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ON THE INTERPRETATION OF THE OUTPUT OF HOT-FILM ANEMOMETERS AND A SCHEME OF DYNAMIC COMPENSATION FOR WATER TEMPERATURE VARIATION

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J. Tan-atichat, H. M. Nagib, and J. W. Pluister

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On the Interpretation of the Output of Hot-Film Anemometers and a Scheme of Dynamic Compensation for Water Temperature Variation

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ABSTRACT

Using a special calibration tunnel developed during the course of this study, the static and dynamic response of several kinds of commercially available hot-film probes with single and multiple sensors of the cylindrical-fiber type are examined. The effects of different parameters, including those of the anemometer bridge, on the output and performance of the probes are evaluated. In particular, the consequences of variations in water temperature on the hot-film anemometer output are determined. The low turbulence level (less than 0.1%) calibration tunnel is equipped with a heater capable of raising the water temperature to any desired value up to 120°F and controlling it within 0.2°F over a range of calibrated mean velocities from 0.01 to 1.4 ft/sec (better than $\pm 0.2\%$ accuracy except for $U < 0.1$ ft/sec where the accuracy is approximately $\pm 0.5\%$). The results reveal a large effect of the water temperature on the calibration curves (in an extreme case a change in temperature of only 5.5°F can result in a 100% error in the mean velocity reading). A scheme which utilizes a temperature sensing probe immersed in the working fluid is used to compensate for the water temperature variation. Several possible circuit configurations for this scheme, including an optimum circuit design, are investigated and the results from some of them are presented and discussed. The circuit has a frequency response to temperature variations which depends on the thermal time constant of the temperature

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probe (up to several cycles per second can be obtained using commercially available probes) and can be used to compensate for temperature variations of more than 20°F with an accuracy better than $\pm 0.2\%$. By using an effective value (much smaller than E_o) instead of the zero-velocity bridge voltage (E_o) in exponential-type linearizers, a constant exponent is found useful in linearizing the anemometer output over a wider range of velocities, especially the very low ones. Finally, a linearized hot-film anemometer compensated for temperature variation by utilizing the present scheme is successfully used to obtain precision measurements in a standard laminar flowfield where the water temperature varied. The results compare favorably with classical theory which is quite encouraging in view of the low overheat ratio used with hot-films and the large effects of temperature on water density and viscosity.

INTRODUCTION

Although the basic concepts involved in the usage of hot-wire anemometers have been well known for more than half a century (since the work of King[1]), it is only during the last decade that hot-wire systems have become available as off-the-shelf items. Today it is possible and even quite simple for a researcher to use ready-made commercial models of hot-wire probes, anemometer bridges, linearizers and signal processing equipment provided his working fluid is air. However, it is more complicated to apply the same concepts and use available equipment in water in spite of recent significant advancements in sputtering techniques that facilitate the production of small conical hot-film probes and cylindrical hot-film fibers of the type used in the present work and shown in Fig. 1.

Since the early work of King[1] various efforts have been made to further the understanding of the operation of hot-wire anemometers and to better the interpretation of hot-wire systems (e.g., see Collis and Williams[2] and Davies and Fischer[3]). Numerous studies related to the operation of hot-wires in air are described in Corrsin's review article[4] and in the texts of Bradshaw[5] and Sandborn[6]. The recent work of Perry and Morrison[7] is a representative example of the continued efforts in this field.

On the other hand, hot-wire and hot-film anemometry in water received considerably less attention from the researchers in fluid mechanics. Although they have been used in water for a number of years, it is only recently that

attention has been focused on the special problems arising in this working fluid. Some of these recent efforts are listed in the Bibliography[8-14]. The high electrical conductivity of water , its low boiling temperature and the effect of temperature on its density and viscosity are a few of the factors that must be properly accounted for before meaningful measurements can be made.

An added complication is introduced if the velocities used are in the low range. Various attempts have been made recently to calibrate and to use hot-wire and hot-film probes at low velocities in water (e.g., see Goodman[12], Dring and Gebhart[15] and Hollasch and Gebhart[16]). In spite of the success of these techniques the influence of free convection remains the main factor setting the lower limit of the velocity at which a probe can be accurately operated, in particular when the direction of the mean velocity relative to the direction of the gravitational force varies, which is the case in numerous experiments (see Goodman[12] and Warpinski et al.[17]).

A number of other factors must also be understood and accounted for in order to make successful hot-film measurements. Some of these are: the static and dynamic calibration and linearization of the anemometer bridge output (see References 18 through 21); the effect of complex nonuniform flowfields on the measurements (see References 22 and 23); and the effect of the probe on these flowfields[24].

EXPERIMENTAL FACILITY

A facility for the calibration of hot-film probes is an essential part of the equipment required for the present investigation. The limitations and drawbacks of commercially available systems led us to the design and construction

of the calibration tunnel described below. The evaluation of the calibration capabilities of this tunnel are discussed in detail in References 25 and 28.

The tunnel was constructed during the initial phases of the present investigation by Pluister[25] and was later modified and used by Tan-atichat[26,27] and Nagib[28]. A schematic diagram of the tunnel is shown in Fig. 2. The tunnel operates in a recirculating mode in a free-jet or a fully-developed pipe flow configuration. Its circulating pump (Wagner Electric Corporation) is capable of a maximum pressure head and flow rate of 30 ft. of water and 9 GPM, respectively. The flow rate can be monitored by either one of three flowmeters: Fischer and Porter Model 12-P-S, Rotameter #1, and Model 12-P-L, Rotameter #2, and a turbine-type flowmeter (Potter Aeronautical either Model No. 1/4-483A-AMF-6-FL69 or Model 1/8-483A-AMF-4). The ranges of the flowmeters are 0.9, 4.0, 2.5 and 0.75 GPM, respectively. All flowmeters were calibrated in position in the tunnel and were found capable of measuring average velocities from 0.01 to 1.4 ft./sec. in the free-jet or the fully-developed pipe flow. A filter (Commercial Filters Corp., Fulflo-Filter Model BR-4) located downstream of the pump is used to catch all particles larger than three microns in size at a maximum flow rate of 4 GPM. Details of the construction of the tunnel including features for easy alignment, disassembling and reassembling are described by Pluister[25].

To calibrate the hot-film probes, the free-jet configuration is used which provides a calibration stream closely approximating a plug profile and a very low level of turbulence (less than 0.1%). A number of free-stream turbulence manipulators were selected based on the study of Loehrke and Nagib[29] and used in the settling chamber which is followed by a 16:1 slow contraction section. A long distance is provided between the last manipulator and the inlet to the contraction for the decay of turbulence. The 1.034-inch diameter free-jet discharges in a large open top settling tank.

In order that the centerline jet velocity (i.e., the velocity used for calibrating the hot-film probes) be known for the free-jet, the tunnel had to be first "calibrated." The principle used for this calibration is based on the knowledge of the jet centerline velocity as a function of the flow rate through the jet. Since the flow rate can be monitored very accurately, the relation between it and the jet centerline velocity provides the information required for calibrating the probes with excellent accuracy, as long as the error in this relation is small compared to the error in measuring the flow rate. One method of obtaining this relation is through the knowledge of the jet velocity profile as a function of the flow rate. For the present tunnel this was accomplished[30] by an iterative technique utilizing a hot-film probe which automatically traverses the jet at a fixed rate. The accuracy of this scheme is further improved if the jet velocity profile is almost uniform. (If it is uniform the accuracy of the technique is equal to the accuracy of measuring the flow rate.) As pointed out earlier the design of the tunnel aimed at achieving a uniform jet velocity profile. The success in achieving this task helped in obtaining the results presented here.

Using the scheme discussed in Reference 30 better than $\pm$ 0.2% accuracy of the resulting calibration curve was obtained for the entire range of flow rates except at very low velocities, $U < 0.1$ ft./sec., where the accuracy is approximately $\pm$ 0.5%. A probe in position of calibration is shown in Figs. 2 and 3. Some typical mean velocity profiles of the calibration jet, which were measured at the axial position used for calibration, are shown in Fig. 4.

By inserting a special pipe section into the upstream settling tank, as shown in the top of Fig. 2, the tunnel can be converted to the fully-

developed pipe flow configuration (d = 1.034 inch, L = 163 inches and L/d = 157) with the entrance conditions remaining in this case the same as in the free-jet configuration. When a dye probe was positioned in the settling chamber upstream of the contraction section and a dye streak was introduced along the centerline of the pipe, the transition Reynolds number was determined. Due to the high quality of the apparatus transition was delayed up to a Reynolds number of 10,000.

Hot-film data can also be obtained in the downstream end of the pipe as the probe shown in the bottom right-hand side of Fig. 2 indicates. The pipe flow discharging into the downstream tank with a fully-developed parabolic profile, or the last section of the pipe, can also be used for calibration and evaluation of the performance of the probes. However, the free-jet configuration with the uniform axial profile is found to be more accurate and convenient.

The tunnel is easily adaptable to the use of a number of visualization techniques including the hydrogen-bubble method and dye streaks and particle visualization. It was used by Tan-atichat[26] and Nagib[28] to study different types of turbulence manipulators, i.e., for the control of the level of free-stream turbulence by means of techniques similar to those used by Loehrke and Nagib[29].

RESULTS AND DISCUSSION

Calibration and Operational Difficulties

Quality Control of Water. Although carefully constructed hot-film probes, particularly those coated with an insulating material such as quartz, can be

used in hard tap water, considerable care must be exercised to insure satisfactory performance and to obtain adequate life-time of the probes[11].

In experiments where line power is used to drive the pump or any other experimental equipment in direct contact with the working fluid, it is necessary to minimize the conductivity of the water. Commercially available deionizing units are found adequate for this purpose. Even with deionized water (and if high frequency response of the probes is not essential) it is advisable to use coated hot-film probes. As demonstrated by the turbulence energy spectra of Resch[8], for most experiments in water a frequency response of 1 kHZ is more than adequate. This frequency response is easily attained using standard anemometer units and commercially available probes such as those shown in Fig. 1.

The second important problem encountered in hot-film anemometry in water concerns the amount of air dissolved in the working fluid. When tap water is used a probe placed in position will collect a sheet of bubbles even with no current passing through it. If the probe is operated with this sheet of bubbles it will not only give erroneous and inconsistent results, but it will also fail due to mechanical or thermal effects. Experience has taught us that when tap water is left standing to deaerate in an open-top tank for approximately 72 hours and its temperature and pressure reach equilibrium with the ambient air, it can be used without difficulties in most experimental facilities. If the apparatus contains a section with free-falling water in its flow loop, the added air in that region will lead to the accumulation of bubbles on the probe.

Air bubbles adhering to the film have such a drastic effect on the heat transfer characteristics of the probe that unless this problem is eliminated

no meaningful measurements can be made. The following simple demonstration using deaerated water and a hot-film anemometer will readily convince non-believers of this. First, one stirs the water ahead of the probe just enough to trap some air bubbles and waits until a very small bubble adheres to the film. Then watching the anemometer output the probe is tapped lightly to shake the bubble off noting the change in the output. If the magnitude of this change is compared to the changes in the hot-film calibration curve it becomes evident that the accumulation of air bubbles is causing errors that may be as large as 50% of the mean velocity reading.

The impurities present in tap water and additional ones that find their way continuously into the working fluid represent another problem. When one uses hot-wires in air one becomes easily aware of the effect of impurities, such as dust particles, on the probe since the result will usually be a probe with a broken wire. Hot-film probes are much more rugged so that the bombardment and accumulation of the impurities on the probe will not give rise to easily detectable signals, especially if the flowfield is turbulent. Fortunately this problem can be readily resolved with the aid of commercially available filters capable of removing particles larger than 1 or 2 microns from the working fluid.

The final and most important problem is caused by the effect of changes in the water temperature on the output of the hot-film probe. Most of this paper is devoted to this complication. It can be stated at the outset that if the physical arrangement of the equipment and the funds permit, experimental facilities employing water in which hot-film measurements are being contemplated

should be equipped with a precise heating-cooling unit including feedback-type temperature sensing and control capabilities. This unit should be able to control the water temperature within 0.1° F, otherwise the types of problems discussed in this paper cannot be solved.

There are a number of reasons why experimental setups for flow studies employ closed loop flow circuits. Some of these reasons were discussed above (e.g., the need to filter, deaerate and deionize water for hot-film anemometry); others relate to improvements in the quality and controllability of the flow-field in a recirculating flow experiment that are important characteristics in experiments dealing, for example, with stability and transition. The heat generated by the pump in a recirculating flow system and added to the working fluid complicates the required temperature control unit. (In one of the I.I.T. facilities the temperature of the working fluid increases from 70° F to 120° F at very low flow rates in less than ten hours.)

Filtering, deaerating and deionizing the water can usually be accomplished with relative ease and economy. The adequate control of the water temperature, however, may require relatively costly temperature control units (see Goodman[12]) or alternative methods similar to those outlined later in this paper.

The water treatment facility of the I.I.T. Swirling Flow Laboratory employs commercially available (supplied by Continental Water Conditioning Corp.) deionizing filtering units that are connected to the main supply water line. The units are capable of deionizing up to 1,500 gallons and filtering up to 10,000 gallons of water at the rate of 4 GPM. The water is deionized to

18 megaohm-cm resistivity and all particles larger than one micron are removed from it. The water is then stored in a 100-gallon stainless steel tank. The tank has an open top with a dust cover which allows the water to be kept at room pressure. The tank is located 10 feet above floor level and supplies water to all Swirling Flow Laboratory facilities when hot-film anemometry is used. Each of the closed loop experimental setups is equipped with a filter which continuously removes any impurities that may find their way into the system from the laboratory atmosphere or from parts of the facility itself. The electrical conductivity of the water is monitored in each apparatus by means of simply constructed probes. When a probe indicates a drop in resistivity the loop is drained and refilled with filtered, deionized and deaerated water from the tank. This procedure may be required at times as often as once every week but sometimes the same water is used for a month, depending on the apparatus, its condition, the number of hours of operation, the condition of the laboratory environment, etc.

Calibration for Mean Velocity and Temperature. Two types of cylindrical hot-film fiber probes are used in the present work: DISA55F06-70 micron element made of a quartz fiber with a sputtered film of nickel covered by a quartz coat and TSI 1240-2 mil element made of a quartz fiber with a sputtered coat of platinum covered by an insulating coat. (While the TSI is a two sensor probe, only the upstream element was used oriented normal to the flow direction.) A selection of single element and double element X-probes are shown in Fig. 1. Using an overheat ratio of 1.08 a large signal is obtained from the anemometer bridge and an adequate frequency response is attained (A frequency response of 1 kHz is measured using the square wave method at velocities up to 1.5 ft./sec.). The lifetime of the probes is also improved by using this

relatively low overheat ratio instead of the commonly used values from 1.1 to 1.15 (one probe lasted for 12 months with more than 200 hours of operation before it failed).

Using the hot-film anemometer instrumentation outlined in Fig. 5, the probes can be calibrated in the free-jet of the calibration tunnel for velocity and directional sensitivity. The top curve in Fig. 6 is a typical mean velocity calibration curve obtained in this manner.

The calibration tunnel is equipped with a stainless steel rod heater, with powerstat controlled input power, which is capable of raising the tunnel temperature to any desired value from room temperature up to 120° F. This is accomplished by increasing the input voltage to the heater and waiting for the tunnel thermal conditions to reach steady state, while monitoring the temperature of the fluid in the settling chamber as well as in the free-jet. The probe can then be calibrated at this temperature after temperature corrections have been applied to the flowmeter calibration curves. (The flowmeters were calibrated originally in the tunnel over a range of temperatures.)

As long as the tests can be run in a systematic manner the temperature of the working fluid can be kept constant within 0.2° F. First, the tunnel controls are set for operation at the maximum flow rate by switching the flow control loop of the tunnel to bypass the flowmeters (see Fig. 2); under these conditions the tunnel reaches steady state usually in a few minutes. Next, the flowmeter control valves are set approximately to give the desired velocity while the tunnel is still operating at the maximum flow rate. Finally, the flow bypass is closed so that the entire flow passes through the flowmeters

and the reading of the flowmeter and the anemometer bridge are recorded. For calibration at other velocities, the bypass is operated again returning, thereby, to maximum rate of flow and the above procedure is repeated.

Using the same anemometer setting as for the top curve of Fig. 6 (a fixed bridge resistance) calibration curves at various free-stream temperatures can be obtained. Typical curves are shown in Fig. 6. The most important information revealed by these data is the large effect of the water temperature on the calibration curves. Comparing the top two curves at an anemometer output voltage of 7 volts, it is easily concluded that an increase of water temperature of only 5.5° F can give a 100% error in the mean velocity reading. Figure 6 demonstrates that the changes in the anemometer output due to the temperature of the fluid and its velocity are of the same order of magnitude. If a similar comparison is made with hot-wire data in air it is found that the errors are almost two orders of magnitude smaller. A number of factors are involved in this most drastic effect, the most important of these being the low operating film temperature used in water. (As demonstrated by Nagib[28], a similar effect is found in air if the wires are operated at overheat ratios below 1.1.)

Water Temperature Effects. The first attempt made to remove the water temperature effect demonstrated in Fig. 6 was done by repeating the calibration curves at the various temperatures and changing for each temperature the bridge resistance which controls the overheat ratio, thereby maintaining a constant overheat ratio at all temperatures. While a large improvement was made, this approach was not satisfactory as one would expect based on the governing equations.

The hot-wire equation can be written as:

$$\frac{I_p^2 R_H}{R_H - R_c} = A + B\,U^n \qquad (1)$$

where U is the fluid velocity, I_p is the current through the probe, whose resistance at the fluid temperature and the operating temperature are R_c and R_H, respectively; A, B and n are nearly constant. The overheat ratio is defined as

$$r_o \equiv \frac{R_H}{R_c} \qquad (2)$$

Based on this relation and since for constant temperature operation the anemometer servo-amplifier maintains the probe temperature and hence its resistance R_H constant, one may conclude, assuming that the changes in A and B due to temperature are not large, that a better scheme of compensation can be achieved by maintaining the overheat resistance difference $R_H - R_c$ constant.

In Fig. 7 a probe is calibrated at different water temperatures using the technique outlined earlier and the bridge resistance is adjusted at each temperature so that the difference between the operating hot-film probe resistance and its resistance at the water temperature remains constant. The correlation between the data in this case is much improved compared to the case of fixed overheat ratio. However, this solution is still not acceptable for precision hot-film measurements.

Two final attempts for improvement were made. In the first, the anemometer resistance at each of the temperatures was adjusted to yield the same bridge output at the maximum velocity used during the calibration. The second attempt is similar except that the anemometer resistance was adjusted to yield the same output at the average velocity of the curve (0.55 ft./sec.). The overheat ratios used here are approximately the same as those used in the two previous attempts. It is clear from the results of the last two attempts shown in Figs. 8 and 9 that the best correlation is obtained using the last scheme. Although this result does not provide complete understanding of this problem at least it provides an empirical road to an acceptable solution. The impact of these results on our compensating techniques is discussed in a latter part of this paper. Whatever the compensating scheme is, in order for it to be reasonably fast in its response the fixed bridge resistance will have to be replaced by an external variable resistance which is dependent on the water temperature. The anemometer bridge (DISA55D01) will then have to be operated in a 1:1 bridge ratio. Some problems that arise when this bridge configuration is used are discussed in the following section. These are presented here because they are of the type often encountered in such an operating configuration.

Anemometer Bridge Ratio Effect. Using one of the available DISA55D01 anemometer bridges and a precision non-inductive potentiometer, a hot-film probe was calibrated as shown in Fig. 10. The difference between the two curves appearing in the figure is the bridge ratio setting of the anemometer. Operation at a bridge ratio of 1:1 was performed with the potentiometer adjusted to the same value of the fixed bridge resistance (except for a factor of 20 from the bridge ratio) used with the 1:20 bridge ratio operating mode. This procedure was repeated using a number of different DISA55D01 anemometers, different types of probes, and a number of non-inductive potentiometers at a

number of overheat ratios. Although some differences were found in the data the following basic trend was evident in all of them: calibrating a probe using the same overheat ratio setting with 1:1 and 1:20 bridge ratios does not yield the same calibration curves.

In order to understand this effect, first the circuit characteristics of the DISA anemometer bridge were examined. No evidence of any limiting currents or unbalance of the bridge was noted in the anemometer characteristics listed in the manual. Next, a hot-wire probe was calibrated in air[28] with the same anemometer at different overheat ratios (see Fig. 11). While this effect was not evident at the high overheat ratios used in air some difference between operation at 1:1 and 1:20 bridge setting was detected at $r_o = 1.08$.

When the anemometer circuits were carefully checked and compared to the specifications listed in the manual, the problem was finally traced to a mismatch between the bridge ratio of the top two legs of the bridge and that of the bottom two legs (i.e., the stated bridge ratio) when compared at the 1:1 and 1:20 bridge settings. This difference between the actual and specified bridge resistance was found to be present to varying degrees in all seven DISA55D01 anemometers in use at I.I.T. The design values for the bridge resistances are 900, 100, 45, 5, 45, and 5 ohms, respectively. The corresponding measured resistances of the anemometer which produces the largest error are 902.5, 99.3, 44.7, 4.9, 45 and 4.9 ohms, while in the one with the least error the measured resistances are 900, 99.4, 44.9, 4.95, 44.9, 4.9 ohms. The discrepancies between the measured and the specified values of the individual resistances is of the same order of magnitude in both units (and most of them within factory specifications) but the bridge balance condition and the bridge ratios in the latter of the two are more closely matched.

Compensating for the above differences between 1:1 and 1:20 bridge ratios the curve in Fig. 12 was obtained with a DISA anemometer using the same techniques and potentiometers that led to Fig. 10. The calculated overheat ratios (given in the Figure) are, of course, different even though the actual probe overheat ratios used were identical since the error in the bridge resistances affects the calculated overheat ratio.

There are two reasons that these discrepancies have more pronounced effects on hot-film measurements than in hot-wire studies: the overheat ratio or overheat resistance difference is much smaller in water than in air and this results in a larger percent of error due to the bridge mismatch (see the effect of high and low overheat ratios in the case of a hot-wire in Fig. 11); the second reason (which applies only to nickel hot-film sensors) is the higher thermal coefficient of electrical resistivity of the hot-films compared to the tungsten hot-wires which results in larger bridge outputs and hence larger bridge differences in the case of nickel hot-films. In the case of platinum hot-films, its lower thermal coefficient of electrical resistivity may result in minimizing this difficulty, however, we have not investigated this yet.

To avoid this bridge ratio effect the probe to be used in a given experiment should be calibrated using the same anemometer bridge, bridge configuration, bridge components and overheat ratio as those to be used in the experiment. This is a recommended procedure which should be used with all anemometers. Otherwise, a large number of corrections will be required resulting in unavoidable errors.

Bridge Output Linearization. An interesting result of the numerous experiments performed with hot-film probes in the present study deals with

the optimal values of the constants involved in the linearization of the bridge output with exponential-type linearizers. Equation (1) can be written as

$$E^2 - E_o^2 = C\,U^n \tag{3}$$

A logarithmic plot of the various calibration curves indicating the value of the exponent n (as in the middle curve in Fig. 13) reveals that the experimental points gradually deviate from this relationship at the lower values of the velocity. When different values are substituted instead of E_o (these values are referred to as effective zero velocity bridge voltages E_o') into the Equation (3) the resulting correlation is sometimes better and sometimes worse. In particular, if E_o' is very small compared to E_o (i.e., $E_o' \approx 0$) the correlation is better than if $E_o' \geq E_o$. This is demonstrated in Fig. 13. Based on data obtained with different hot-film probes over the same range of velocities it can be concluded that $E_o' << E_o$ yields the best correlation of the data. For the top curve in Fig. 13 the equation can be written as

$$E^2 = C\,U^n \tag{4}$$

where n is approximately equal to 0.23. Note that for air the value of n in Equation (3) is approximately 0.5. Even a plot of the standard TSI probe calibration curve which is found in the TSI linearizer manual leads to the same result as shown plotted in Fig. 14.

If Equation (3) is written in the form

$$E^2 - E_o'^2 = C\,U^n \tag{5}$$

and the data obtained[28] with various hot-wires are reduced using a least square

fit, a value of $E_o' \approx 0.9\ E_o$ is found to be an optimum as demonstrated in Fig. 15 (reproduced from Reference 28). We conclude therefore that Equation (5) should be written as

$$E^2 - a^2 E_o^2 = C\ U^n \qquad (6)$$

where $a \approx 0.9$ for hot-wires in air over the range of velocities from 10 to 100 ft./sec. and $a \approx 0$ for cylindrical hot-film fibers in water over the range of velocity from 0.05 to 2 ft./sec.

For water at velocities below 0.05 ft./sec. the effect of free convection strongly influences the operation of the probe. This lower limit of operation is based on the criterion proposed by Warpinski, et al.[17] and is in agreement with the results of the present measurements.

The small value of the constant a in Equation (6) when applied to hot-film data in water can be explained by the following arguments. Due to the small overheat ratios typically used the contribution of free convection is negligible in the forced convection range of operation of the film. (Recall that the value of E_o is proportional to the heat transfer due to free convection.) In addition, the high values of the temperature coefficient of a nickel hot-film and its heat transfer coefficient in the forced convection range, h, result in very large values of the constant C in Equation (6). These two reasons combine to make the second term in the left-hand side of Equation (5) negligible compared to the right-hand side of the equation and hence result in small values of the constant a.

Anemometer Output Drift. Detailed measurements of hot-film and hot-wire output drift when used in water are given by Morrow and Kline[11]. Some observa-

tions of drift obtained during the course of this investigation are given in Figure 16. While some of the drift is due to permanent effects such as the aging of the probe, a part of the drift can be corrected by cleaning the probe (e.g., with an ultrasonic cleaner). However, in spite of all the precautions that are taken the drift encountered in hot-film anemometry in water remains appreciable. For this reason it is a recommended procedure (which was used in the present study) to calibrate the probe just before and just after performing an experiment and to correct for the observed drift which is in this case quite small.

Schemes of Compensation for Ambient Temperature Variation

A number of temperature compensating schemes have been proposed by the hot-film manufacturers. All of these schemes depend on a temperature sensing probe which can be used in the anemometer bridge shown in Fig. 17 instead of the bridge resistance R_3. The ideal probe for this purpose should have the following properties:

1. Its resistance R_T should be given by

$$R_T = r_o M R_c = M R_H \tag{7}$$

where M is the bridge ratio and r_o is the overheat ratio.

2. The dependence of R_T on temperature should be identical to that for the hot-film probe resistance R_H.

3. The size of the probe should be sufficiently small to have a reasonably fast response and sufficiently large so as not to be heated by the bridge current. The latter requirement assures that the probe is independent of the fluid

velocity. Such a temperature probe is almost impossible to manufacture and even if it could be made, it could only be used with one hot-film probe.

Two other compensating schemes were proposed by Burchill and Jones[13] and Chevray and Tutu[31]. The first is a simplified version of the one described in Fig. 17 in which R_3 is adjusted manually as the fluid temperature changes; the adjustment being based on calibration curves obtained earlier at different fluid temperatures. The amount of time wasted during an experiment is the major objection to this scheme. The second technique involves a complex compensating scheme which is applied to the linearized signal through the linearizer's constants. This scheme also depends on a temperature sensing probe and its frequency response is limited by that of the probe.

A number of compensating circuits, shown in Fig. 17, are employed in order to facilitate the use of probes that do not meet the specifications of the ideal temperature compensating probe listed above, excepting the requirements regarding frequency response of the temperature sensor and its insensitivity to velocity that must always be satisfied. The closer the probe conforms to the other requirements the better the compensation will be.

A detailed analysis of the compensating circuit denoted by No. 1 is given in Reference 28. Based on that analysis and similar ones for the other two circuits of Fig. 17, it was concluded that the most suitable of the circuits is the one labeled No. 3. In addition to having performance curves similar to those reported in Reference 28, it offers the most flexibility and it requires the least effort to adjust for optimum temperature compensation with any set

of temperature and velocity probes. A representative example of the type of compensation achieved with circuit No. 1 is given in Fig. 18.

A problem which was encountered with some of the temperature probes is associated with their heating due to the current passing through them. This heating not only results in making the temperature probes sensitive to velocity, which is an undesirable feature, but it also affects the calibration curve of the velocity probe[28]. Using temperature probes which are not influenced by the electrical current passing through them (see probe in the top left-hand corner of Fig. 1) and operating the hot-film at slightly lower overheat ratios resulted in the elimination of this problem.

A typical calibration curve for a temperature compensated hot-film probe is shown in Fig. 19. Based on the circuit analysis of Nagib[28] a velocity and a temperature probe were selected and connected in the configuration of circuit No. 1 of Fig. 17 and the values of R_P and R_S were set based on the performance curves obtained from the analysis. The calibration curves were obtained using this system after minor adjustments in the values of R_P and R_S were employed. To perform these adjustments the mean velocity of the calibration jet was set at the average value of the velocity range of interest (see discussion of Fig. 9) and the temperature of the water was changed over the temperature range in which the compensation was required. Slight changes were then made in the values of the resistances R_P and R_S to minimize the change in the anemometer output with the temperature variations. The data in Fig. 19 were then obtained. A probe can be equally compensated using this scheme without referring to the performance curves derived from the analysis.[28] However, more time will be spent in

adjusting the circuit and selecting the temperature probe by using some sort of an iterative scheme.

Due to the advantages of circuit No. 3 of Fig. 17, two small electronic boxes were designed and constructed according to this circuit and are extensively used for all the temperature compensation requirements at I.I.T. The output of the integrated circuit box can be directly connected to the anemometer bridge and the temperature probe cable is then connected to its input. All four resistances, R_{P1}, R_{P2}, R_{S1} and R_{S2}, can be measured and adjusted in their position with minimum interference with the operation of the circuit and the hot-film anemometer.

Applying similar techniques to the ones described above, in relation to Fig. 19, the calibration curves of Fig. 20 were obtained using these specially constructed temperature compensation circuits. The calibration data from the probe are plotted in Fig. 20 using logarithmic coordinates by utilizing Equation (6) with the value of the constant a = 0. A linearizer (DISA55D10) was then set according to the curve of Fig. 20 and its output was checked against the calibration velocity.

Utilizing the above scheme a hot-film probe can be calibrated and compensated for variations in the water temperature in a matter of one hour using the facilities of the Swirling Flow Laboratory. This probe can then be transferred to any experimental facility, with its associated anemometer bridge, temperature probe, compensating circuit, linearizer and associated signal processing equipment, and used to perform precise mean and fluctuating

velocity measurements.

Using the techniques outlined above the measurements reported in Fig. 21 were obtained in the flowfield inside a cylindrical annulus. The outer wall of the annulus is made of a Plexiglas pipe 3.20±0.002 inches inside diameter. The inner wall consists of an aluminum pipe with an outside diameter of 2.000±0.001 inches. The resulting annulus radius ratio is equal to 0.625 and the gap is 0.60 inches in size. The entrance length-to-gap ratio at the position of the hot-film measurements of Fig. 21 is 83. This ratio is sufficiently large to allow laminar flow through the annulus to become fully developed.

The measurements reported in Fig. 21 are for a wide range of Reynolds numbers, N_R, within the laminar flow regime. For $N_R < 1100$ the values of W measured across the annulus included velocities which are in the mixed convection range of the hot-film (W < 0.05 ft./sec.). Therefore, data for $N_R < 1100$ are considered unreliable and are not presented here. For $N_R > 2200$ frequent turbulent bursts were observed on the oscilloscope displaying the hot-film output and the flow was considered not sufficiently laminar to compare to the theoretical fully-developed, viscous and laminar velocity profile shown in Fig. 21. The calibration curve of the single element, cylindrical fiber, hot-film probe used in these measurements is that shown in Fig. 20. This probe was compensated for temperature variations between 70° and 90° F during the experiments from which the results of Fig. 21 are obtained. The effects of the annulus walls on the measurements prevented the collection of reliable data for $r/R_o > 0.95$ and $r/R_o < 0.65$ (where R_o is the outside radius of the annulus).

In view of the large effects of the water temperature on the output of hot-film anemometers, as demonstrated in Fig. 6, the agreement between

the measurements and the theoretical results displayed in Fig. 21 is a strong indication of the success of the compensating scheme. Since the water temperature varied during these tests between approximately 70° F and 90° F and since no corrections whatsoever were applied to the linearized output of the anemometer to obtain these data we came to the conclusion that the aim of this work, which is to obtain precision hot-film measurements in water facilities, has been accomplished.

CONCLUSIONS

1) A very large effect of the water temperature on the output of hot-film anemometers is documented. In an extreme case a change in temperature of only 5.5° F can result in a 100% error in the interpretation of the mean velocity reading.

2) The successful compensation for the water temperature variation is demonstrated using a scheme which utilizes a temperature sensing probe immersed in the working fluid. Several possible circuit configurations for this scheme were investigated and the one which employs an optimum circuit design is found capable of compensation for temperature variations of more than 20° F with an accuracy of better than $\pm$ 0.2%.

3) By using an effective value (much smaller than E_o) instead of the zero velocity bridge voltage, E_o, in exponential-type linearizers a constant exponent is found useful in linearizing the anemometer output over a wider range of velocities, especially the very low ones.

4) A probe to be used to perform precision hot-film measurements should be calibrated using the same anemometer bridge, bridge configuration, bridge components and overheat ratio as those to be used in the experiment. Otherwise, a large number of corrections will be required resulting in unavoidable errors. In addition, the water used in the experiment should be filtered (one or two micron filter) deaerated and deionized (e.g., 18 megaohm-cm resistivity).

5) A linearized hot-film anemometer compensated for temperature variation by utilizing the present scheme is successfully used to obtain accurate measurements in a standard laminar flowfield where the water temperature varied and the results compare favorably with the classical theory.

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NOTATION

A	Constant used in Equation (1)
a	Constant used in Equation (6)
B	Constant used in Equation (1)
C	Constant used in Equation (3)
D_i	Diameter of inner wall of annulus
D_o	Diameter of outer wall of annulus
d	Diameter of calibration jet
E	Anemometer output voltage
E_o	Anemometer output voltage at zero velocity
E'_o	Effective anemometer output voltage at zero velocity used to linearize the anemometer output according to Equation (5)
I_p	Anemometer bridge current passing through probe
$L_{L,T}$, $L_{L,V}$	Industances of lead cables to temperature and velocity probes
M	Anemometer bridge ratio
N_R	Axial Reynolds number $\equiv \overline{W}(D_o - D_i)/\nu$
n	Exponent in Equation (1)
R_1, R_2, R_3	Anemometer bridge fixed resistances (see Fig. 17)
R_c	Probe resistance at fluid temperature
R_H	Operating probe resistance = $R_c r_o$
$R_{L,T}$, $R_{L,V}$	Resistances of lead cables to temperature and velocity probes
R_P, R_{P1}, R_{P2}	Adjustable parallel resistances in temperature compensating circuit of anemometer bridge
R_S, R_{S1}, R_{S2}	Adjustable series resistances in temperature compensating circuit of anemometer bridge

R_T	Temperature compensating probe resistance
r	Radial direction measured from axis of calibration free jet or annulus
r_o	Hot-film overheat ratio $\equiv R_H/R_c$
T_∞	Fluid ambient temperature
t	Time
U	Time-mean value of velocity in the streamwise direction
W	Time-mean of axial velocity
$\overline{W}$	Flow rate average axial velocity
ν	Fluid kinematic viscosity

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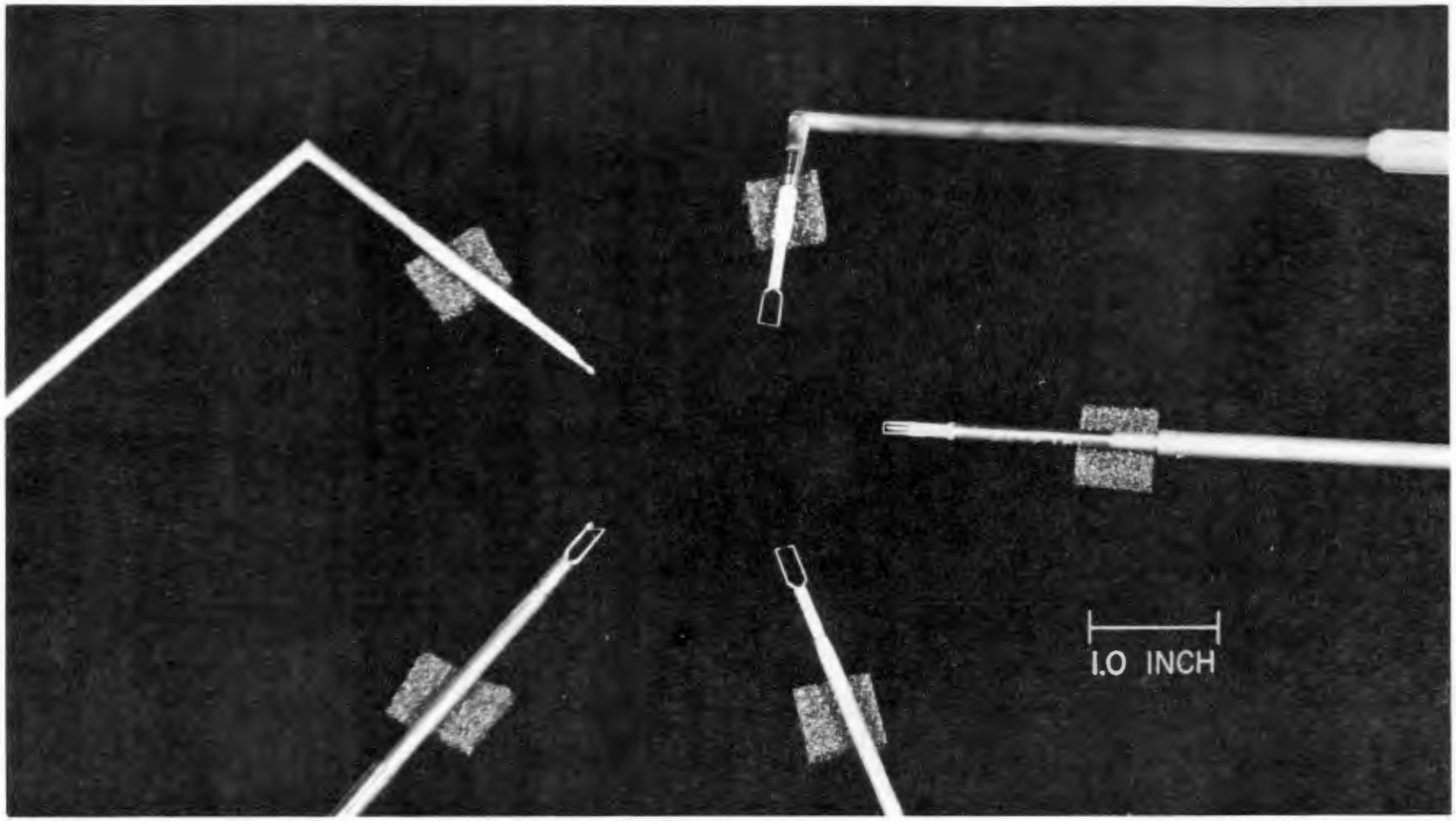

FIG. 1. HOT-FILM PROBES

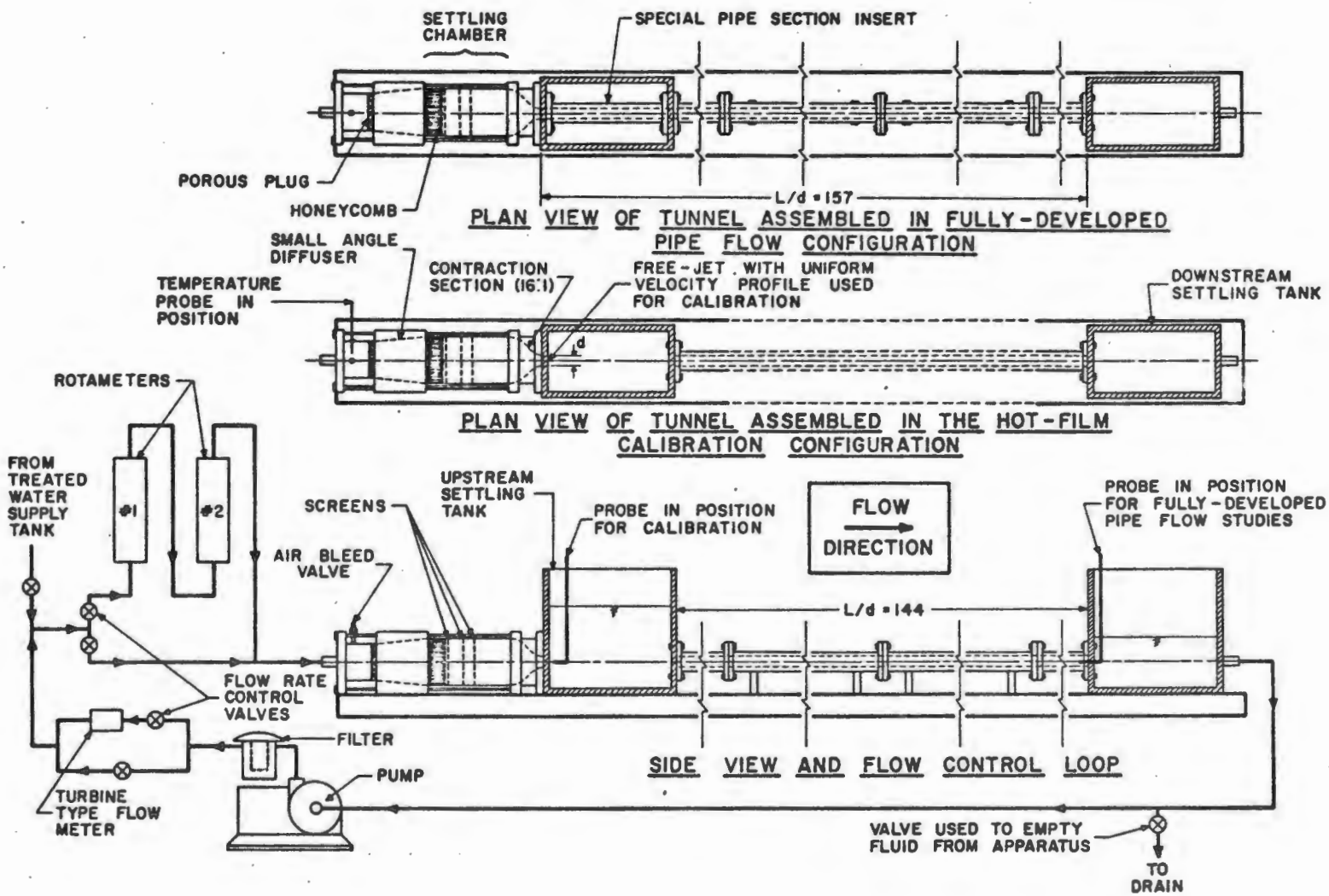

FIG. 2. SCHEMATIC OF HOT-FILM CALIBRATION TUNNEL

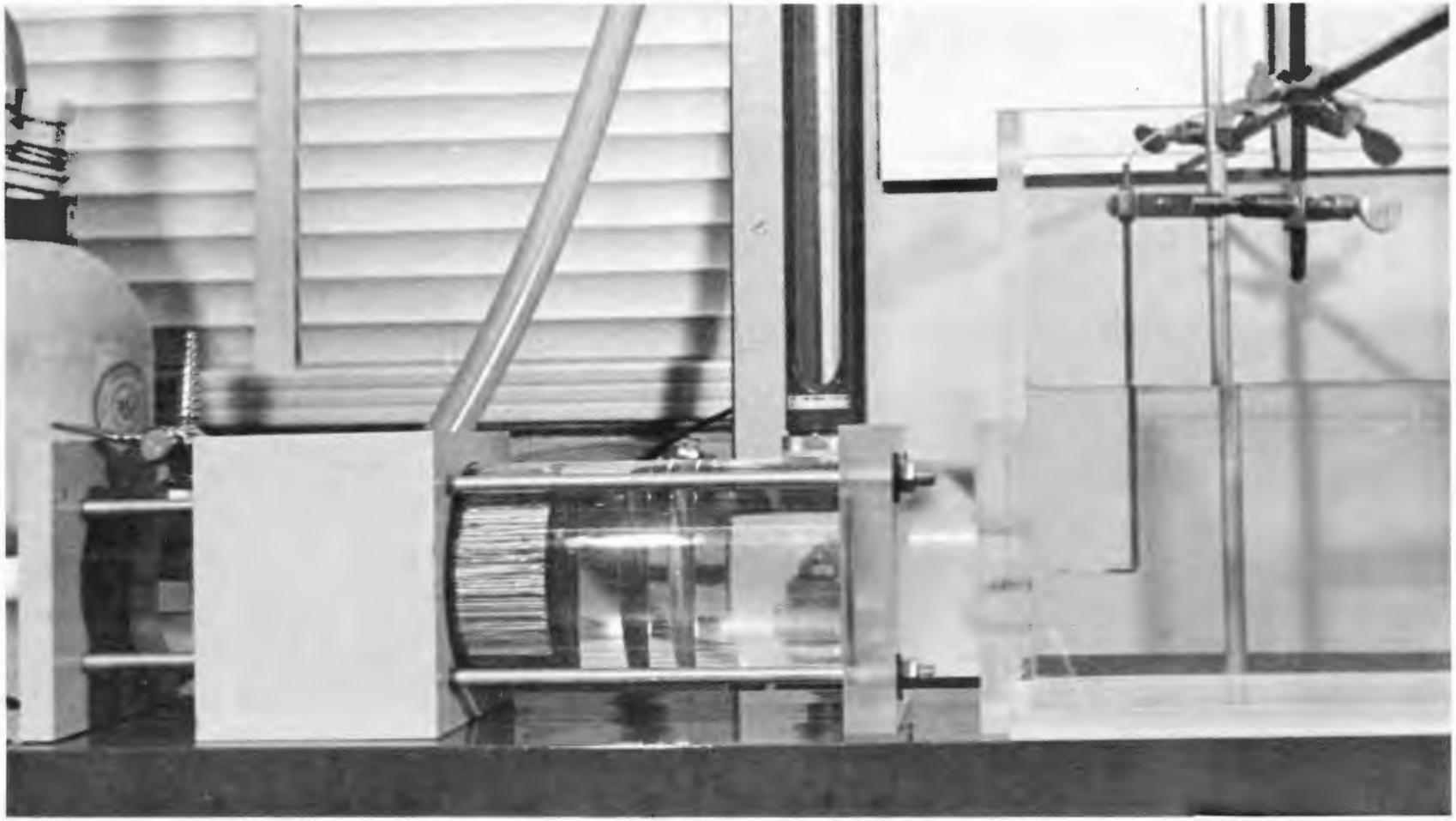

FIG. 3. HOT-FILM PROBE IN POSITION FOR CALIBRATION

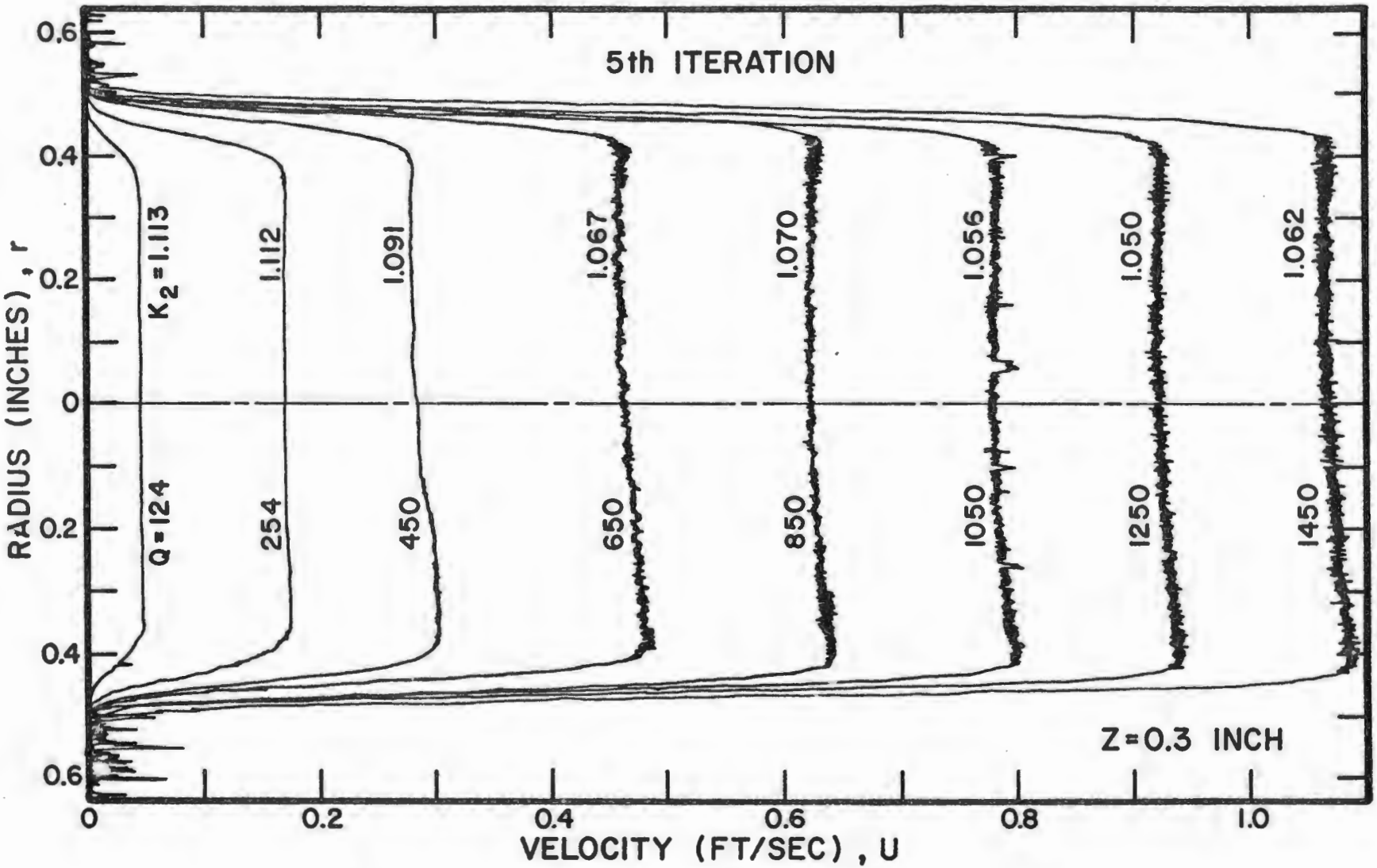

FIG. 4. TYPICAL MEAN VELOCITY PROFILES USED FOR CALIBRATION OF TUNNEL FREE-JET

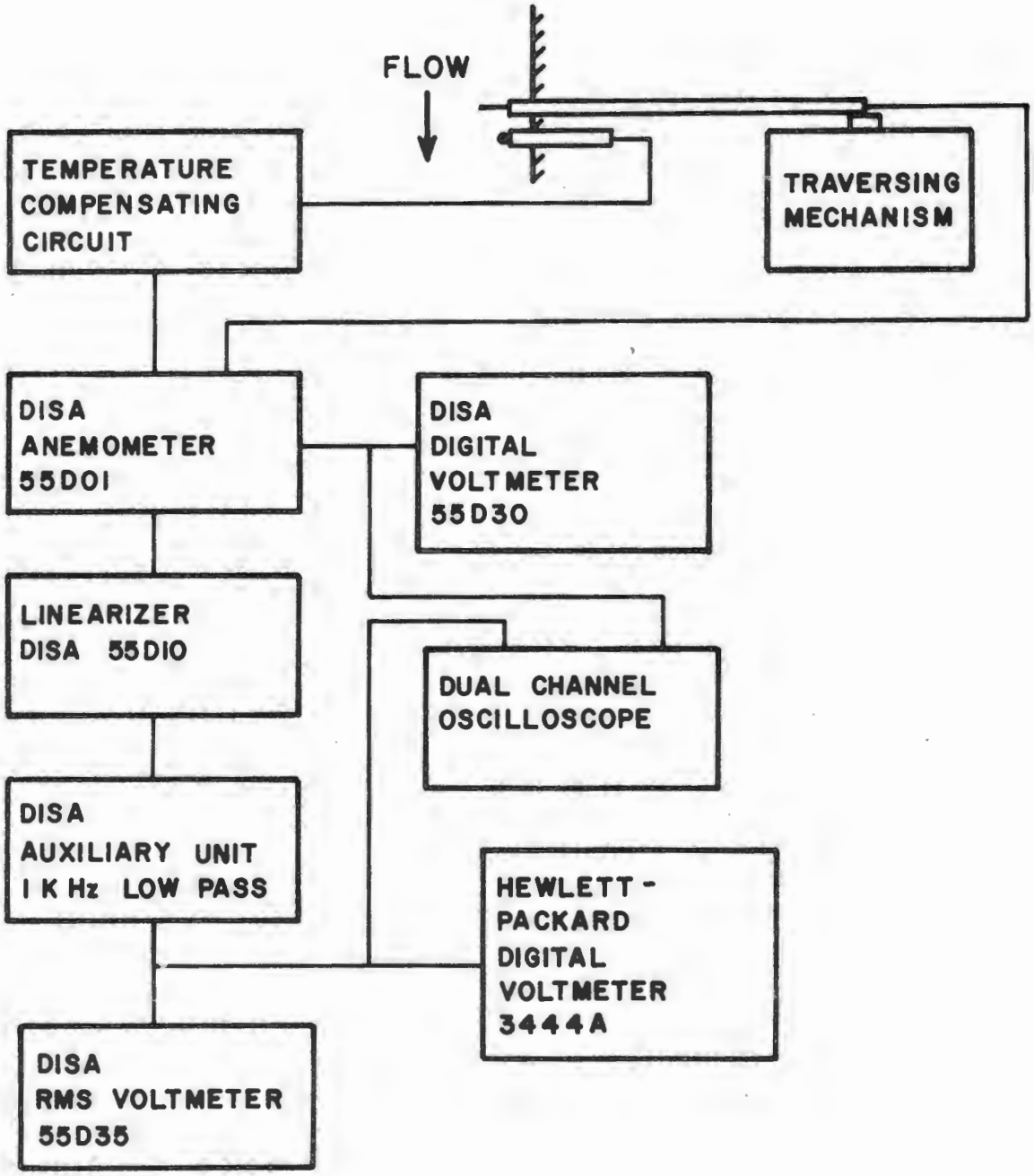

FIG. 5. INSTRUMENTATION SCHEMATIC

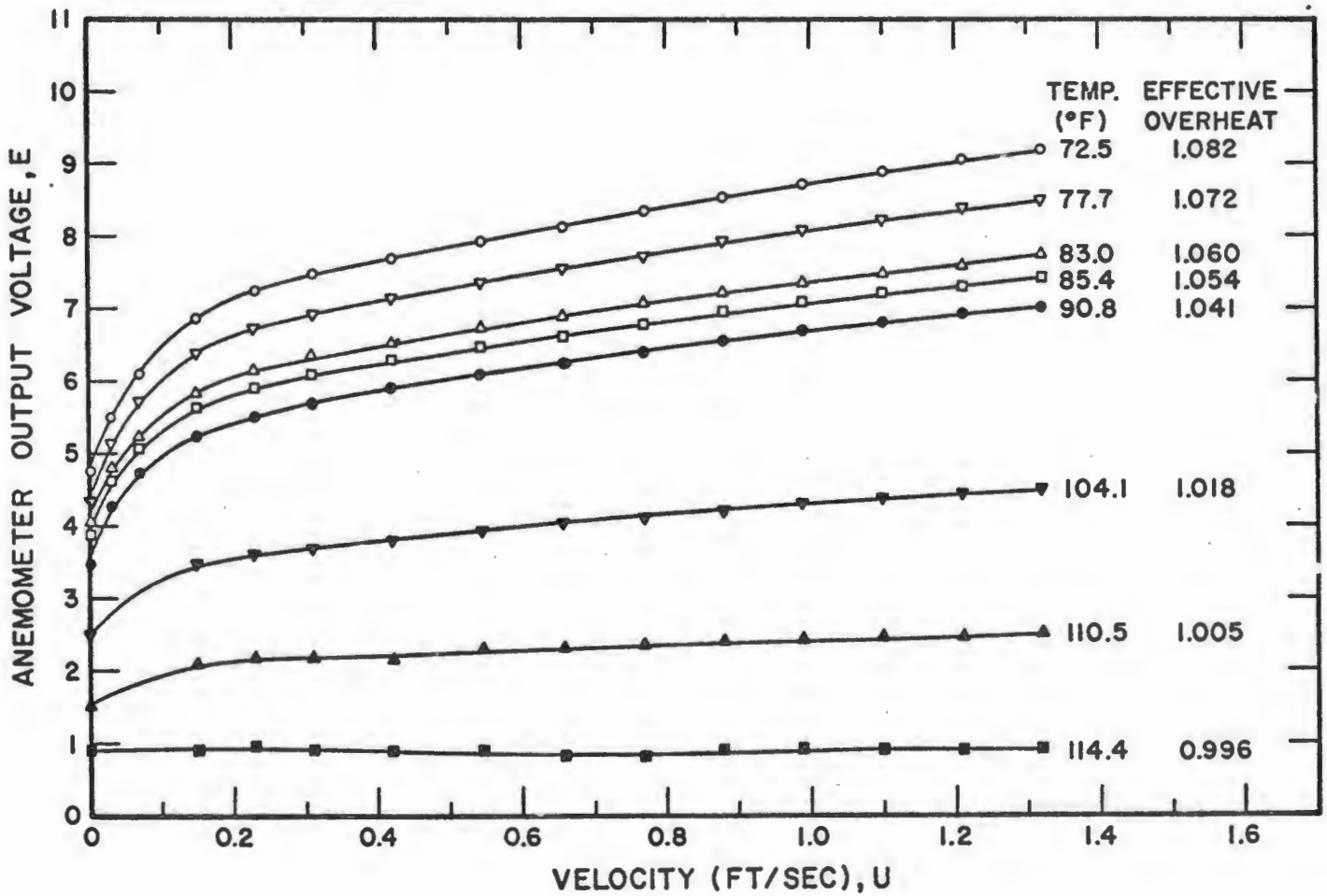

FIG. 6. MEAN VELOCITY CALIBRATION CURVES FOR DIFFERENT WATER TEMPERATURES

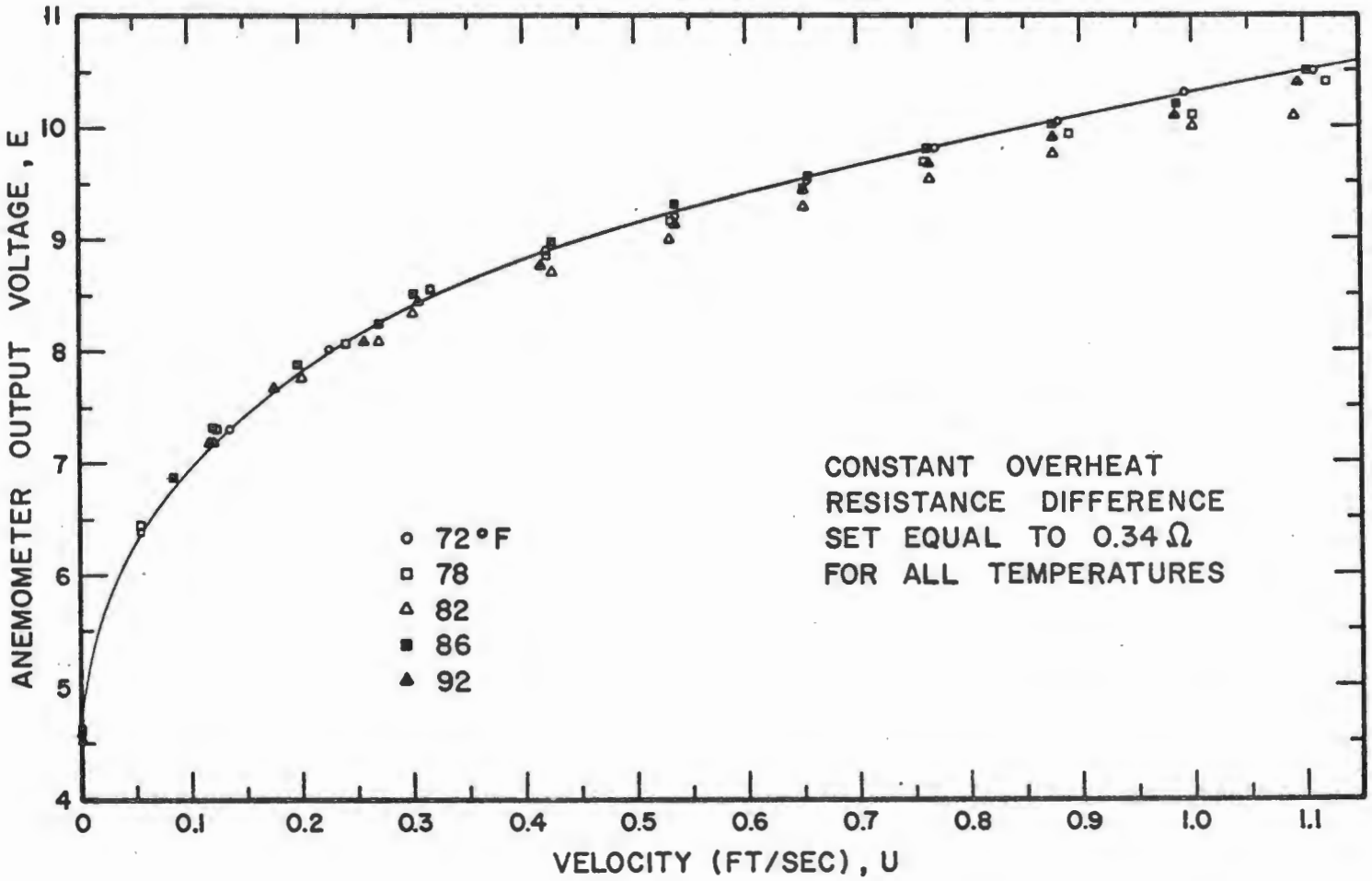

FIG. 7. MEAN VELOCITY CALIBRATION CURVES FOR DIFFERENT WATER TEMPERATURES USING A CONSTANT OVERHEAT RESISTANCE DIFFERENCE

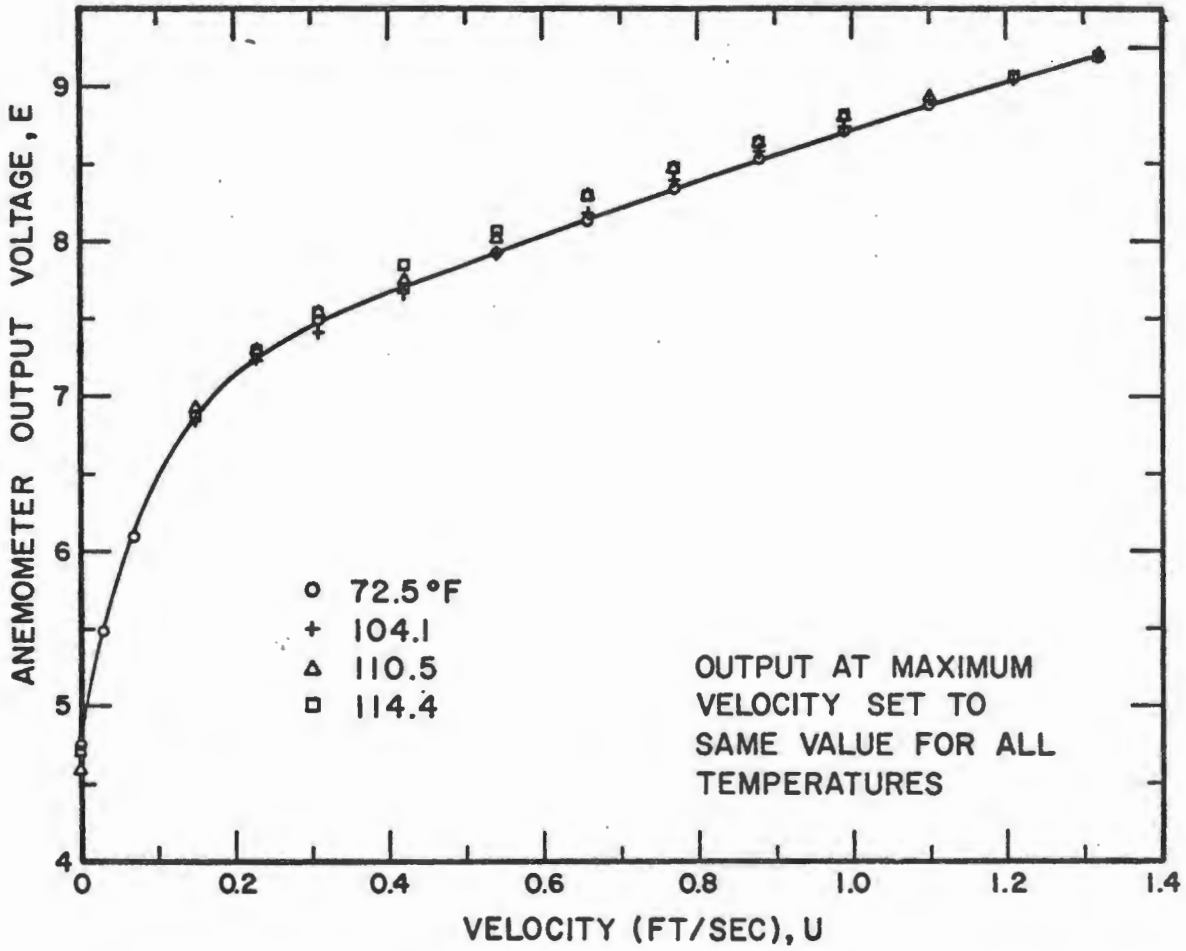

FIG. 8. MEAN VELOCITY CALIBRATION CURVES FOR DIFFERENT WATER TEMPERATURES AND SAME ANEMOMETER OUTPUT AT MAXIMUM VELOCITY

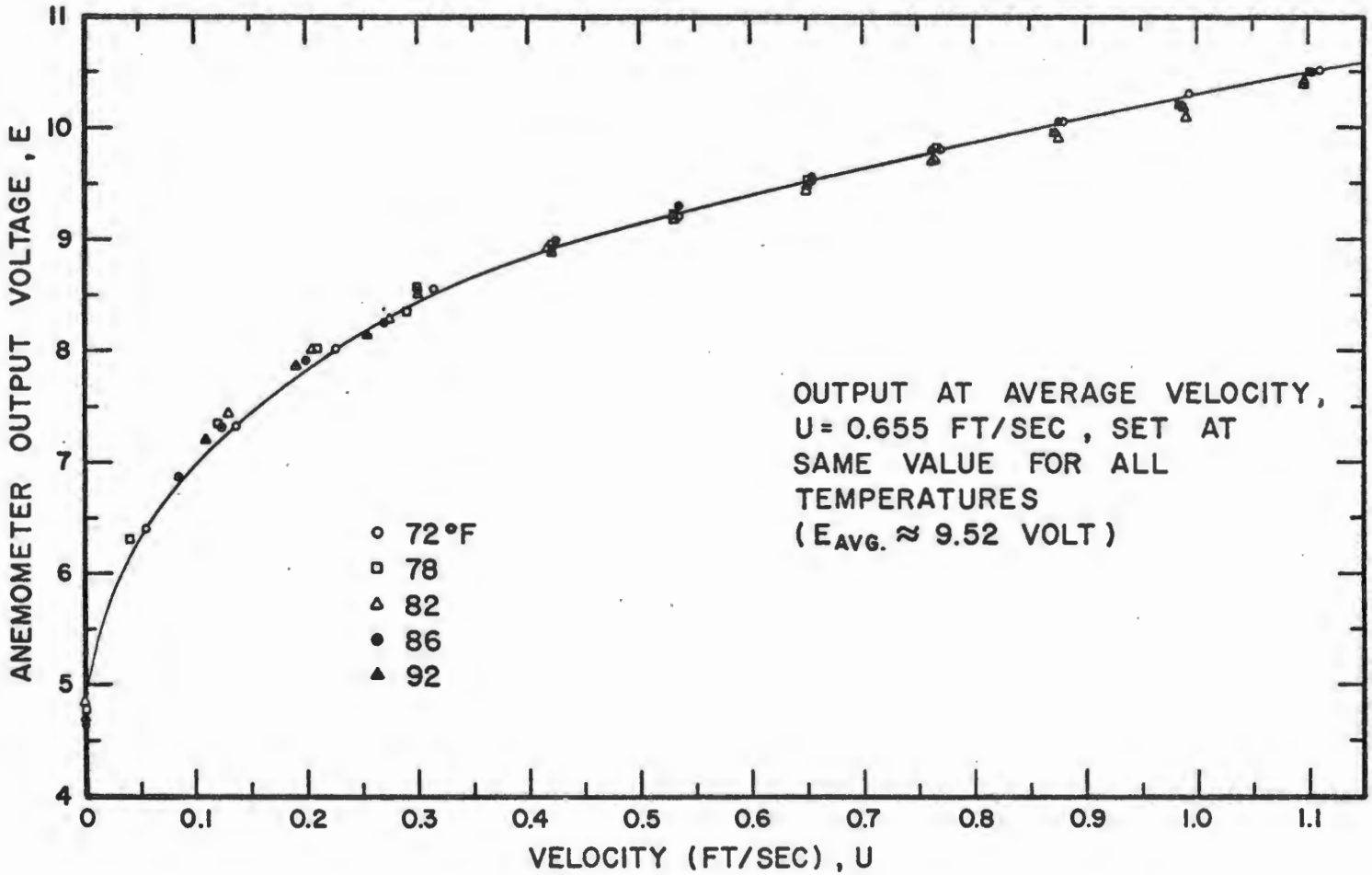

FIG. 9. MEAN VELOCITY CALIBRATION CURVES FOR DIFFERENT WATER TEMPERATURES AND SAME ANEMOMETER OUTPUT AT AVERAGE VELOCITY

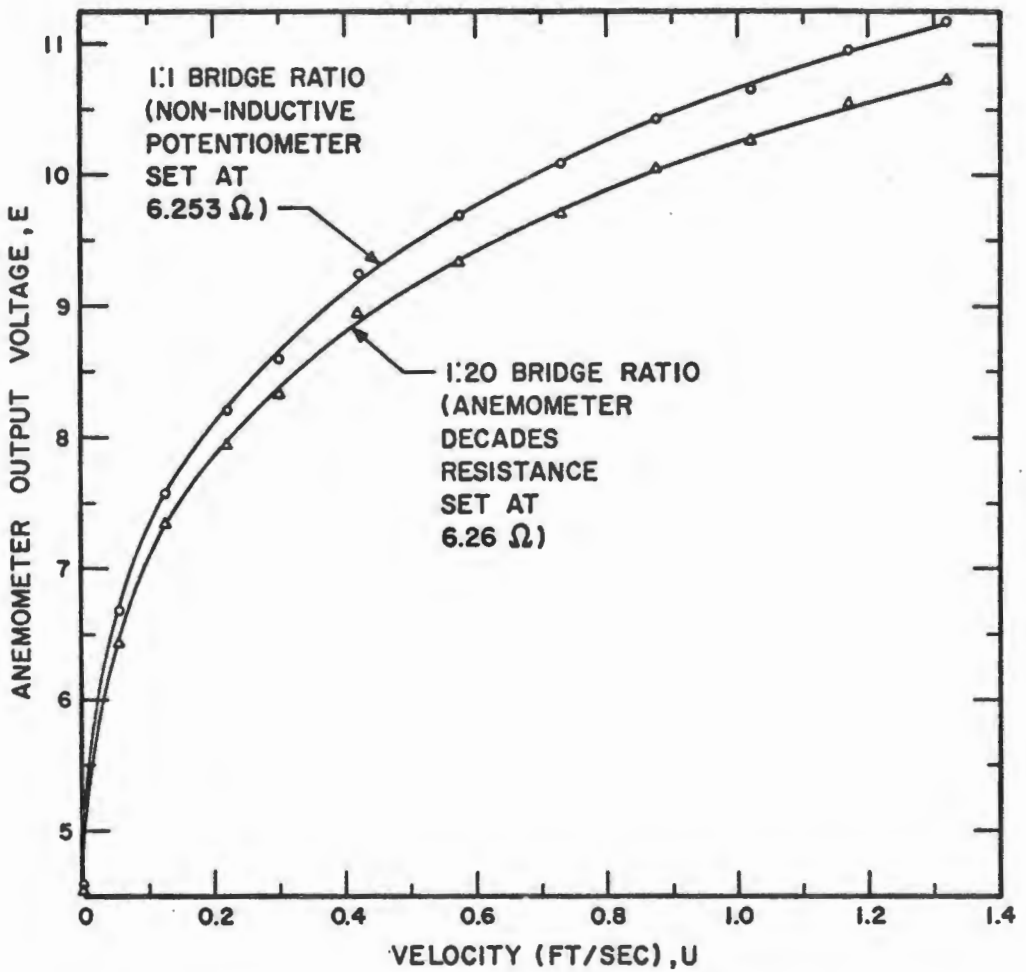

FIG. 10. MEAN VELOCITY CALIBRATION CURVES USING 1:1 AND 1:20 ANEMOMETER BRIDGE RATIOS

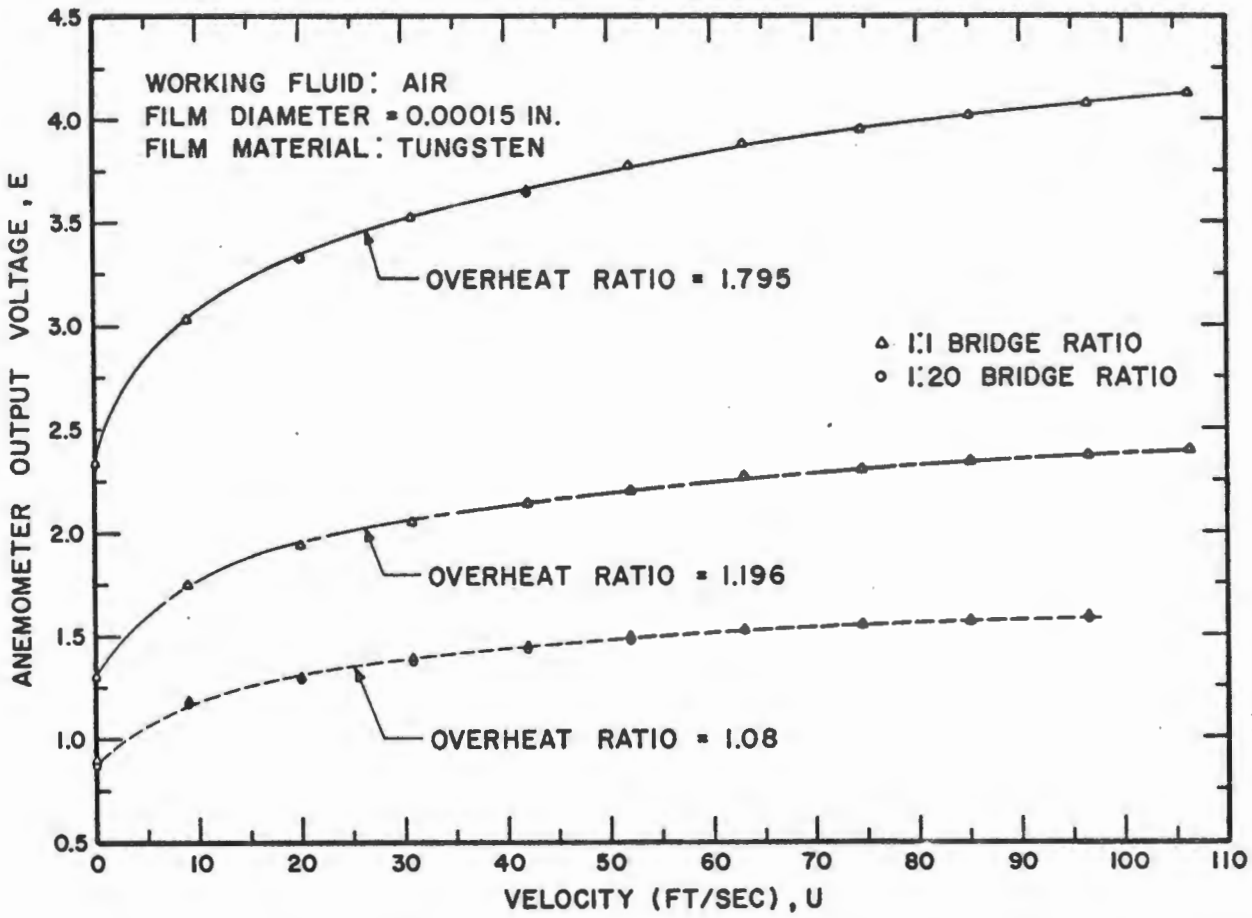

FIG. 11. MEAN VELOCITY CALIBRATION CURVES USING 1:1 AND 1:20 ANEMOMETER BRIDGE RATIOS FOR DIFFERENT HOT-WIRE OVERHEAT RATIOS

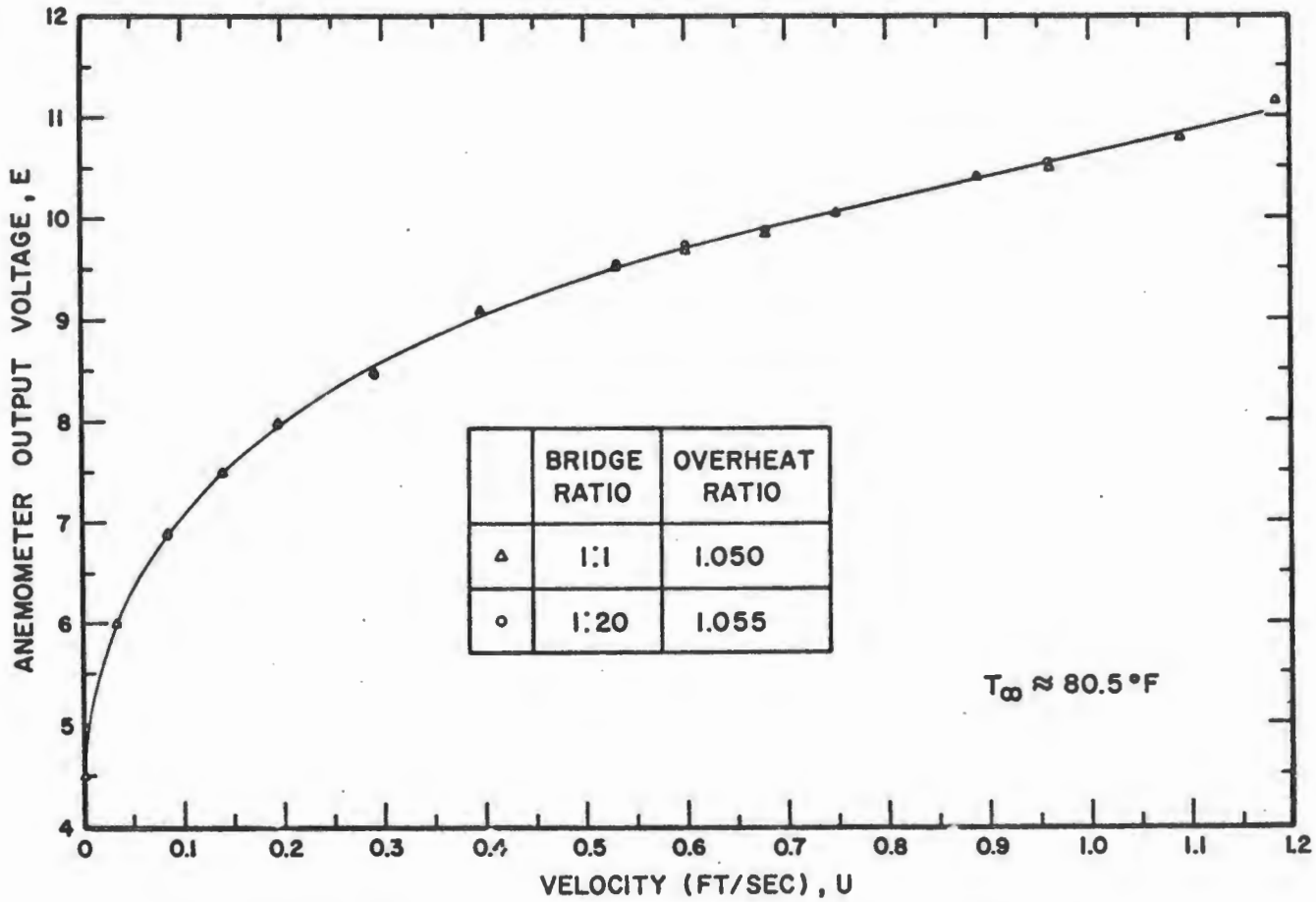

FIG. 12. MEAN VELOCITY CALIBRATION CURVES USING COMPENSATED 1:1 AND 1:20 ANEMOMETER BRIDGE RATIOS

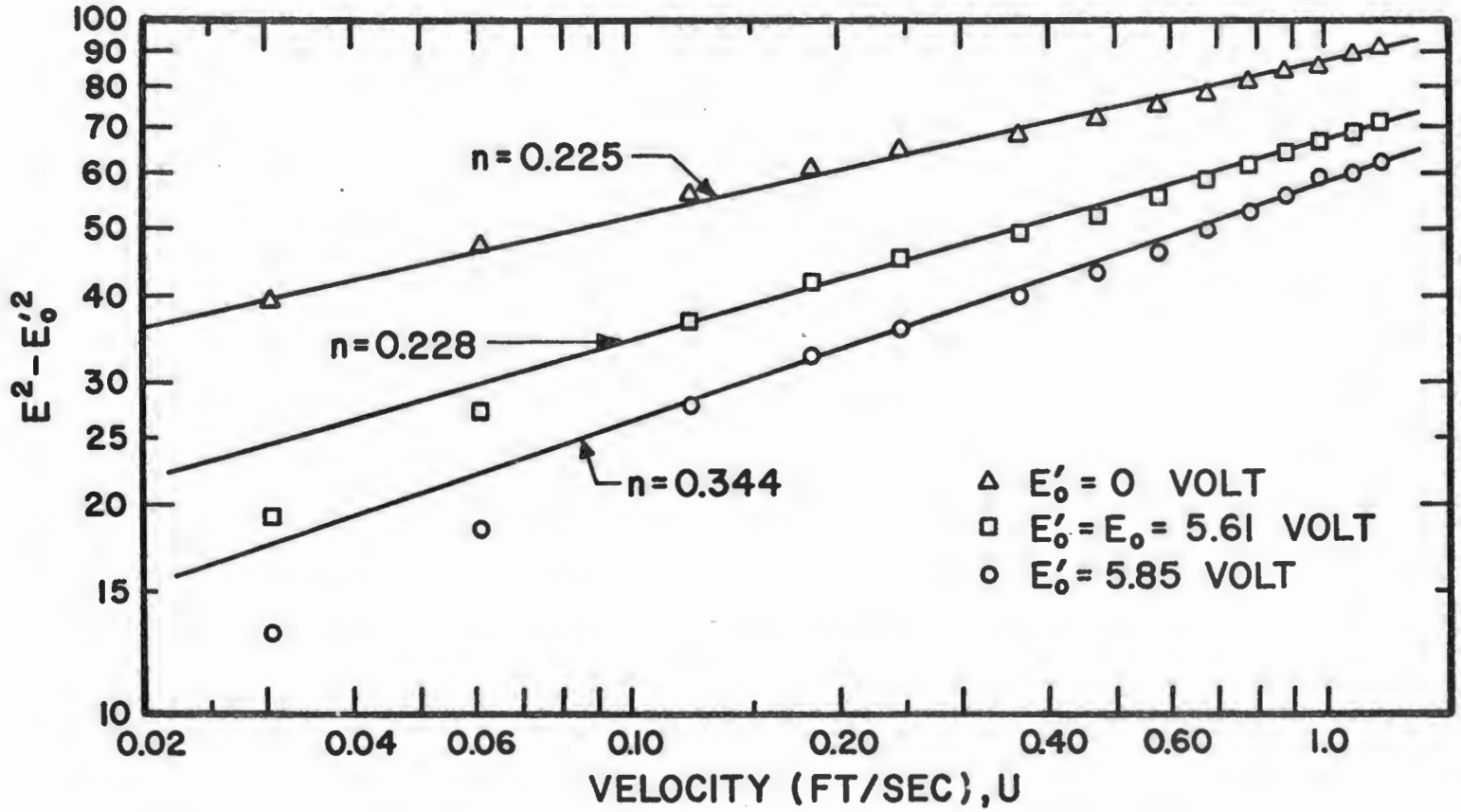

FIG. 13. BRIDGE OUTPUT LINEARIZATION USING DIFFERENT EFFECTIVE ZERO VELOCITY BRIDGE VOLTAGES

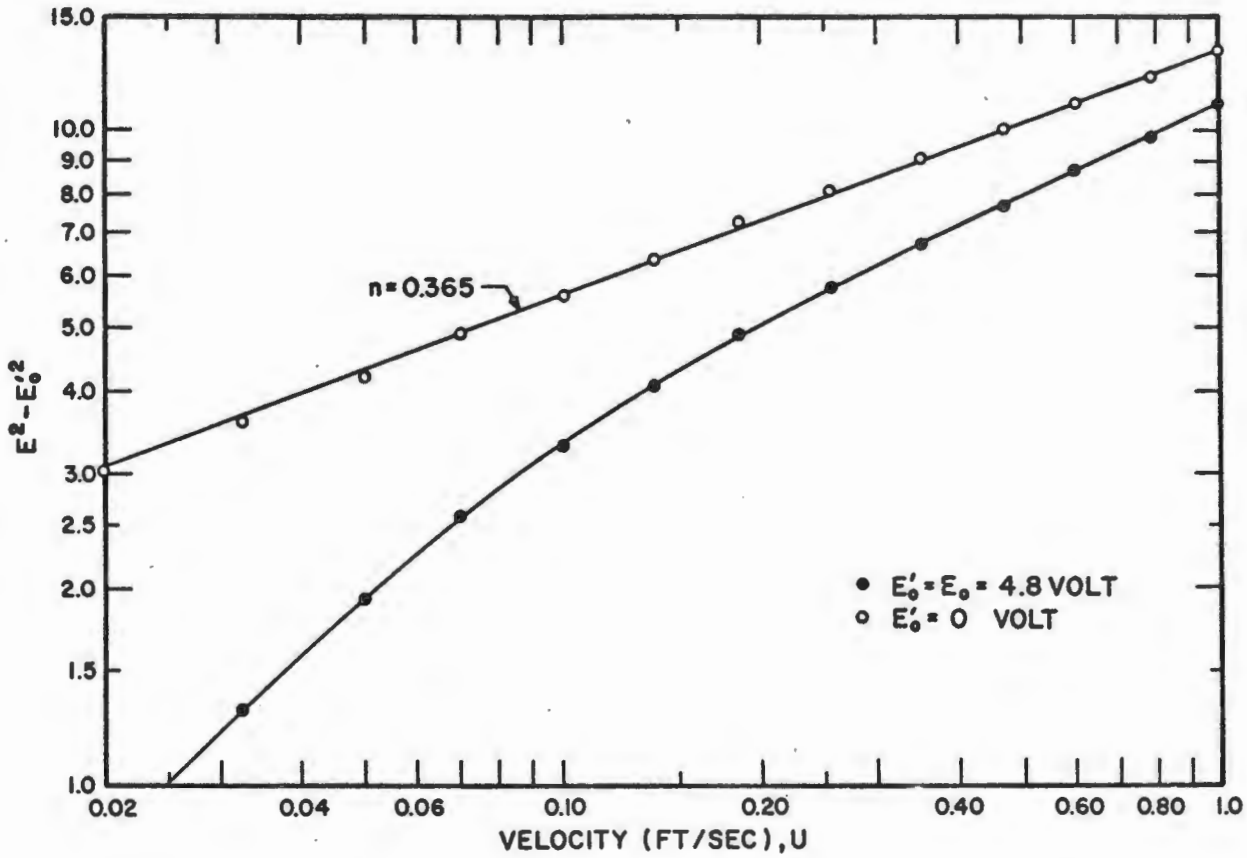

FIG. 14. BRIDGE OUTPUT LINEARIZATION USING DIFFERENT EFFECTIVE ZERO VELOCITY BRIDGE VOLTAGES; TSI CALIBRATION CURVE

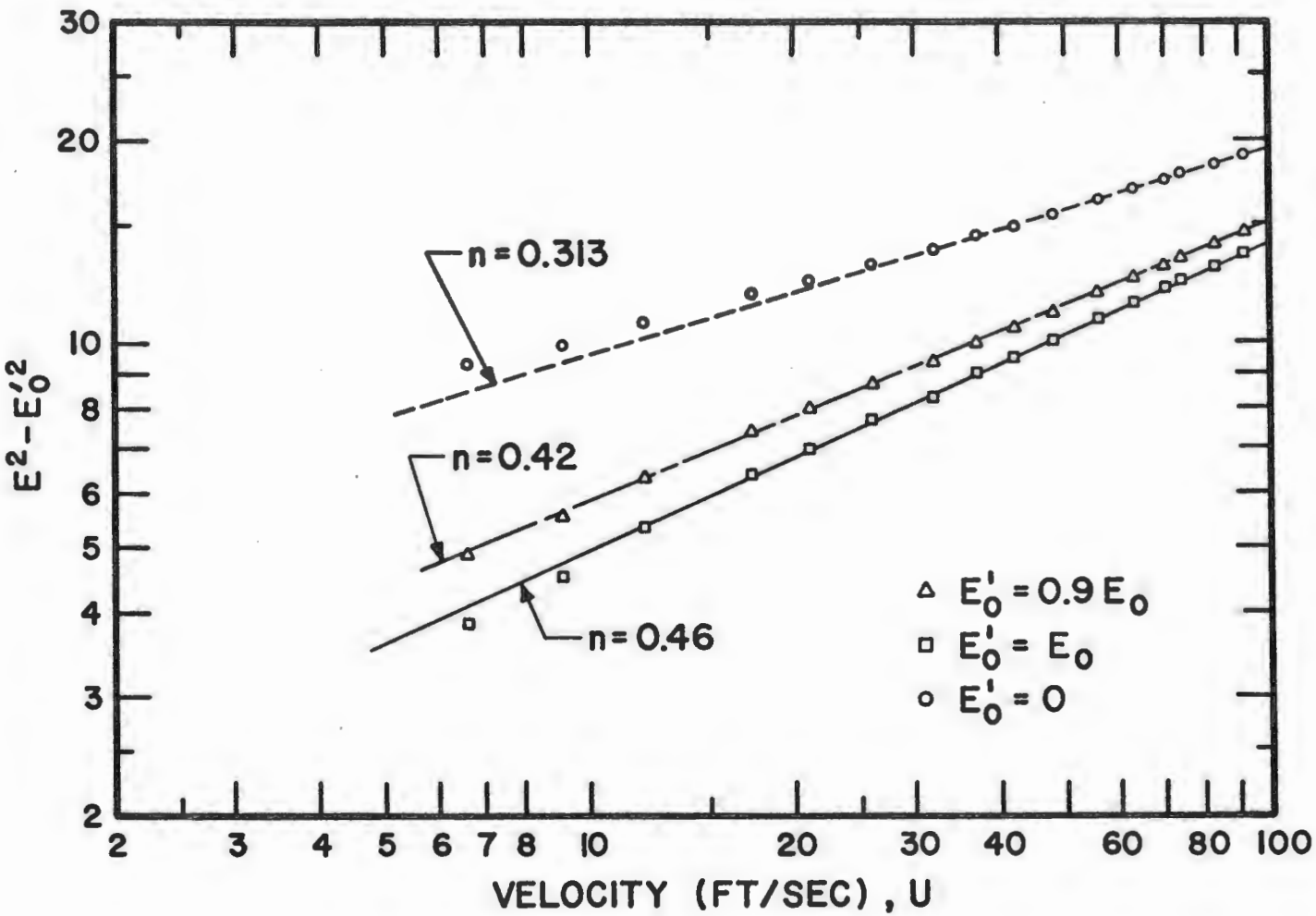

FIG. 15. BRIDGE OUTPUT LINEARIZATION USING DIFFERENT EFFECTIVE ZERO VELOCITY BRIDGE VOLTAGES FOR HOT-WIRE PROBE

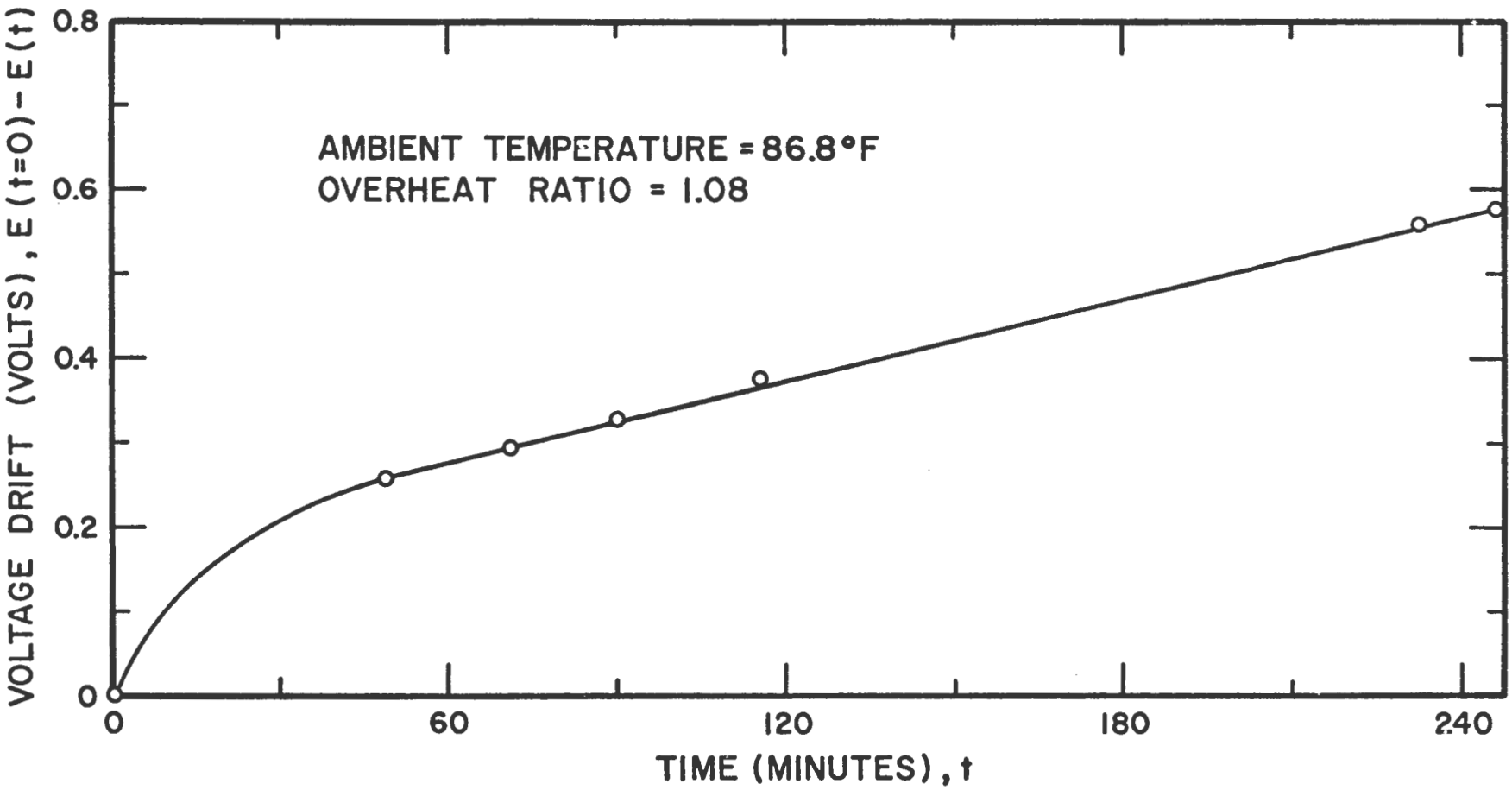

FIG. 16. ANEMOMETER OUTPUT DRIFT OVER FOUR-HOUR PERIOD

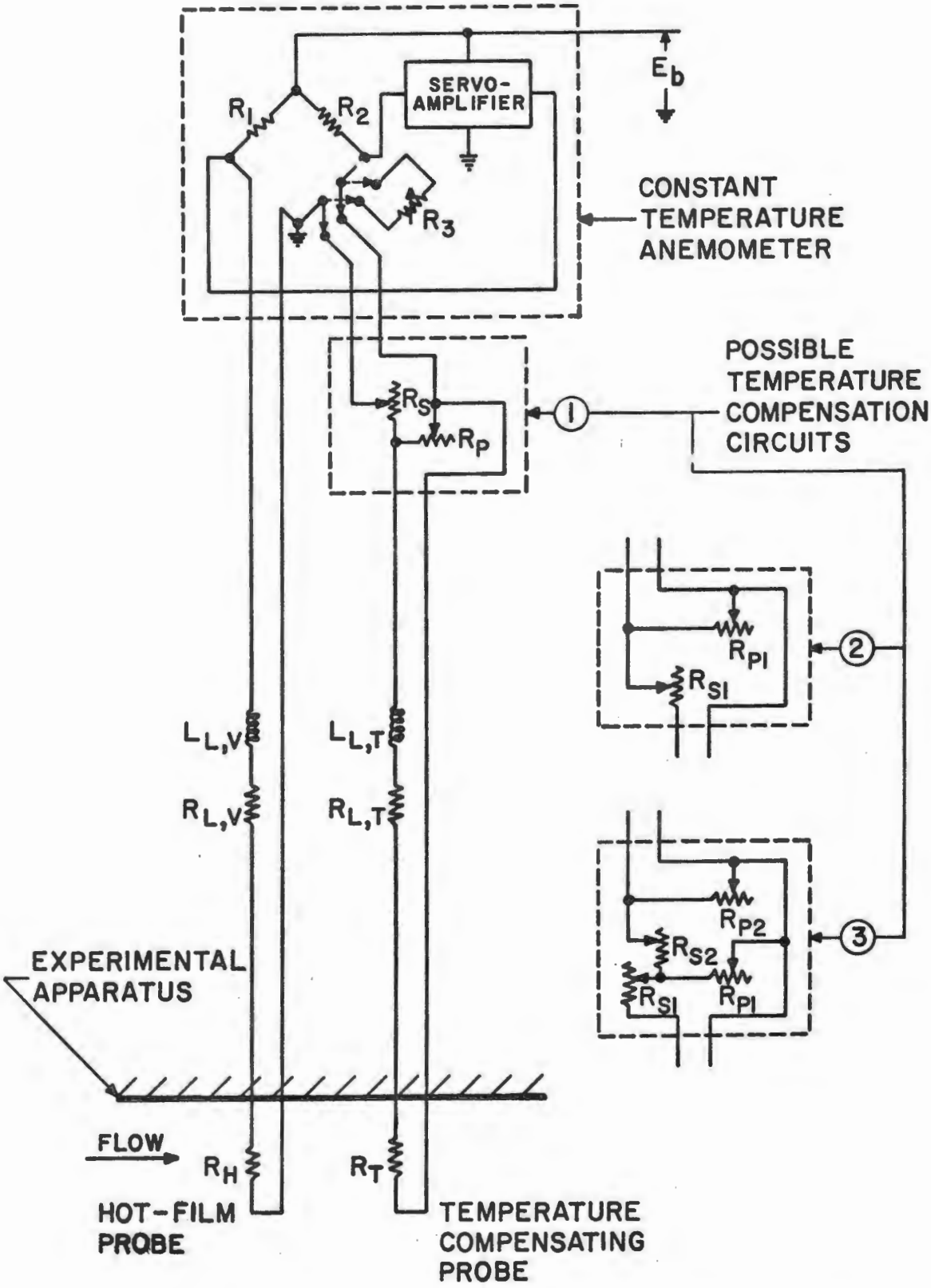

FIG. 17 SCHEMATIC CIRCUITS FOR WATER-TEMPERATURE VARIATIONS COMPENSATING SCHEMES

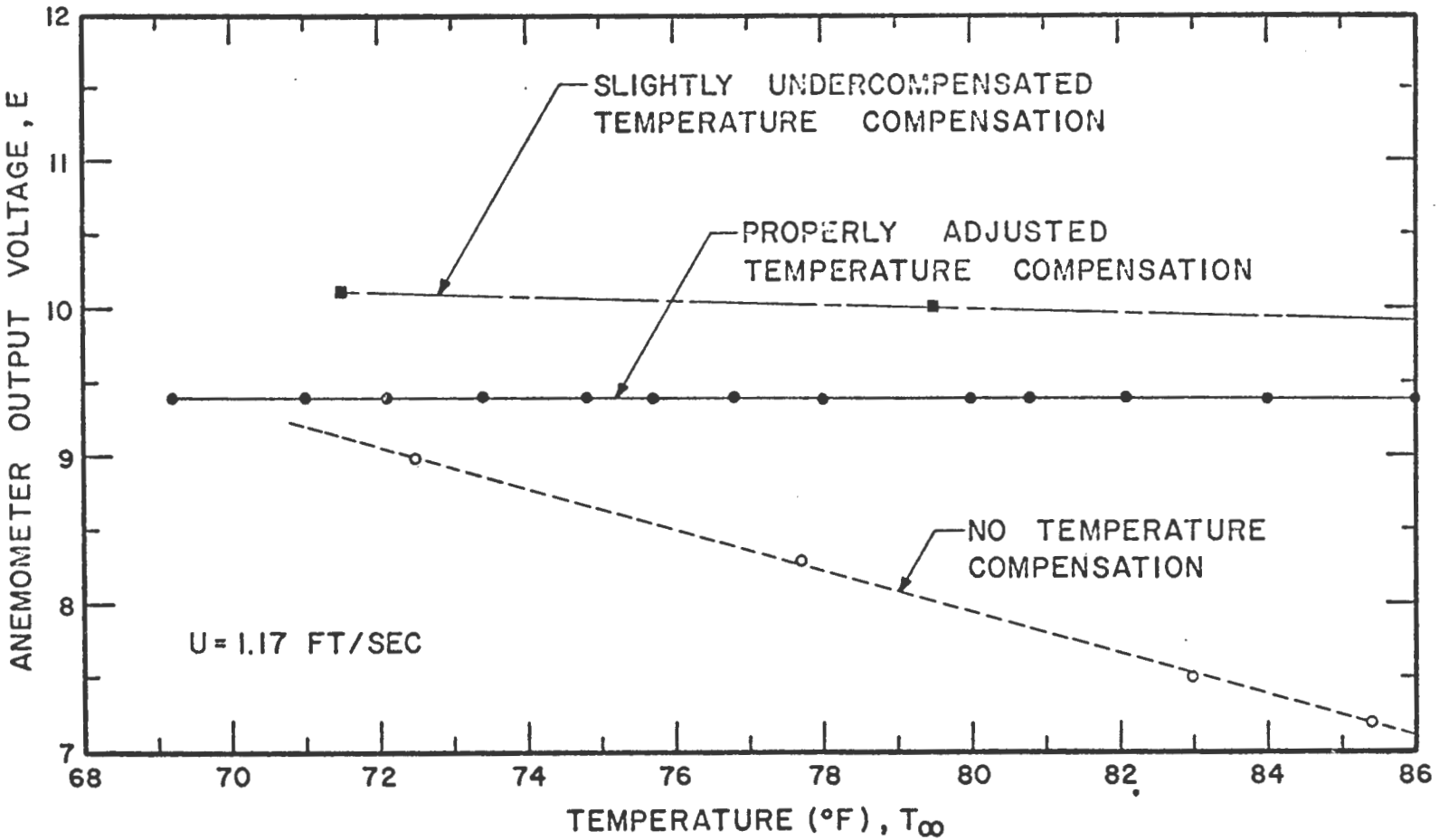

FIG. 18. EFFECT OF COMPENSATION FOR WATER TEMPERATURE VARIATIONS ON ANEMOMETER OUTPUT AT A FIXED VELOCITY

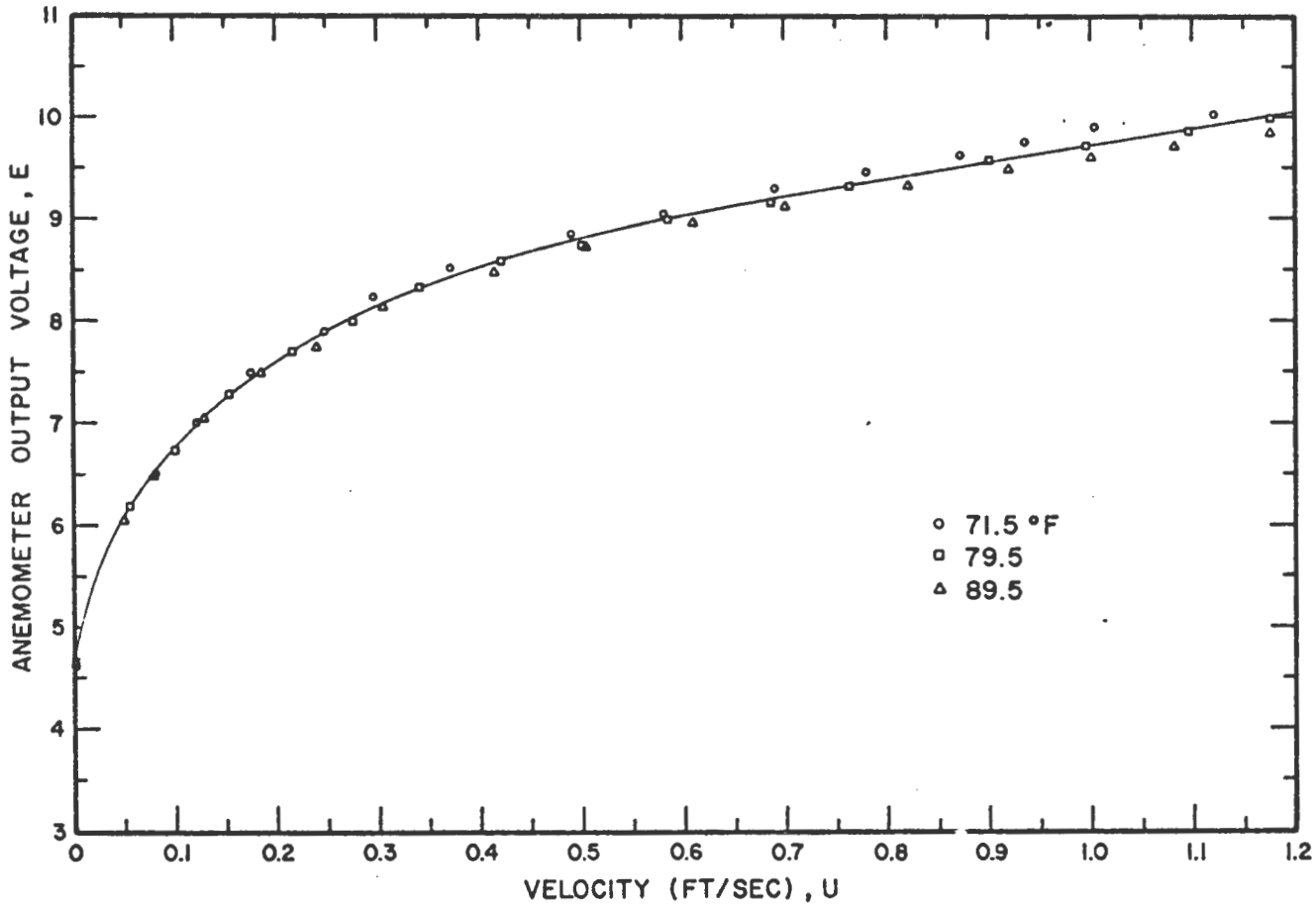

FIG. 19. MEAN VELOCITY CALIBRATION CURVES FOR DIFFERENT WATER TEMPERATURES USING A TEMPERATURE COMPENSATING SCHEME; PLATINUM HOT-FILM

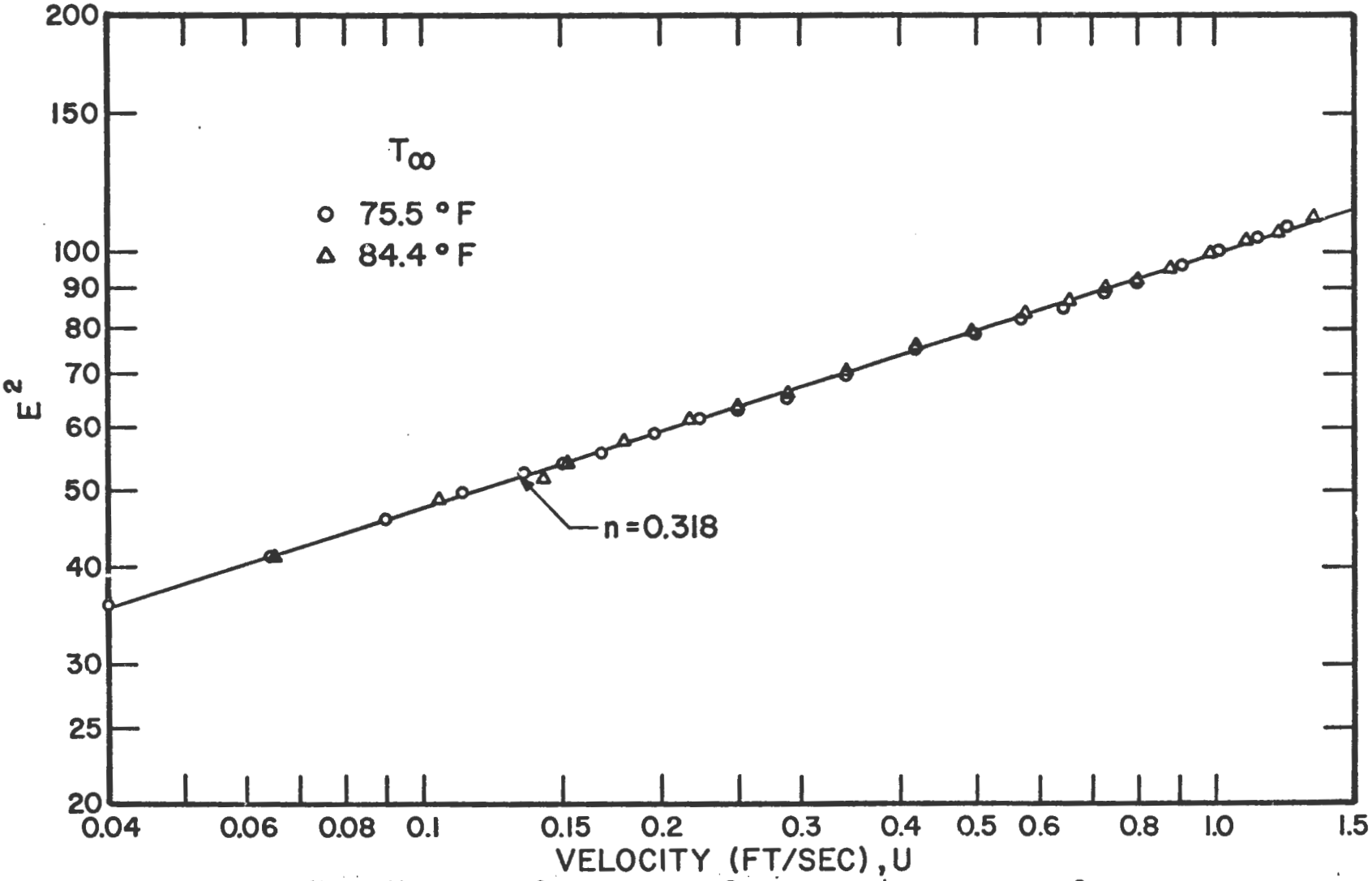

FIG. 20. MEAN VELOCITY CALIBRATION CURVES IN LOGARITHMIC COORDINATES FOR DIFFERENT WATER TEMPERATURES USING A TEMPERATURE COMPENSATING SCHEME; NICKEL HOT-FILM

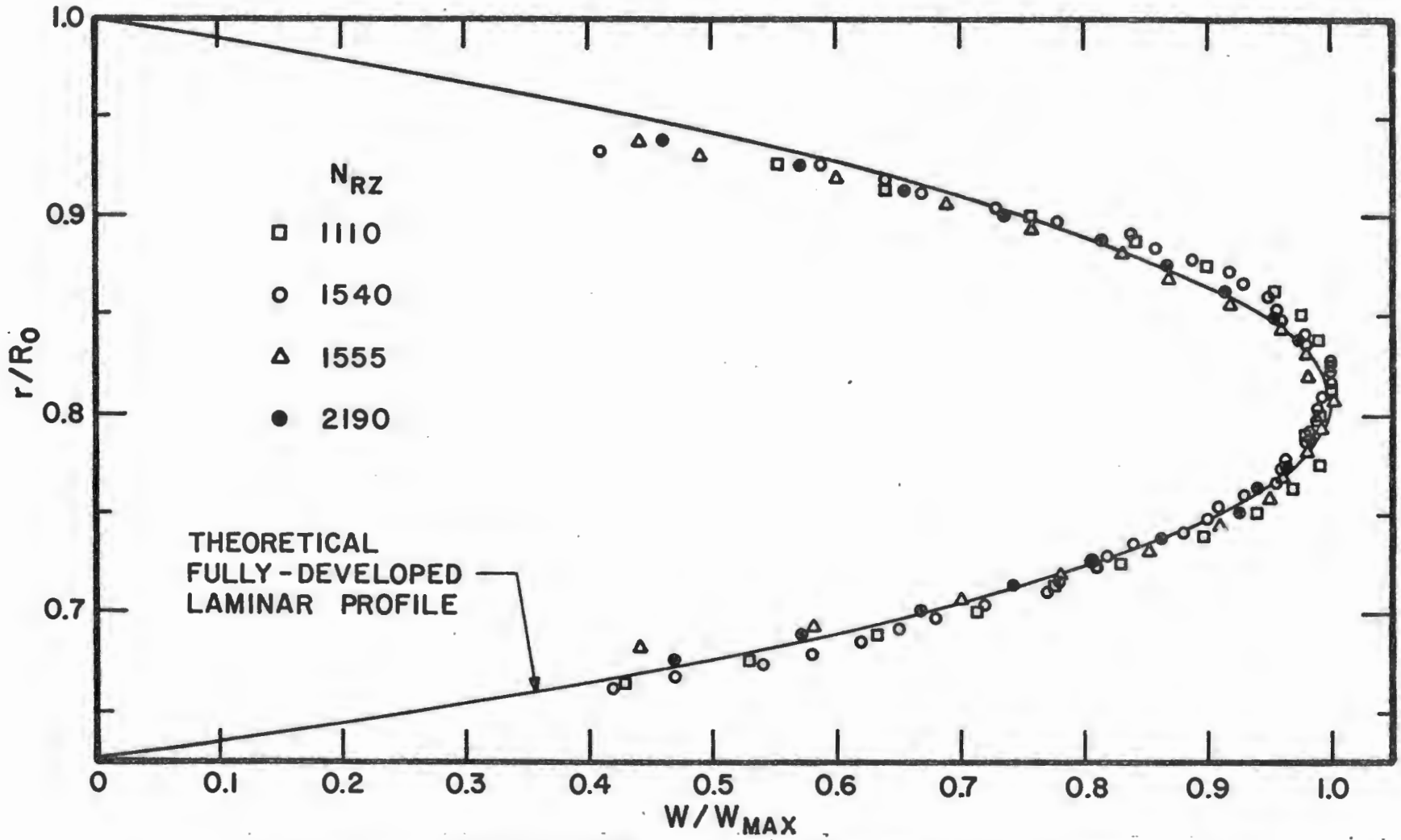

FIG. 21. MEAN AXIAL VELOCITY PROFILES FOR LAMINAR FLOW THROUGH THE ANNULUS $\eta = 0.625$ AND DIFFERENT VALUES OF N_{RZ}; COMPARISON BETWEEN EXPERIMENT AND THEORY

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13. ABSTRACT
Using a special calibration tunnel developed during the course of this study, the static and dynamic response of several kinds of commercially available hot-film probes with single and multiple sensors of the cylindrical-fiber type are examined. The effects of different parameters, including those of the anemometer bridge, on the output and performance of the probes are evaluated. In particular, the consequences of variations in water temperature on the hot-film anemometer output are determined. The low turbulence level (less than 0.1%) calibration tunnel is equipped with a heater capable of raising the water temperature to any desired value up to 120°F and controlling it within 0.2°F over a range of calibrated mean velocities from 0.01 to 1.4 ft/sec (better than $\pm 0.2\%$ accuracy except for $U < 0.1$ ft/sec where the accuracy is approximately $\pm 0.5\%$). The results reveal a large effect of the water temperature on the calibration curves (in an extreme case a change in temperature of only 5.5°F can result in a 100% error in the mean velocity reading). A scheme which utilizes a temperature sensing probe immersed in the working fluid is used to compensate for the water temperature variation. Several possible circuit configurations for this scheme, including an optimum circuit design, are investigated and the results from some of them are presented and discussed. The circuit has a frequency response to temperature variations which depends on the thermal time constant of the temperature probe (up to several cycles per second can be obtained using commercially available probes) and can be used to compensate for temperature variations of more than 20°F with an accuracy better than +0.2%. By using an effective value (much smaller than E_o) instead of the zero velocity bridge voltage (E_o) in exponential-type linearizers, a constant exponent is found useful in linearizing the anemometer output over a wider range of velocities.

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14 KEY WORDS	LINK A ROLE	LINK A WT	LINK B ROLE	LINK B WT	LINK C ROLE	LINK C WT
HOT-FILM ANEMOMETERS						
WATER TEMPERATURE EFFECT						
TEMPERATURE VARIATION						
DYNAMIC COMPENSATION						
CALIBRATION TUNNEL						
COMPENSATING CIRCUITS						
PRECISION MEASUREMENTS						

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