCLUSIONS

The graphs of the data taken for each of the two wires, operated first at constant temperature difference and variable velocity and second at constant velocity and variable temperature difference, has been plotted in such a manner as to show a variation of the constants if the experimental data does not fall on a straight line. This experimental data, in each case, has formed a straight line within the limits of this experiment and over the range for which the data was taken. The experiment was only accurate enough to give an indication and not within close enough limits to give proof.

Since the theory of the two-wire equations presented requires that these "constants" be constant over a rather large range, the data presented gives a definite indication that these two-wire instruments are feasible; although, it would take a much more accurate and better controlled experiment to prove or disprove this. The indication given here is that the variation of the constants over the range investigated is only very slight, if at all, and that there would be a fairly good range where a straight line would approximate the curve very closely.

The advantages these Two-Wire Instruments seem to offer are: the eliminating of the need to know the ambient fluid temperature so accurately in measuring velocities, a method of finding the ambient fluid temperature at high velocities and more accurate information on the thermal conductivity of fluids.

As a velocity measuring device, its disadvantages as compared to the One-Wire Instruments would be: the construction of a direct reading instrument would be much more costly and complicated and the size of the instrument head would be more than doubled.

In general, if the instrument is feasible, it would only be profitable to use it where considerable, accurate information on both temperature and velocity were needed.

APPENDIX A

NOTATIONS

Fluid and Wire Notations

k is the thermal conductivity of the fluid.

s is the specific heat of the fluid.

ρ is the density of the fluid.

T_a is the ambient temperature of the fluid.

v is the velocity of the fluid.

θ_0 or ΔT is the temperature difference between the wire and the fluid at some distance from the wire.

d is the diameter of the wire.

L is the length of the wire.

T, T_w, T_1 and T_2 are wire temperatures.

i is the amperage flow through the wire.

R is the resistance of the wire at some temperature T.

R_0 is the resistance of the wire at the reference temperature T_0.

α is the temperature coefficient of resistance for the wire.

T_0 is the resistance reference temperature for the wire.

J is a conversion factor between watt-sec and BTU's.

a is a constant correcting the first term of King's equation.

b is a constant correcting the second term of King's equation.

Constants of The Two-Wire Equations

$\beta = (L/J)a$

$\delta = (2L/J)\ \sqrt{\pi d}\ (b)$

$d = \delta_1/\delta_2$

$f = (\beta_1/\delta_1) - (\beta_2/\delta_2)$

$g = \beta_1\ \beta_2/\delta_1\ \delta_2$

$h = \delta_2/(\beta_2\ \delta_1 - \beta_1\delta_2)$

$j = 1/(\alpha R_{o1})$

$m = \alpha R_{o1}/\ 1$

$n = (\alpha R_{o1}\ \beta_2)/(\delta_1\delta_2)$

$p = (T_o - 1/\alpha\ )$

$q = \beta_1/\beta_2$

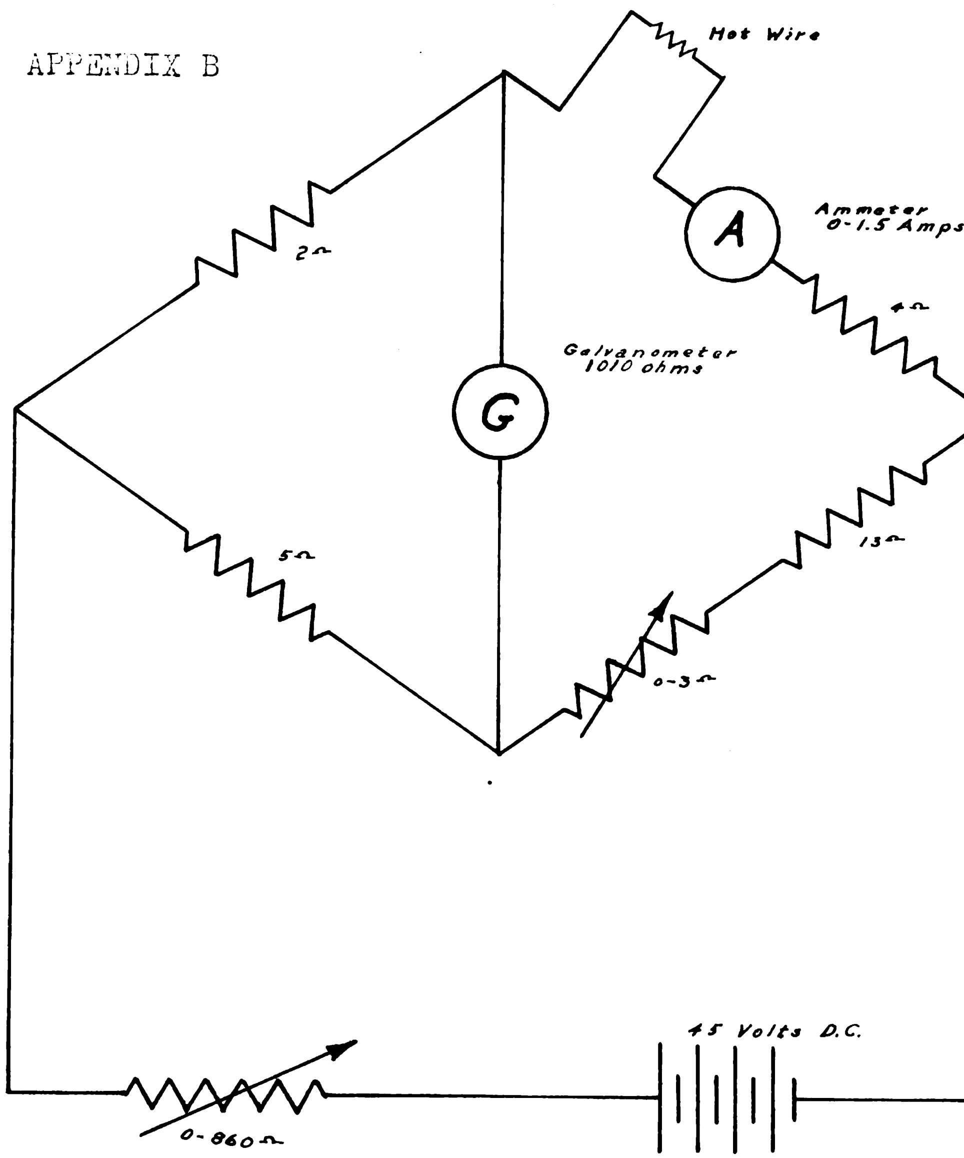
$r = 1/(\alpha^2 R_{o1}R_{o2})$

$u = 1/[\beta_2(d - q)]$

$w = \beta_2/\delta_2$

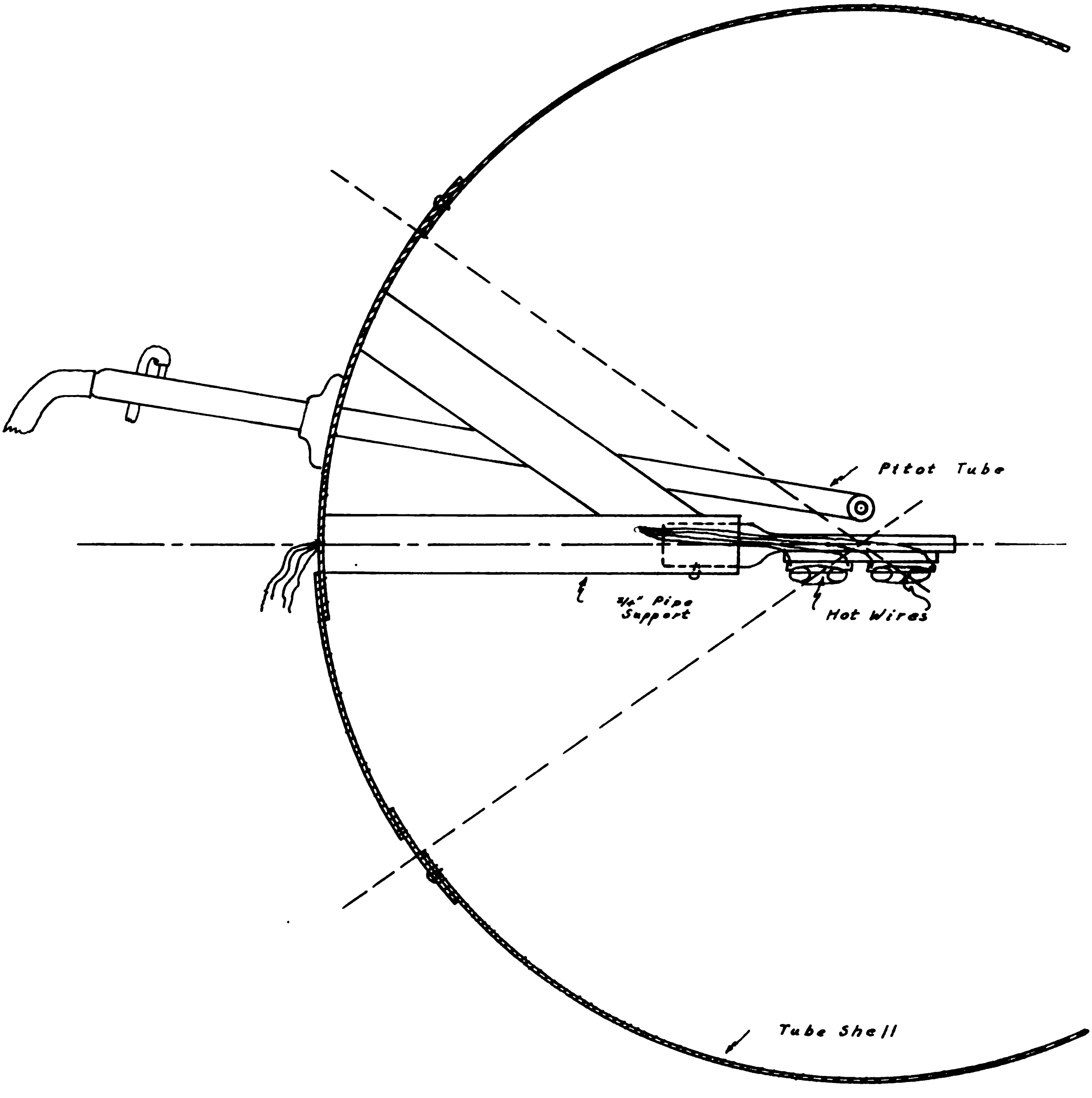
$z = R_{o1}/\ R_{o2}$

APPENDIX B



Bridge Circuit

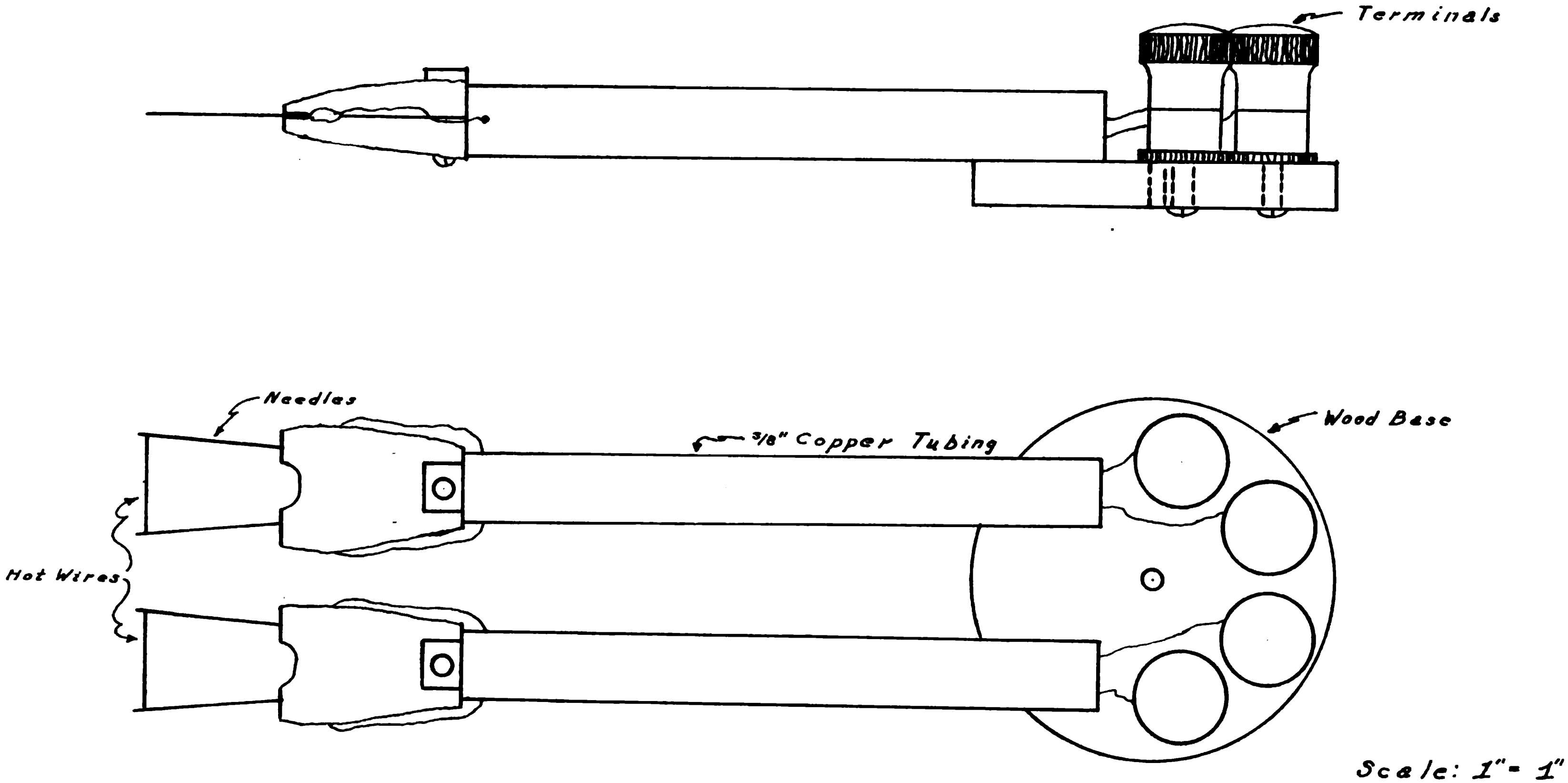
Figure 1



Section Drawing of Wind Tube at Test Section

Scale 1" = 2"

Figure 2



Hot Wire Mounting

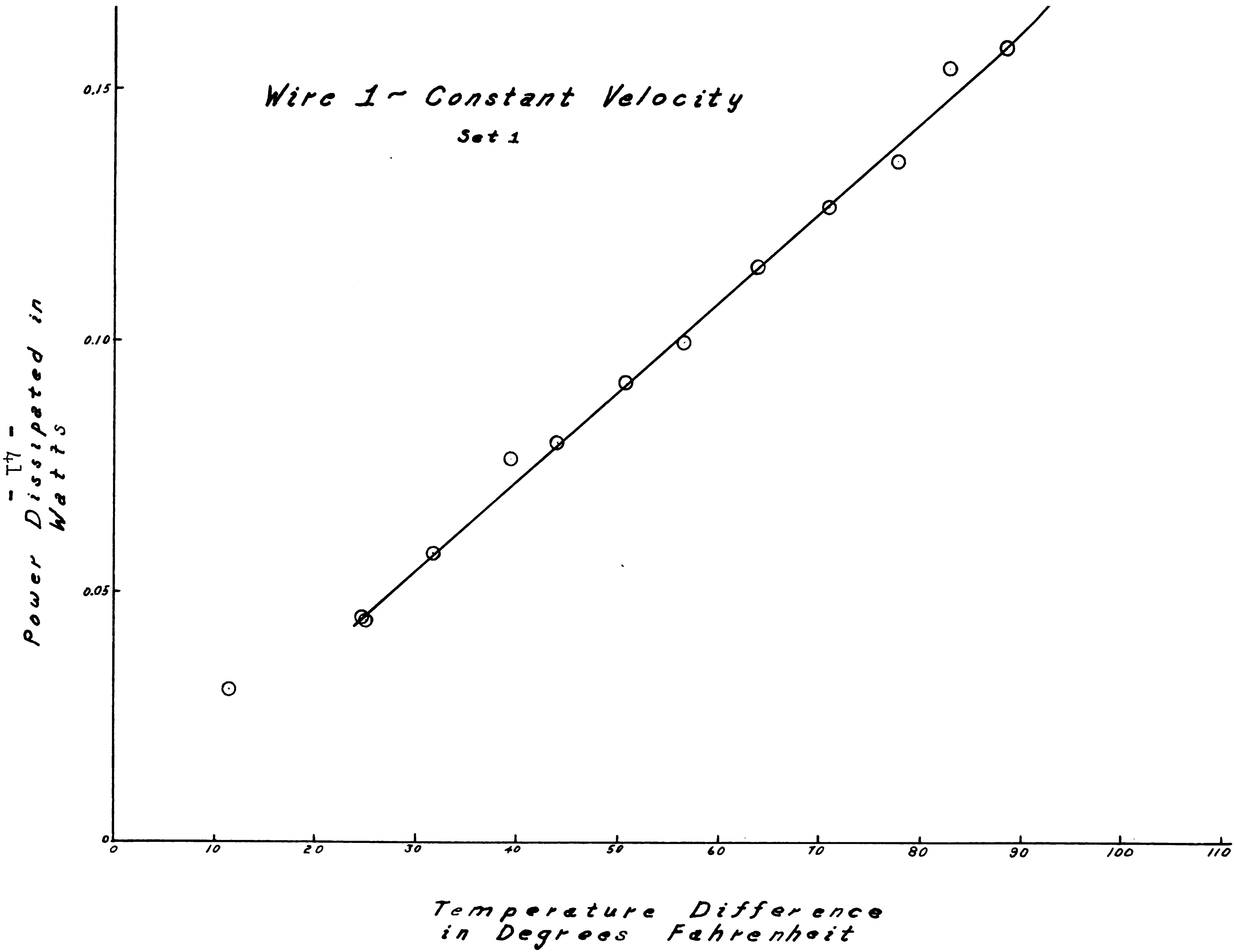
Figure 3

APPENDIX C

A. Data for constant velocity curve for Wire 1 (Set 1)

Diameter	0.0015 inch
Length (approximately)	0.5 inch
α	0.00204/°F
R_o	1.191 ohm
Barometric Pressure	29.17 in. of Hg.
Velocity	27.2 ft. per sec.

i amps	R ohms	T_a °F	i^2R watts	T_w °F	ΔT °F	$i^2R/\Delta T$ Watts/°F
0.150	1.355	88.2	3.09×10^{-2}	99.6	11.4	2.71×10^{-3}
0.179	1.386	87.4	4.44	112.3	24.9	1.78
0.180	1.386	87.6	4.49	112.3	24.7	1.82
0.203	1.401	87.0	5.77	118.5	31.5	1.82
0.232	1.417	86.0	7.63	125.1	39.1	1.95
0.236	1.432	87.5	7.98	131.3	43.8	1.82
0.251	1.447	87.0	9.14	137.5	50.5	1.81
0.261	1.463	87.8	9.97	144.1	56.7	1.77
0.278	1.478	86.5	1.14×10^{-1}	150.2	63.7	1.79
0.291	1.493	85.5	1.26	156.4	70.9	1.78
0.300	1.509	85.5	1.36	163.0	77.5	1.75
0.318	1.524	86.5	1.54	169.2	82.7	1.86
0.320	1.539	87.0	1.58	175.4	88.4	1.79
0.337	1.555	87.6	1.77	182.0	94.4	1.87


Wire 1 ~ Constant Velocity
Set 1
Power Dissipated in Watts
0.15
0.10
0.05
0
0
10
20
30
40
50
60
70
80
90
100
110
Temperature Difference in Degrees Fahrenheit

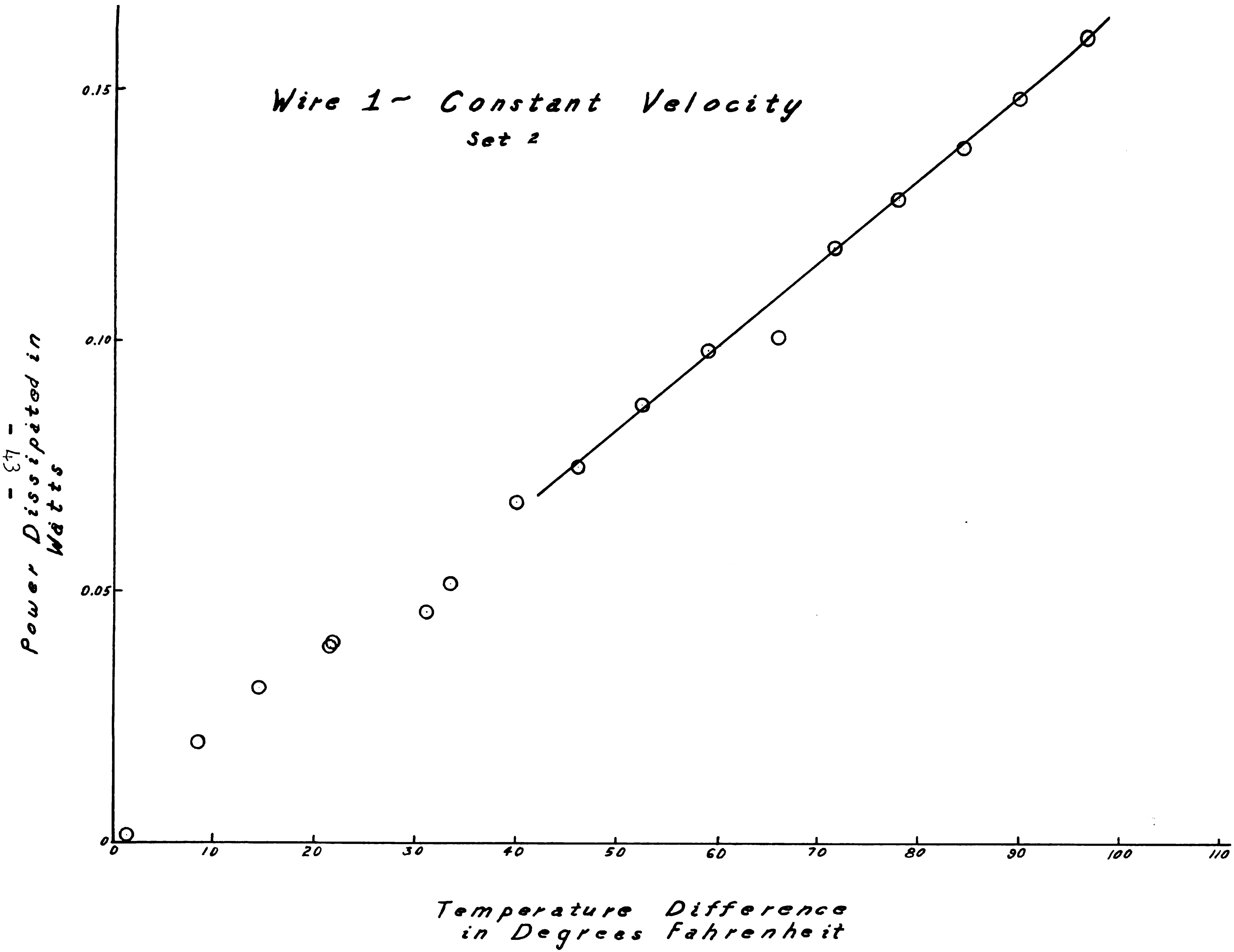
APPENDIX C(continued)

B. Data for constant velocity curve for Wire 1 (Set 2)

Barometric Pressure 29.27 in. of Hg.

Velocity 26.9 ft. per sec.

i amps	R ohms	Ta °F	i^2R watts	Tw °F	ΔT °F	$i^2R/\Delta T$ Watts/°F
0.030	1.326	86.6	1.19×10^{-3}	87.6	1.0	1.19×10^{-3}
0.122	1.343	86.5	2.00×10^{-2}	94.6	8.1	2.47×10^{-3}
0.150	1.358	86.5	3.06	100.8	14.3	2.14
0.168	1.374	86.2	3.88	107.4	21.2	1.83
0.170	1.374	86.0	3.97	107.4	21.4	1.86
0.181	1.398	86.6	4.58	117.3	30.7	1.49
0.191	1.404	86.7	5.12	119.8	33.1	1.55
0.219	1.420	86.6	6.78	126.3	39.7	1.71
0.228	1.435	86.6	7.46	132.5	45.9	1.62
0.245	1.450	86.6	8.70	138.7	52.1	1.62
0.258	1.466	86.4	9.81	145.3	58.9	1.67
0.261	1.481	86.2	1.01×10^{-1}	151.5	65.3	1.53
0.282	1.496	86.5	1.19	157.7	71.2	1.66
0.291	1.512	86.5	1.28	164.2	77.7	1.65
0.301	1.527	86.8	1.38	170.4	83.6	1.65
0.311	1.542	86.8	1.48	176.6	89.8	1.65
0.320	1.558	86.8	1.60	183.2	96.4	1.66
0.338	1.573	86.2	1.80	189.4	103.2	1.74



Wire 1 ~ Constant Velocity
Set 2
0.15
0.10
0.05
0
0
10
20
30
40
50
60
70
80
90
100
110
Power Dissipated in Watts
Temperature Difference in Degrees Fahrenheit

C. Data for constant wire temperature for Wire 1

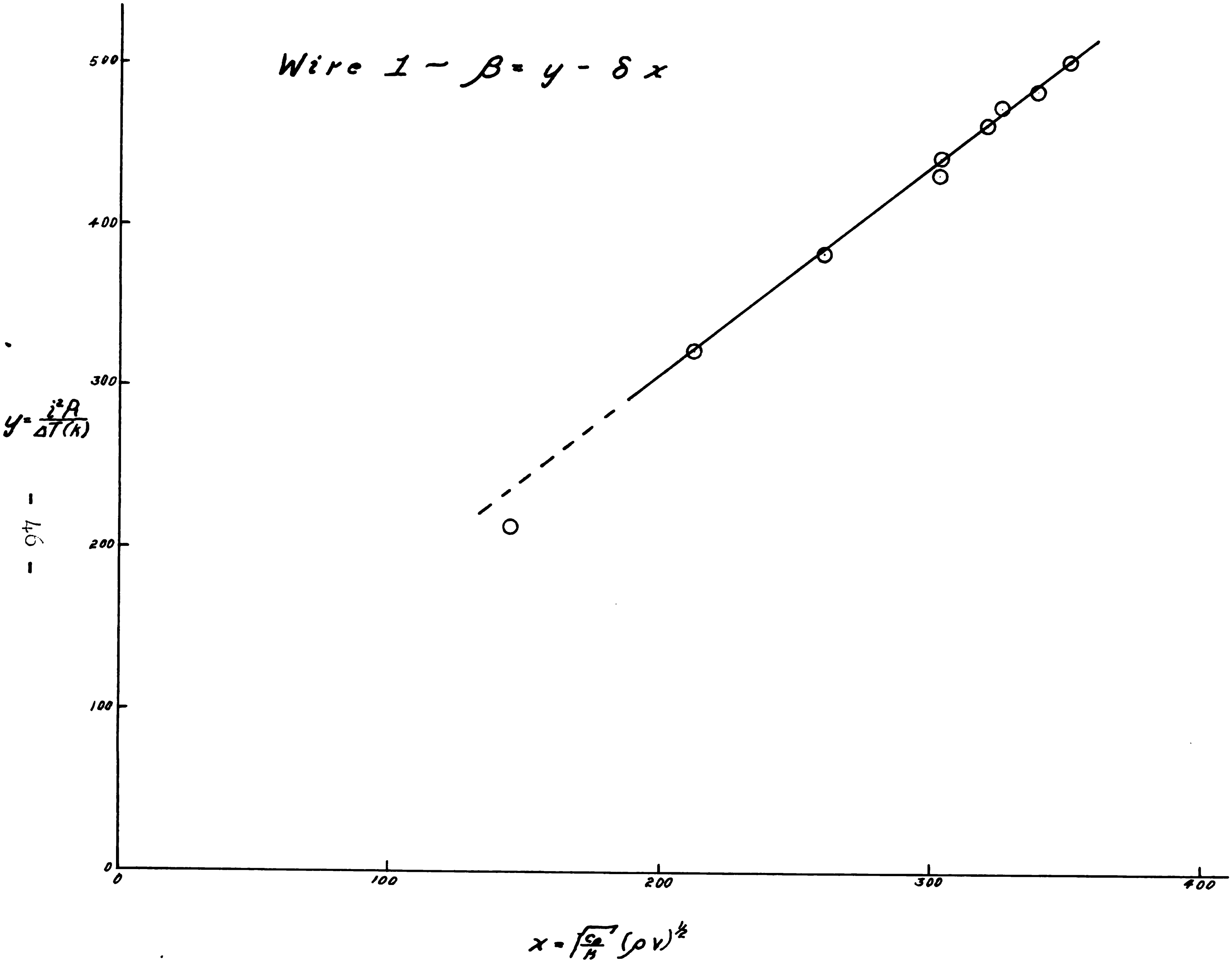
Barometric Pressure	29.17 in. of Hg.
Wire Temperature	188.1 °F
Wire Resistance	1.57 ohm

i amps	i^2R watts	T_a °F	k^* BTU/°F/ft/sec	V ft/sec	$(\rho V)^{\frac{1}{2}}$ $(lb/ft^2 sec)^{\frac{1}{2}}$
0.353	2.01×10^{-1}	85.5	3.892×10^{-6}	27.4	1.40
0.352	1.94	85.2	3.890	25.3	1.35
0.348	1.90	85.4	3.891	23.7	1.30
0.333	1.84	86.2	3.896	23.1	1.28
0.332	1.73	87.8	3.906	20.5	1.21
0.330	1.71	87.0	3.901	20.6	1.21
0.310	1.51	87.5	3.905	15.4	1.04
0.281	1.24	90.5	3.922	10.3	0.85
0.248	8.18×10^{-2}	91.0	3.925	4.9	0.58

*Values of thermal conductivity and specific heat are taken, reference 14, p 395 and 1909.

APPENDIX C (continued)

ΔT $^{\circ}F$	$\sqrt{s/k}$ (ft.-sec./lb.)$^{\frac{1}{2}}$	y $i^2R/(\Delta T)(k)$	x $\sqrt{s/k}\,(\rho v)^{\frac{1}{2}}$
102.6	251.6	504	352
102.9	251.6	485	340
102.7	251.6	475	327
101.9	251.4	464	322
100.3	251.2	442	304
101.1	251.3	433	304
100.6	251.3	384	261
97.6	251.1	324	213
97.1	250.9	215	146



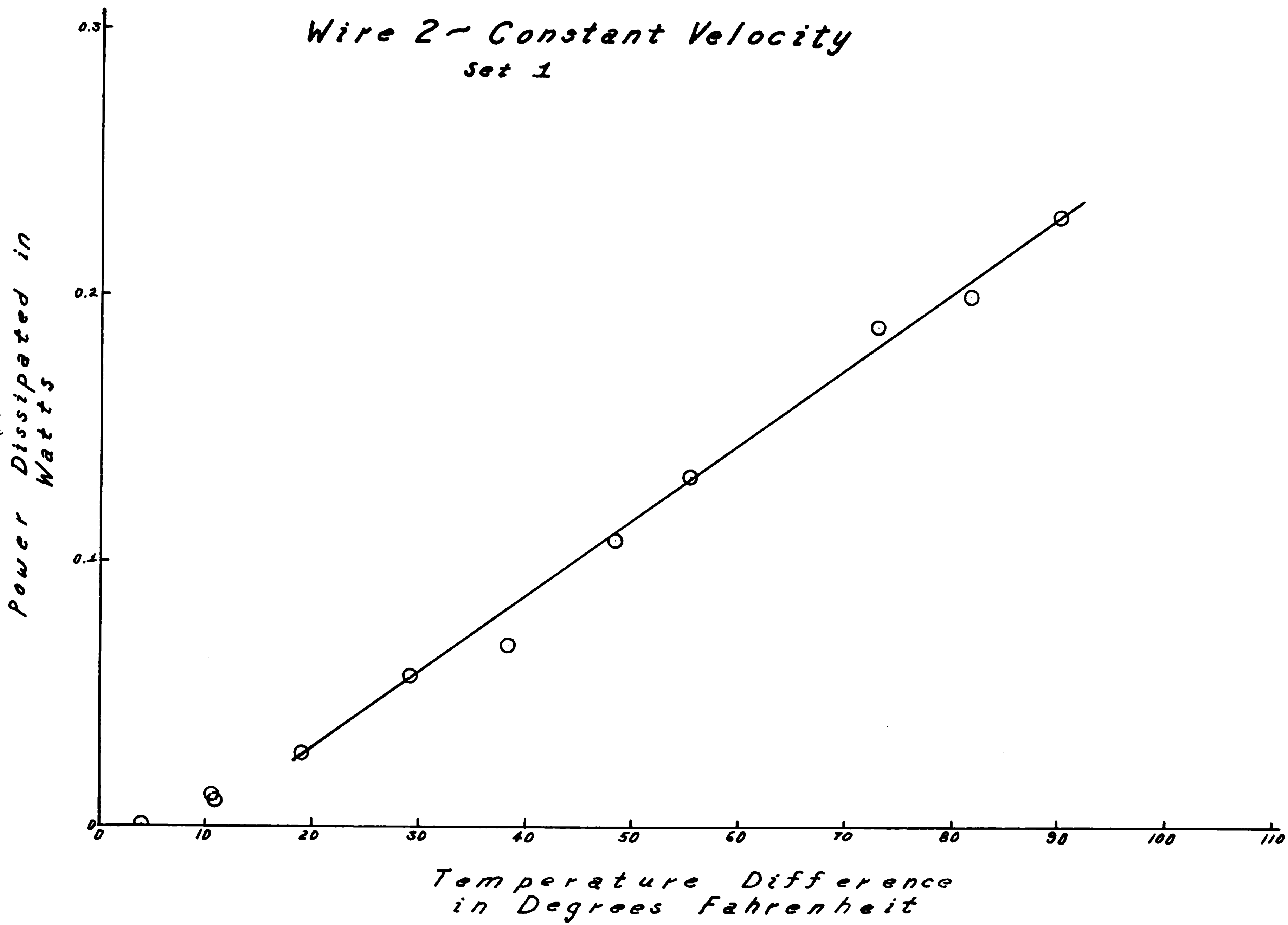
Wire 1 ~ β = y - δ x
500
400
300
200
100
0
100
200
300
400
y = i²R / ΔT(k)
x = √(Cp/K) (ρV)^½

APPENDIX C (continued)

D. Data for constant velocity curve for Wire 2 (Set 1)

Diameter	0.002 inch
Length (approximately)	0.5 inch
α	0.00204/°F
R_o	0.850 ohm
Barometric Pressure	29.07 in. of Hg.
Velocity	27.5 ft. per sec.

i amps	R ohms	T_a °F	i^2R watts	T_w °F	ΔT °F	$i^2R/\Delta T$ Watts/°F
0.030	0.944	82.2	8.50×10^{-4}	86.2	4.0	2.12×10^{-4}
0.110	0.956	82.4	1.16×10^{-2}	93.2	10.8	1.07×10^{-3}
0.116	0.956	82.6	1.29	93.2	10.6	1.21
0.172	0.971	82.8	2.87	101.8	19.0	1.51
0.233	0.987	82.8	5.75	111.1	28.2	2.04
0.262	1.002	81.6	6.88	119.7	37.1	1.85
0.326	1.018	82.8	1.08×10^{-1}	128.9	47.1	2.30
0.358	1.033	82.4	1.32	137.6	55.2	2.40
0.360	1.033	82.4	1.34	137.6	55.2	2.42
0.422	1.064	82.8	1.90	155.5	72.7	2.61
0.431	1.079	82.8	2.00	164.1	81.3	2.47
0.460	1.094	83.2	2.32	172.8	89.6	2.58



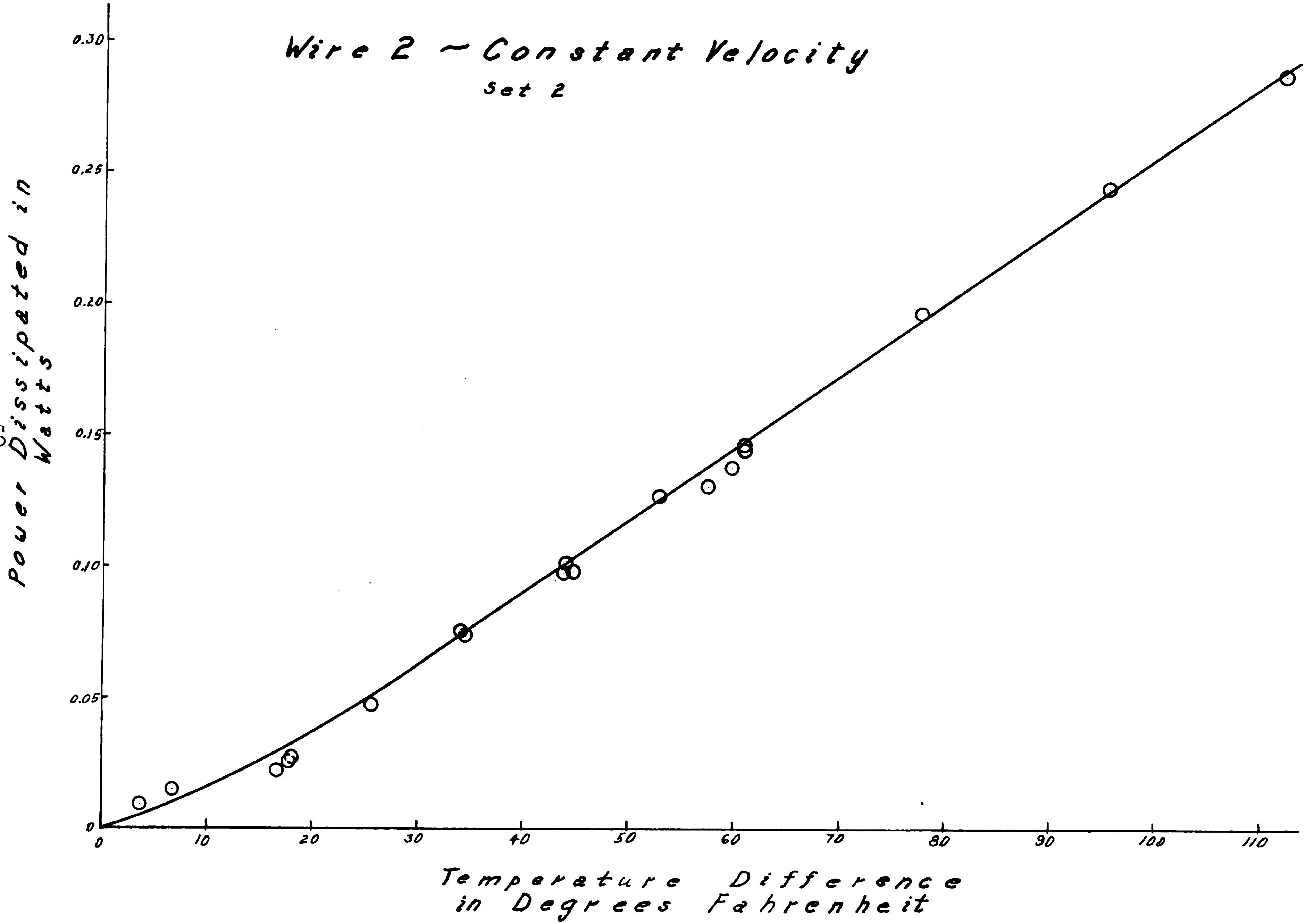
Wire 2 ~ Constant Velocity
Set 1
0.3
0.2
0.1
0
0
10
20
30
40
50
60
70
80
90
100
110
Power Dissipated in Watts
Temperature Difference in Degrees Fahrenheit

E. Data for constant velocity curve for Wire 2 (Set 2)

Barometric Pressure 29.27 in. of Hg.

Velocity 26.9 ft. per sec.

i amps	R ohms	T_a °F	i^2R watts	T_w °F	ΔT °F	$i^2R/\Delta T$ Watts/°F
0.100	0.950	86.2	9.50×10^{-3}	89.6	3.4	2.80×10^{-3}
0.122	0.955	86.1	1.42×10^{-2}	92.4	6.3	2.26
0.150	0.971	85.2	2.18	101.6	16.4	1.33
0.162	0.971	84.2	2.55	101.6	17.4	1.46
0.168	0.971	84.0	2.74	101.6	17.6	1.56
0.220	0.987	85.6	4.78	110.8	25.2	1.90
0.270	1.002	85.0	7.30	119.4	34.0	2.15
0.272	1.002	85.6	7.41	119.4	33.8	2.19
0.310	1.018	84.2	9.78	128.6	44.4	2.20
0.310	1.018	85.0	9.78	128.6	43.6	2.24
0.314	1.018	85.0	1.00×10^{-1}	128.6	43.6	2.30
0.349	1.033	84.5	1.26	137.2	52.7	2.39
0.353	1.042	85.0	1.30	142.4	57.4	2.26
0.362	1.048	86.2	1.37	145.8	59.6	2.30
0.371	1.048	85.0	1.44	145.8	60.8	2.37
0.372	1.048	85.0	1.45	145.8	60.8	2.38
0.425	1.079	86.1	1.95	163.7	77.6	2.51
0.430	1.079	86.0	2.00	163.7	77.7	2.57
0.467	1.110	86.0	2.43	181.5	95.5	2.53
0.469	1.110	86.0	2.44	181.5	95.5	2.56
0.500	1.139	85.4	2.85	198.2	112.8	2.52



Wire 2 ~ Constant Velocity
Set 2
Power Dissipated in Watts
0
0.05
0.10
0.15
0.20
0.25
0.30
0
10
20
30
40
50
60
70
80
90
100
110
Temperature Difference in Degrees Fahrenheit

APPENDIX C (continued)

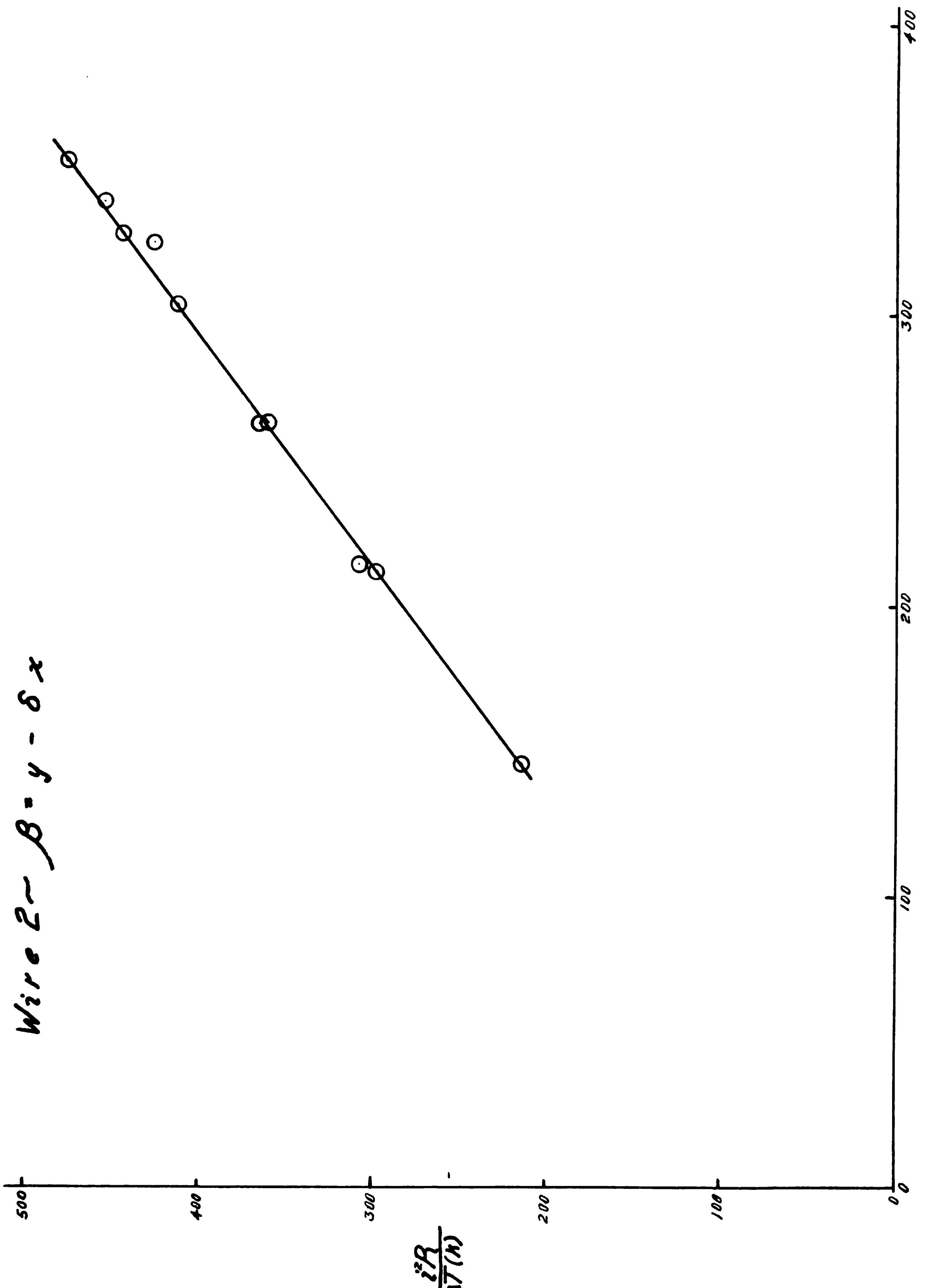
F. Data for constant wire temperature curve for Wire 2

Barometric Pressure	29.17 in. of Hg.
Wire Temperature	363.7 °F
Wire Resistance	1.079 ohm

i amps	i^2R watts	T_a °F	k BTU/°F/ft/sec	V ft/sec	$(\rho V)^{\frac{1}{2}}$ (lb/ft^2-sec.)$^{\frac{1}{2}}$
0.366	1.45×10^{-1}	85.5	3.892×10^{-6}	27.4	1.40
0.358	1.38	85.5	3.892	25.3	1.34
0.351	1.33	86.5	3.897	23.8	1.30
0.348	1.30	85.9	3.894	23.3	1.29
0.338	1.23	87.5	3.905	20.5	1.21
0.318	1.09	87.0	3.901	15.4	1.04
0.288	8.94×10^{-2}	89.5	3.916	10.3	0.85
0.282	8.58	90.0	3.919	10.3	0.84
0.236	6.11	91.5	3.928	4.8	0.58

APPENDIX C (continued)

ΔT °F	$\sqrt{s/k}$ (ft.-sec./lb.)$^{\frac{1}{2}}$	y $i^2R/(\Delta T)(k)$	x $\sqrt{s/k}\,(\rho v)^{\frac{1}{2}}$
78.2	251.6	475	352
78.2	251.6	455	338
77.2	251.4	444	327
77.8	251.5	426	324
76.6	251.3	413	303
76.7	251.3	365	263
74.2	250.9	308	213
73.7	250.9	297	211
72.2	250.8	215	146


Wire 2 — β = y - δx
$x = \sqrt{\frac{c_p}{k}}\,(\rho V)^{1/2}$
$y = \frac{i^2R}{\Delta T(k)}$
0
100
200
300
400
500

APPENDIX D

REFERENCES

Specific References

1. Kennelly, A. E., Wright, C. A. and Van Bylevelt, J. S., "The Convection of Heat From Small Copper Wires", The Transactions Of The American Institute of Electrical Engineering, Vol. 13, Part 1, 1910, pp. 363-397.

2. MacGregorond and Morris, J. T., "The Electrical Measurement of Wind Velocity", Engineering, Vol. 94, Dec. 27, 1912.

4. Ferrari, Carlo, "Electrical Equipment For The Experimental Study of Fluids", National Advisory Committee For Aeronautics, Technical Note, No. 1006, 1942.

5. King, L. V., "On The Convection of Heat From Small Cylinders In a Stream of Fluid: Determination of The Convection Constants of Small Platinum Wires With Application To Hot-Wire Anemometer", Philosophical Transcripts Of The Royal Society (London), Sec. A., Vol. 214, Nov. 1914, pp. 373-432.

6. Dryden, H. L. and Kuethe, A. M., "The Measurement of Fluctuations of Air Speed By The Hot-Wire Anemometer", National Advisory Committee For Aeronautics, Rep. 320, 1929.

7. Weske, J. R., "Method of Measurement of High Air Velocities By The Hot-Wire Method", National Advisory Committee For Aeronautics, Tech. Note No. 880, 1943.

8. Weske, J. R., "A Hot-Wire Circuit With Very Small Time Lag", National Advisory Committee For Aeronautics, Tech. Note No. 881, 1943.

9. Weske, J. R., "Measurement of Arithmetic Mean Velocity of Pulsating Flow of High Velocities By Hot-Wire Method", National Advisory Committee For Aeronautics, Tech. Note No. 990, April 1949.

10. Corrsin, Stanley, "Extended Applications Of The Hot-Wire Anemometer", National Advisory Committee For Aeronautics, Tech. Note No. 1864, April, 1949.

Specific References (continued)

11. Simmons, L. F. G. and Bailey, A., "An Instrument for Measuring Speed and Direction of Air Flow", Philosophical Magazine, Vol. 3, 1927, pp. 81-96.

12. MacAdams, W. H., Heat Transmission, New York and London: McGraw - Hill Book Co., 1933.

13. Davis, Alfred H., "An Instrument For Use In Measuring Convected Heat", Physical Society of London - Proceedings, Vol. 33, 1920-21, pp. 152-163.

14. Marks, L. S. (Edited by), Mechanical Engineer's Hand Book, New York and London: McGraw - Hill Book Co., 1941, p. 1966.

15. Schubauer, G. B., "Effects of Humidity In Hot-Wire Anemometer", U. S. Bureau of Standards - Journal of Research, (RP 850), pp. 576-578.

16. Kennelly, A. E. and Sanborn, H. S., "The Influence Of Atmospheric Pressure Upon The Forced Thermal Convection From Small Electrically Heated Wires", Proceedings Of The American Philosophical Society, Vol. 52, 1914, p. 55.

APPENDIX D (continued)

General References

1. Davis, A. H., "The Heat Loss By Convection From Wires In a Stream of Air and Its Relation To The Mechanical Resistance", London, Edinburgh and Dublin Philosophical Magazine and Journal of Science, Vol. 41, 1921, p. 899.

2. King, L. V., "Precision Measurements Of Air Velocity by Means of The Linear Hot-Wire Anemometer", Journal of The Franklin Institute, Vol. 18, 1916.

3. Magnan, A., "Methods of Recording Rapid Wind Changes", National Advisory Committee For Aeronautics, Tech. Memo, No. 692, Nov. 1932.

4. Martinells, R. C., and Randall, R. D., "Behavior of Hot-Wire Anemometer Subject To Periodic Velocity", American Society of Mechanical Engineers - Trans., Vol. 68, June 1946, pp. 75-79.

5. Mock, W. C. and Dryden, H. L., "Improved Apparatus For The Measurement of Air Speed In Turbulent Flow", National Advisory Committee For Aeronautics, Rep. No. 448, 1932.

6. Ower, E., The Measurement of Air Flow, London: Chapman and Hall, 1933.

7. Runyan, R. A. and Jeffries, R. J., "Empirical Method For Frequency Compensation of The Hot-Wire Anemometer", National Advisory Committee For Aeronautics, Tech. Note No. 1331, 1947.

8. Townsend, A. A., "Measurement Of Double and Triple Derivatives In Isotropic Turbulence", Cambridge Philosophical Society - Proceedings, Vol. 43, Oct. 1947, pp. 560-570.