AN ABSTRACT OF THE THESIS OF

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Title: THE USE OF A HOT FILM ANEMOMETER TO MEASURE VELOCITIES BELOW FIVE CM/SEC IN MERCURY

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A constant temperature anemometer, utilizing quartz coated hot film probes, was used to measure velocities from .1 to 5 cm/sec. The effects on anemometer performance due to time, reimmersion, and metallic sensor coatings were examinated by repeated calibrations of the probes. Contrary to previous published results, calibration change due to drift with time was not observed. Furthermore, change in calibration due to reimmersion did not occur if the mercury surface was kept clean. It is believed that these results are the consequence of improved mercury cleanliness and improved vapor deposition techniques utilized by the hot film probe manufacturers.

Metallic sensor coatings of gold, silver, and nickel were examined. The only definite improvement in output voltage fluctuation was from the nickel plated probes, and this improvement lasted only a few hours.

The Use of a Hot Film Anemometer to Measure Velocities Below Five Cm/Sec in Mercury

by

John Calvin Hurt

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INTRODUCTION

This thesis discusses the velocity calibration and performance of hot film probes operated at constant temperature in mercury.

Measurement of velocity in fluid flows is desired for a variety of reasons. Convection heat transfer research often requires mass flow rates within an enclosure or the velocity details within the boundary layer. Experimental velocity measurements are often used to check the validity of analytical models. Also, direct measurement may be the only means available for obtaining details of the velocity profile in certain flow systems which do not lend themselves to analytical or numerical analysis.

Certain requirements, depending on the problem at hand, usually determine the best method to obtain the velocities required. Important considerations are the type of fluid, the speed of flow, the accuracy required, and the money available.

Liquid metal flow presents somewhat unique requirements for a velocity measuring device. Because of fluid opacity, optical techniques are eliminated. Deterioration effects may be important, depending on the liquid metal of interest and the materials present in the measuring device. Also, most liquid metals present some danger in one

form or another to experimentalists working with them, and the velocity measuring instrument must coexist with the protective apparatus associated with the system. For a mercury system, the protective apparatus is usually a cover fluid of some kind, and may present a problem. For a sodium flow situation a closed system is usually required which may present considerable difficulties to velocity measurement devices which must be inserted into the flow stream. Liquid metals in general present a variety of unique fluid properties, in particular high thermal and electrical conductivities, which influence the applicability of velocity measurement systems. It is these unique fluid properties that are often the reason for much of the interest in liquid metal flow today.

Liquid metal heat transfer research has been greatly stimulated by the concept of liquid metal coolants for nuclear reactors. Although sodium is the particular coolant of interest in this field, heat transfer results pertaining to fluids with very low Prandtl numbers (on the order of .01) will in general be representative of the heat transfer behavior of sodium. The development and refinement of velocity measurements in mercury presented in this thesis are primarily for the measurement of velocities resulting from laminar natural convection heat transfer to mercury. The heat transfer to another fluid of low Prandtl number may then be inferred from the mercury results.

This is not necessarily true of hot film anemometry results in mercury. Such factors as fluid-sensor contact and fluid purity are extremely important and may not be generalized to all liquid metals.

Hot Wire and Hot Film Anemometry

Hot wires and hot films have been successfully used for a wide variety of velocity measurements in different fluids. A small sensing element is placed in the flow field and electrically heated to a temperature above the flowing fluid temperature. The power dissipated by the sensor is correlated with the velocity of the surrounding fluid. Thus, a measurement of the voltage across the sensor allows deduction of the velocity of the fluid from an experimentally determined calibration. The conventional hot films and hot wires are not the only possibilities for utilizing the general principles involved. For example, Reference (21) discusses the use of a thermistor anemometer for velocity measurements.

A brief presentation of the theory of hot wire and hot film anemometry is presented in this section. The reader should review this presentation if he is not familiar with the concepts of constant temperature hot film anemometry and in particular with quartz coated hot film probes. References (23) and (26) may also be examined for a more detailed presentation of the subject in general. Laminar flow was the subject of interest in this work and for this reason the

measurement of turbulent flow is not discussed here. It should be mentioned that the hot film anemometer is an excellent device for measurement of turbulent flow fields.

The experiments presented in this thesis utilized a quartz coated hot film probe[1] operated in the constant temperature mode. The dimensions of the probe are shown in Figure 1. The cylindrical body

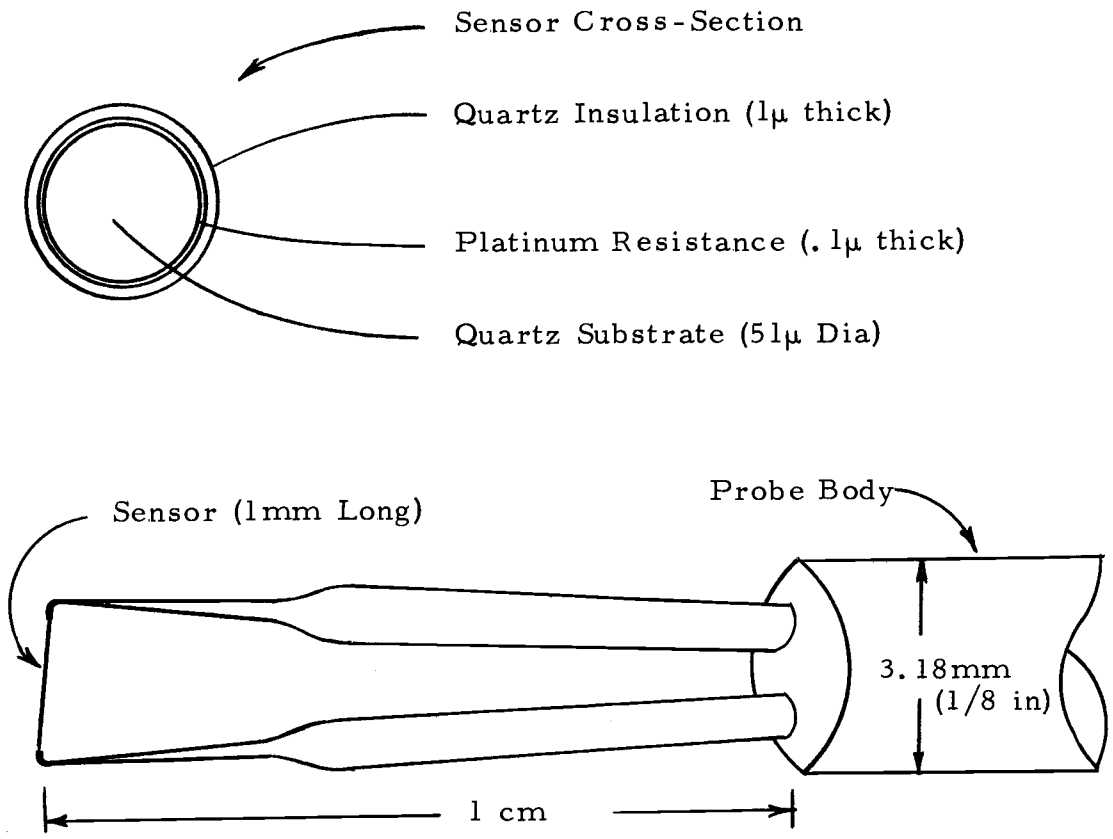

Figure 1. Schematic of hot film probe

[1] Obtained from Thermo-Systems Inc., St. Paul, Minnesota.

of the probe extended 30 cm to a BNC connection. When considering the dimensions of the sensor it is interesting to note that it is on the order of the diameter of the human hair. The quartz substrate is positioned between the two support prongs and the platinum is deposited over the quartz substrate. Gold is used at each end of the sensor to provide the electrical connection between the support needles and the platinum film. The quartz insulation is then sputtered onto the platinum, and the ends of the sensor, as well as the needles, are insulated with epoxy paint. In reference to future usage, it is helpful to note that the term anemometer implies the complete system comprising both the probe and electronic equipment. The term probe implies only the cylindrical probe body and the attached sensing element.

The small size of the sensing element is one of the advantages to the use of hot film probes for velocity measurements. This small size is important when flow obstruction due to the transducer's presence in the flow field is an important consideration. It is also important because it allows rapid response to velocity changes (turbulent flow). Unfortunately, this small size results in a very fragile transducer, which may be destroyed by small particles impacting it during measurement or by mechanical damage due to routine handling. Because of the quartz substrate the hot film probe is less susceptible to mechanical damage than the hot wire probe.

The hot film sensor forms one leg of a Wheatstone bridge as shown in Figure 2. This film is heated electrically to a constant temperature which is a predetermined amount higher than the surrounding fluid temperature. The film is heated from the output current of a DC differential amplifier. The gain of the amplifier is such that any small change in the sensor temperature will be immediately corrected by a change in current through the sensor. It is helpful to recall that constant temperature is the same as constant resistance, thus the bridge is striving to remain balanced.

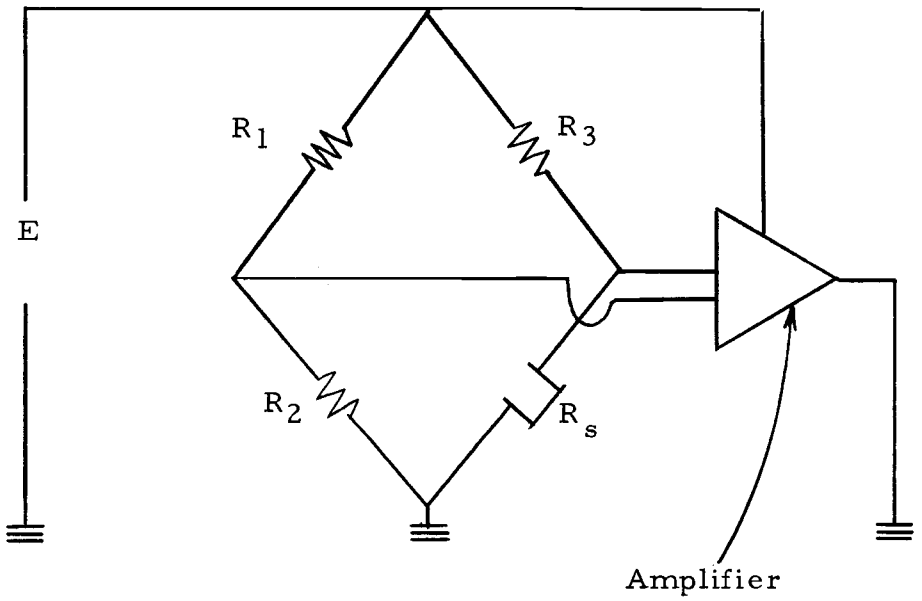

Figure 2. Constant temperature anemometer circuit

A change away from the balanced position is a result in a change of the fluid velocity. (It will be assumed for this discussion that the fluid temperature remains constant.) Thus, as the fluid velocity

increases, the convective heat transfer coefficient around the sensor increases, and more current through the sensor is required to balance the bridge. This increase in current is monitored by the anemometer in the form of the output voltage E. The feedback control theory of constant temperature anemometers will not be reviewed here. The reader is referred to Reference (7) for further information.

The setting of the overheat ratio determines the temperature difference between the sensor and the surrounding fluid. The overheat ratio is defined as

$$OHR = R_r/R_e = 1 + \alpha(T_s - T_e) \qquad (1)$$

where R_r = resistance of sensor at the run temperature, R_e = resistance of sensor at the environment temperature, T_s = average sensor operating temperature (run temperature), T_e = environmental fluid temperature, and α = temperature coefficient of resistance for the film material. ($\alpha = .0026/^{o}C$ for the hot films used in this work.) The overheat, and consequently the operating temperature, is set by inserting the correct resistance in the bridge leg opposite the sensor. This corresponds to the adjustment of resistance R_2 to the appropriate resistance.

The power dissipated from the sensor is easily calculated from

$$P = I^2R = \frac{E^2R_s}{(R_s + R_3)^2} \qquad (2)$$

where P = power dissipated into the surrounding fluid, E = bridge voltage (anemometer output), R_s = sensor resistance, and R_3 = bridge resistance in series with R_s.

An additional relationship is available from the definition of the convective heat transfer coefficient:

$$P = h \pi d_o L(T_o - T_e) \tag{3}$$

where h = average convective heat transfer coefficient, d_o = outside diameter of the sensor (52μ for this work), L = active length of the sensor (1mm for this work), and T_o = average surface temperature of the sensor.

Note that equation (3) is valid if d_o is the outside diameter of the sensor, including any thin layer of contaminants surrounding the quartz. Thus, this diameter is estimated at 52μ, but in actuality is not known precisely. Also, equation (3) does not account for the heat transfer by conduction through the support needles. The extent of error due to this assumption is not easily calculated. Equation (3) has been presented in the past with T_o replaced by T_s. However, $T_s = T_o$ only if the thermal resistance due to the quartz insulation and the contaminant layer is zero. This is obviously not true, but the small thickness of the insulation allows this to be a fair approximation. To illustrate, consider the equation for the heat transfer by conduction through the insulation surrounding a heated pipe (27, p. 218).

$$P = \frac{2\pi k_q L(T_s - T_o)}{\ln(d_o/d_i)} \tag{4}$$

For the hot film probe, the only unknown in equation (4) is T_o, since T_s may be found from equation (1), P may be found from equation (2), and the other quantities are found from the physics of the mercury and the probe. It is assumed that there is no thermal insulation about the sensing element except the quartz, primarily because this allows k_q, the thermal conductivity of the insulation, and d_o, the outside diameter of the insulation, to be known quantities.

With an overheat of 1.1 and a typical voltage of 13 volts, the temperature drop across the quartz can be calculated as

$$T_s - T_o = 2.14^{o}C.$$

For perspective, an overheat ratio of 1.1 results in a sensing element approximately $38.5^{o}C.$ above the ambient fluid temperature.

The Nusselt number for the probe may be found from

$$Nu = \frac{hd_o}{k_m}, \tag{5}$$

where Nu is the Nusselt number based on the sensor diameter and k_m is the thermal conductivity of the mercury.

If the approximation is made that $T_s = T_o$, then we may combine equations (1), (2), (3), and (5) to obtain

$$Nu = \frac{E^2 R_s}{k_m L \pi (T_s - T_e)(R_s + R_3)^2} = \frac{E^2 R_s a}{k_m L \pi (OHR - 1)(R_s + R_3)^2} \qquad (6)$$

Equation (6) is presented by Hoff (13). A more accurate expression for Nu is obtained by including equation (4). Thus, combining equations (1-5), we obtain

$$Nu = \frac{E^2 R_s}{k_m L \pi (R_s + R_3)^2 \left(T_s - T_e - \frac{E^2 R_s}{(R_s + R_3)^2} \frac{\ln d_o/d_i}{2 \pi k_q L} \right)} \qquad (7)$$

The author feels equation (7) should be used if Nu is desired. The resulting value of Nu will still be an approximation because of end loss due to conduction and the uncertainty of the dimensions d_o, d_i, and L.

The Peclet number for the flow may be found from

$$Pe = Re\,Pr = \frac{d_o \rho c_p V}{k_m} , \qquad (8)$$

where Pe = Peclet number, Re = Reynolds number, Pr = Prandtl number, ρ = mercury density, c_p = heat capacity at constant pressure, and V = fluid velocity. (d_o and k_m are as defined before.)

A common way to present calibration data is in the form Nu = f(Pe). One modification of this approach is to use an equation of the form

$$Nu = a + b(Re)^n . \qquad (9)$$

The constants a, b, and n are determined by the calibration. The

usual value of n is around 0.5. Different values of n have been published in the literature. It is suggested by Rosenberg (22) that n is in fact a function of velocity, which explains the different values for n and indicates that to assume n to be a constant is not the best approach.

As discussed later, a correlation in terms of dimensionless parameters was not the method of calibration presentation used in this work. The author feels that to develop a calibration equation which would be valid for any probe in any vessel of mercury would require much more than the correlation of Pe to Nu, even if the diameters and active lengths of the probes were known to a high degree of accuracy. Two variables which would probably be required in the correlation would be the aspect ratio (L/d_o) and the mercury purity. The development of such an equation would be an interesting study, but is outside the scope of this work.

Literature Review

The first experimentalist to measure velocities in mercury with a hot wire or hot film anemometer was Sajben (24). He was interested in magnetohydrodynamic flow at velocities between 1 cm/sec and 10 cm/sec. The sensing element used was an enamel coated wire 43μ in diameter with an aspect ratio (L/d_o) of 100. The sensor was operated in the constant current mode. Although Sajben was successful in obtaining useful velocity measurements, he experienced difficulties

which have since been reported by subsequent investigators. These difficulties are a drift with time in the anemometer calibration and a change in the calibration every time the sensor was immersed into the mercury. Sajben felt that impurities in the mercury were the prime cause of calibration change. He believed that step changes in calibration with reimmersion were caused by a change in the average thickness of the impurity layer around the sensor. He felt that the slow drift in the calibration with time was the result of the constant addition of small amounts of impurities from the walls of the system. The mercury container used by Sajben was composed mainly of stainless steel. Sajben did not indicate what other possible materials might be in contact with the mercury. It has been the author's experience that interaction between mercury and stainless steel is negligible, but that only a small contact with an amalgamating metal such as a single galvanized bolt, is sufficient to contaminate the mercury to the extent that surface impurities are readily apparent. Mercury purity is discussed in the apparatus section.

Sajben related the voltage output of the anemometer to the velocity of the fluid in terms of Nu vs Pe. The data were correlated by X as a function of Pe, where

$$X = \frac{1}{Nu(0)} - \frac{1}{Nu} ,$$

and Nu(0) is Nu at Pe = 0. Essentially, Sajben plotted a function of

velocity (Pe) as the abscissa and a function of voltage (X) as the ordinate. This is one standard procedure, and has the advantage of dimensionless coordinates. However, if one is interested in using the calibration curve in a practical manner, the easiest method of presentation is a plot of velocity versus change in bridge voltage, with velocity as the ordinate.

Easley (6) investigated the feasibility of turbulence measurements in mercury with a quartz coated hot film probe operated at constant temperature. He experienced significant drift problems, finding that the calibration changed significantly after only three or four hours. It should be noted that his mercury container was built entirely of aluminum, which readily amalgamates with mercury once the usual oxide layer has been penetrated by the mercury. Easley felt that the oxide film protected the aluminum to some extent but he observed that the walls had deteriorated somewhat after prolonged exposure to the mercury.

An interesting part of Easley's results was a photographic study of sensor deterioration. He concluded that the quartz coat was gradually worn away with use, but it should be noted that the velocity range was 6 to 240 cm/sec. Although Easley did include flow induced wear as a possible reason for calibration drift, he felt that oxide deposition onto the sensor was the primary cause for his drift problems.

This appears likely because of the large amounts of aluminum oxide inevitably on the mercury surface. It also seems unlikely that quartz wear would be significant over the short periods of time in which drift was observed.

Malcolm (17, 18, 19) describes measurement of low turbulence intensities in a flow of mercury from .3 cm/sec to 14 cm/sec. He felt that a non-wetting layer of impurities surrounds the sensor and that this variable contact resistance was the cause of change in calibration with time and with reimmersion.

Malcolm examined the effect on anemometer performance from immersion through an air-mercury interface (dry surface) and a water-mercury interface. He concluded that, while the water-mercury interface reduced the thermal contact resistance (increased the heat transfer from the sensor) it also seemed to provide a variable fluid layer about the sensor which resulted in a more erratic voltage output. He felt that the dry surface immersion was more desirable because the voltage output was more stable. Malcolm cleaned the mercury surface periodically but did not clean the sensor throughout his experiments.

Hill (11, 12) investigated the directional sensitivity characteristics of hot films in mercury by calibrating probes at different angles to the flow. Drift of probe calibration was again observed. Hill attributed this to fouling, cold solder creep, and environmental

temperature changes. Hill used mineral oil as a mercury cover film to prevent mercury vapor from contaminating the laboratory. He presents a review of the analytical attempts to predict the heat transfer from cylindrical sensors to mercury. These solutions will not be reviewed here, but the interested reader is referred to Hill (12). The analytical solutions are severely hampered by the lack of knowledge of the end conduction losses and the properties and dimensions of the thermal contact resistance between the sensor and the mercury.

A method to minimize the problems associated with hot film anemometry measurements in mercury was developed by Hoff (13, 14). While attempting to calibrate a probe Hoff experienced continuous cold resistance fluctuation and randomly varying heat transfer from the sensor when it was operated. Furthermore, he found that his calculated Nusselt numbers were 50% below the analytical approximation of Grosh and Cess (9). Hypothesizing that the non-wetting mercury-sensor interface was accumulating impurities, causing the random output, Hoff vapor deposited an amalgamating metal onto the sensor. (He tried both copper and gold, but found the gold to last much longer). The effect of the metal film was remarkable. Cold resistance was stable for long periods of time and the randomness in the voltage output was greatly reduced. Perhaps most significant was an increase of the Nusselt number to almost perfect agreement with the prediction of Grosh and Cess. Figure 3 shows the result of

the plating of a hot film sensor with gold as presented by Hoff. It is interesting to note the close agreement to the development of Grosh and Cess, which was a potential flow solution to the flow about an infinite cylinder. Grosh and Cess estimated their solution, based on

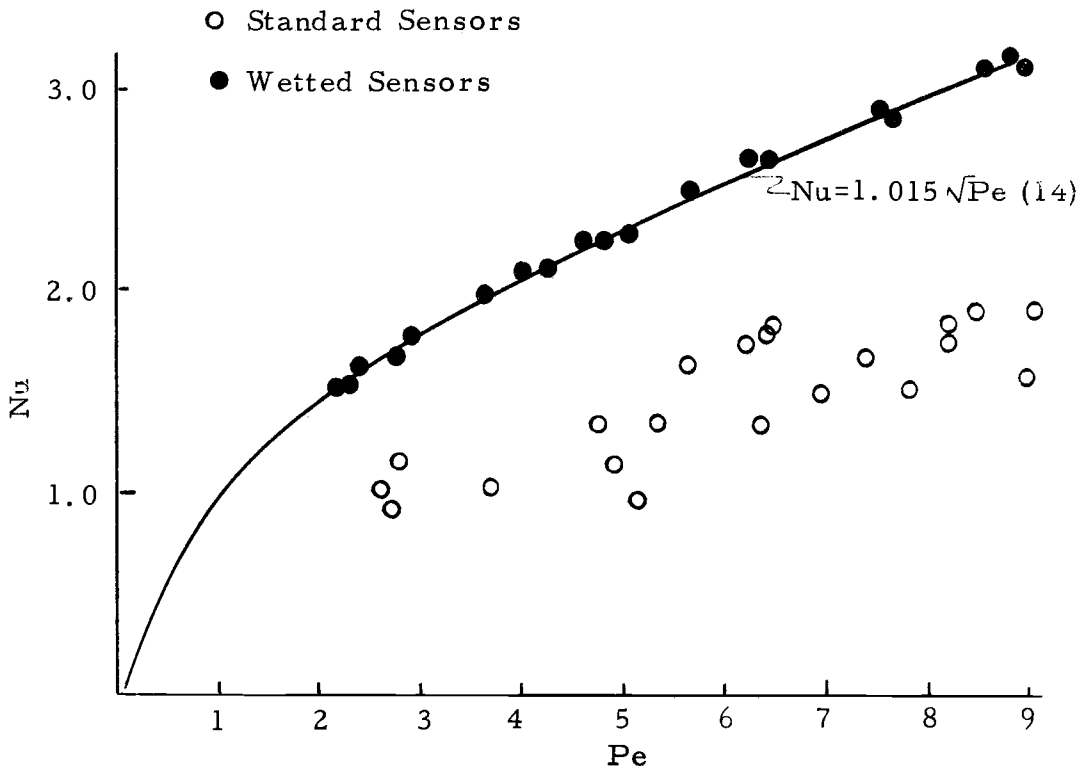

Figure 3. Calibrations by Hoff (14) of quartz and gold probes

the inviscid flow assumption, to predict heat transfer rates approximately 7 to 12% higher than the actual physical situation. Furthermore, from the work of Hill (12), the effect of the finite cylinder is to lower the heat transfer from the limiting case of the infinite cylinder.

White (28, 29) successfully obtained natural convection velocity profiles from a flat plate in mercury using a constant temperature hot

film anemometer. A major difficulty encountered during his experiments was the inability to calibrate a probe in one vessel and then transfer it to the heated vessel without a change in calibration. Also during the course of his experiments there occurred step changes in calibration with no apparent reason. White experienced the usual random voltage variation which is evident in the other literature. He used a number of gold plated probes[2] to improve the velocity measurements. He found the improvement was perhaps no better than that resulting from soaking the probe in the mercury for a few days before making measurements. He used mineral oil as a protective cover fluid. He also found experimentally that the calibration curve for a probe did not change over the 30^{o} F temperature range of his experiment. This is valid only if the OHR is continually adjusted so that it remains a constant.

Researchers at Purdue are currently using a hot film anemometer to measure velocities in mercury under the guidance of Professor Paul Lykoudis. The research work that has reached the author's survey are references (5) and (8). Reference (8) indicates the use of a probe for 75 hours without significant change in calibration.

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[2] The gold was vapor deposited onto the sensor by Marc Hoff, Grumman Aircraft Corp. Bethpage, N. Y.

Questions of Feasibility

A survey of the literature establishes that a hot film anemometer may be used with some degree of success to measure low velocities in mercury. However there are problems of practical importance which are unsolved by past experimenters. It is the purpose of this work to shed further light on the problems involved, and eliminate as many as possible. A summary of the important concerns is presented in this section.

Of prime importance is the rate of change of calibration with time. Most of the previous work indicates this to be a problem. There is the possibility that this drift is a function of variables which may be sufficiently controlled to eliminate this problem. Increased mercury purity and the addition of an amalgamating film are possible factors which could reduce the drift. At any rate, it is necessary to know the time interval between calibrations required to insure accurate velocity measurements.

It is also important to know if it is possible to calibrate a probe in one mercury vessel and make velocity measurements in another vessel without a change in calibration of the probe. The literature definitely indicates that the calibration is likely to change with reimmersion. Because of observed changes in probe performance with reimmersion, White (28) was forced to calibrate his probes in his test

container. This can present serious physical alignment and space problems for many experimental programs. The ability to calibrate in a different system would add great flexibility. It should be determined if this is possible.

Most investigators desire to know the accuracy of their measurement device. In general they would also like to increase the accuracy if to do so would be economically practical. The most obvious method available to do this for anemometry measurements in mercury, assuming the external electronic equipment is of high quality, is to reduce the random variation of the anemometer output. The one outstanding result to date along these lines is by deposition of an amalgamating film onto the sensor, as reported by Hoff (13, 14). There are questions about this process which prevent an immediate decision to plate all sensors with gold. Primarily, will the gold adhere long enough and will it really help enough to warrant the difficulties involved in vapor-depositing a uniform film? Hoff's work indicates a definite yes to this question, but the trend of White's results (28) raises doubts as to whether the accuracy is significantly improved by using gold probes.

Another important question is if different mercury cover fluids have an effect on anemometer performance. Malcolm (17, 18, 19) concluded that an air-mercury interface resulted in the least voltage fluctuations, but it would be desirous to use some fluid cover other

than air to prevent the mercury vapor from entering the laboratory. Hill (11) suggested the use of mineral oil rather than water to prevent a temperature gradient resulting from evaporation, but immersion through the mineral oil may coat the sensor with a thin film which will significantly lower the heat transfer from the sensor. Hill and White both used a stream of air to blow the oil out of the path of the entering sensor. It is the author's belief that a very thin film of oil must still exist over the water and subsequently will form around the sensor. The reader should recall that a typical sensing element is very small (52μ in diameter for the sensors used in this work) and an added thin film may significantly reduce the voltage output.

Finally, there are a wide variety of possible methods of cleaning the sensors before immersion and there is little in the literature regarding this. It is likely that uniform and consistent cleaning would encourage repeatible calibrations. It is also likely that some agents would have a deleterious effect on the sensor. It would be advantageous to have at least a qualitative view of the effect of cleaning agents on probe performance and probe life.

Perhaps in investigating these questions more insight will be gained into the nature of the thermal contact resistance which has been blamed for most of the problems with hot film anemometry in mercury. It is probable that any insight will be qualitative and speculative, because of the complexity of the interaction between the sensor and the mercury.

APPARATUS

Velocity Generation System

Any anemometer calibration system requires a variable relative velocity between the fluid and the probe. It is thus necessary to move the probe through a stationary fluid or force the fluid past a stationary probe. Many different concepts have been applied to obtain the velocity calibrations. They will not be listed here, but the interested reader may begin with reference (4) for a further study. The optimal device is usually decided upon by considering the type of fluid, the range of velocities, the accuracy desired, and the money available.

The calibration system described here was built to calibrate probes which were used to measure velocity profiles resulting from natural convection heat transfer. These fluid velocities are small and in the vertical direction, away from the acceleration of gravity. At lower velocities the heat transfer from the sensor may be a significant combination of both forced and natural convection, and it is for this reason that the probe should possibly be calibrated by a vertical relative motion between the sensor and the fluid. If the probe is calibrated by means of a horizontal relative motion, subsequent measurement of vertical velocities may be slightly in error. It was not determined at what velocities this effect would be important, but if an experimenter

is planning to measure very low vertical velocities with a probe that has been calibrated with horizontal flow he should consider these ideas in detail.

The velocity generation system used in the experiments reported here utilized a vertical descent of the probe through a stationary mercury container. The sensing element was thus oriented horizontally and the relative fluid motion was past the element in the vertical direction, which is a direct simulation of the actual velocity measurements required to obtain velocity profiles resulting from free convection heat transfer to mercury. The velocity range possible was from zero to five cm/sec. Higher velocities could be obtained with very little modification.

Numbers given in the following apparatus description correspond to the numbers in Figure 4. The hot film probe [1] was fastened mechanically to a two cm by two cm by one m bar [2] . The bar was constrained to travel only in the vertical direction by surrounding roller bearings[3] at two positions of the bar. The maximum travel of the bar-probe combination was 25 cm, and the roller bearings were positioned such that they always were in contact with the bar and thus restricted its motion to a vertical descent. Not pictured in Figure 4 are the support structure which held the roller bearings, but the bearings may be considered to roll on pins which are rigidly secured to the laboratory floor. The bar was connected to a three mm steel cable [4]

which traversed up over two pulleys [5] and down to a connection to a piston-like weight [6]. This weight was slightly smaller in diameter than the fluid tube [7] through which it travelled. The tube was filled with a water and water-soluble oil solution, and as the weight travelled upward through the tube (corresponding to a descent of the hot film probe) the solution flowed through a bypass tube [8]. This bypass tube had a needle valve in it and this valve setting determined the velocity of the descending probe. Included in Figure 4 are the mercury container[9], discussed in the mercury section, and the laser[10] and photocell [11], discussed in the velocity measurement section.

Figure 5 presents photographs of the system which may be examined along with Figure 4 to obtain an understanding of the system.

The bar-probe combination weighed more than the piston in the tube. Therefore, if the bar was raised manually and released, it fell at a semi-constant speed depending upon the setting of the needle valve. Adjustment of the needle valve thus allowed the varying velocities required for a calibration. The total drop was 25 cm. The velocity was found to vary as much as ten percent over this distance for some of the runs. This was not considered a problem however because the velocity was measured over a descent of only 5.3 mm.

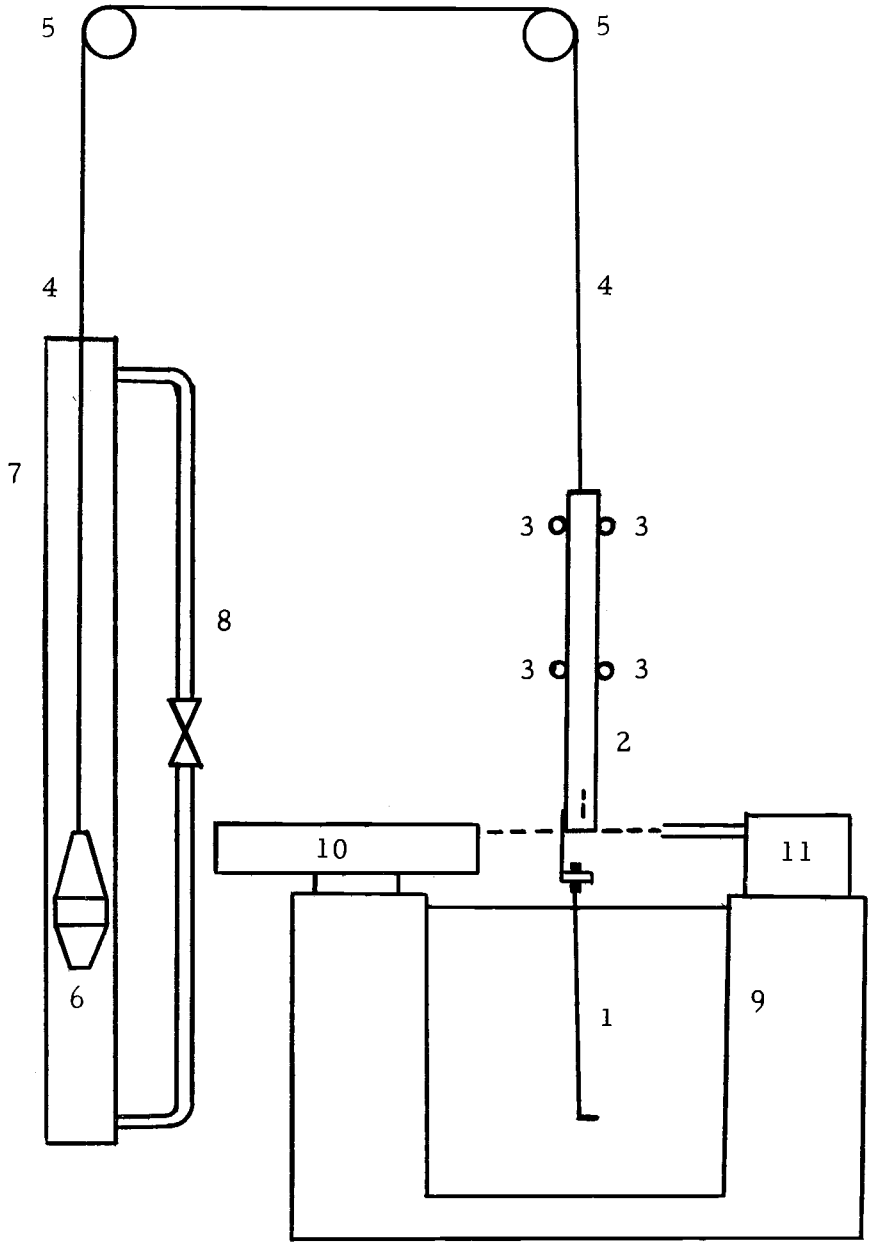

Figure 4. Schematic of velocity generation system

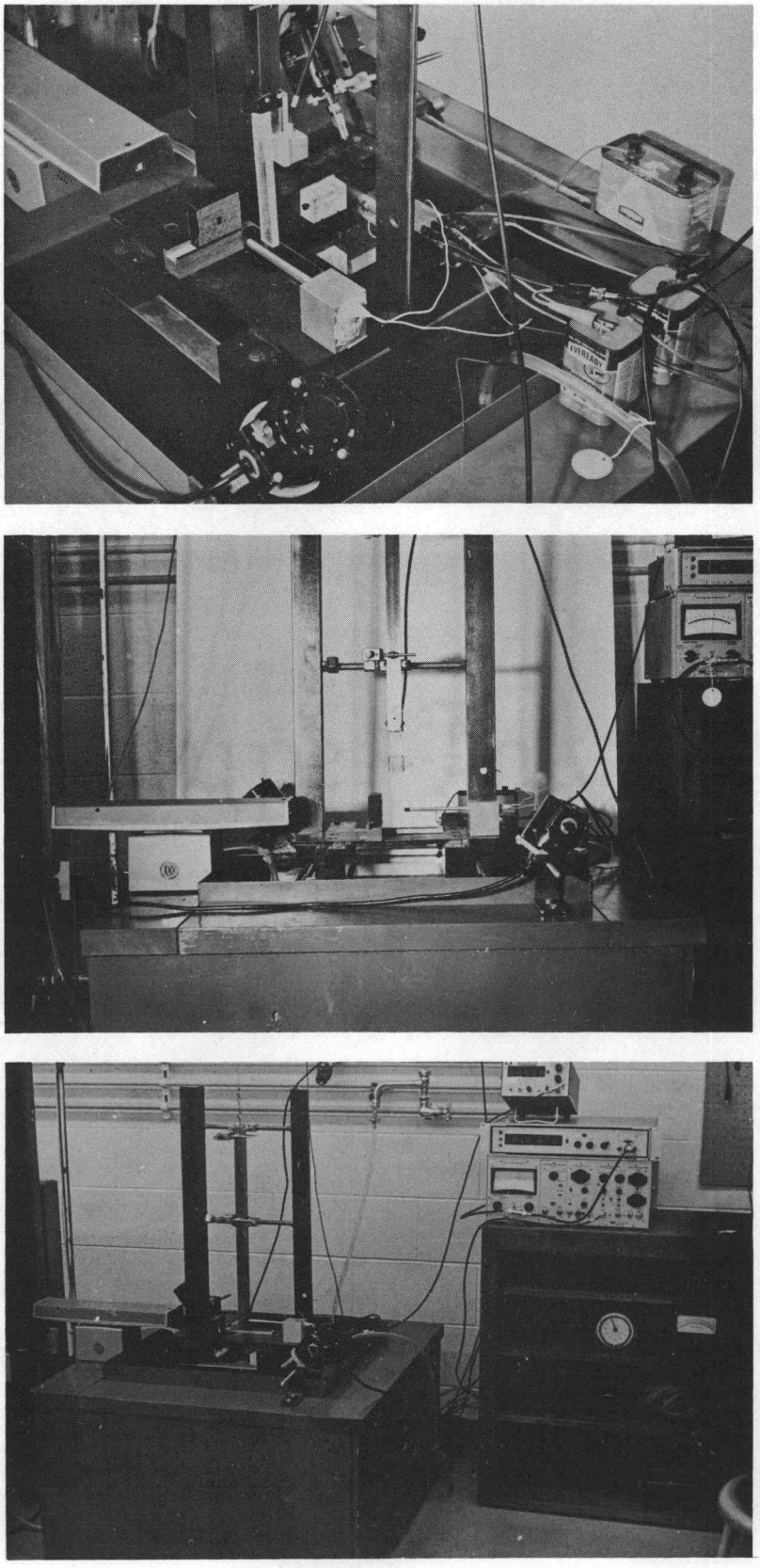

Figure 5. Photographs of apparatus

Velocity Measurement System

An electromechanical schematic of the velocity measurement system is shown in Figure 6. Numbers in brackets correspond to the numbers in the figure. The probe [1] was fastened to the steel bar [2] and together they descended into the mercury, as discussed in the velocity generation section. Attached to the bar were two straight knife blades [3] , projecting out of the bar about two cm. A focused horizontal laser beam was directed into a light sensitive resistance [4], and the beam was oriented such that the projecting knife blades cut it one at a time as they passed by. The laser[3] [5] beam was directed into a lens [6] that was positioned such that its distance from the knife blades was the same as its focal length (5 cm). Thus, the light beam was reduced to a very small diameter directly at the point where the knife blades crossed it. The probe[4] [1] was connected to the anemometer[5] [8] by a five m coaxial cable. The cable was supported at the top of the system with enough slack to prevent its interference with the falling probe.

As the first blade crossed the laser beam, the light passing into the photocell was suddenly blacked out, resulting in a near step change

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[3] Optics Technology Model 190 continuous gas laser

[4] Thermo-systems quartz coated hot film probes

[5] Thermo-systems model 1050 constant temperature anemometers

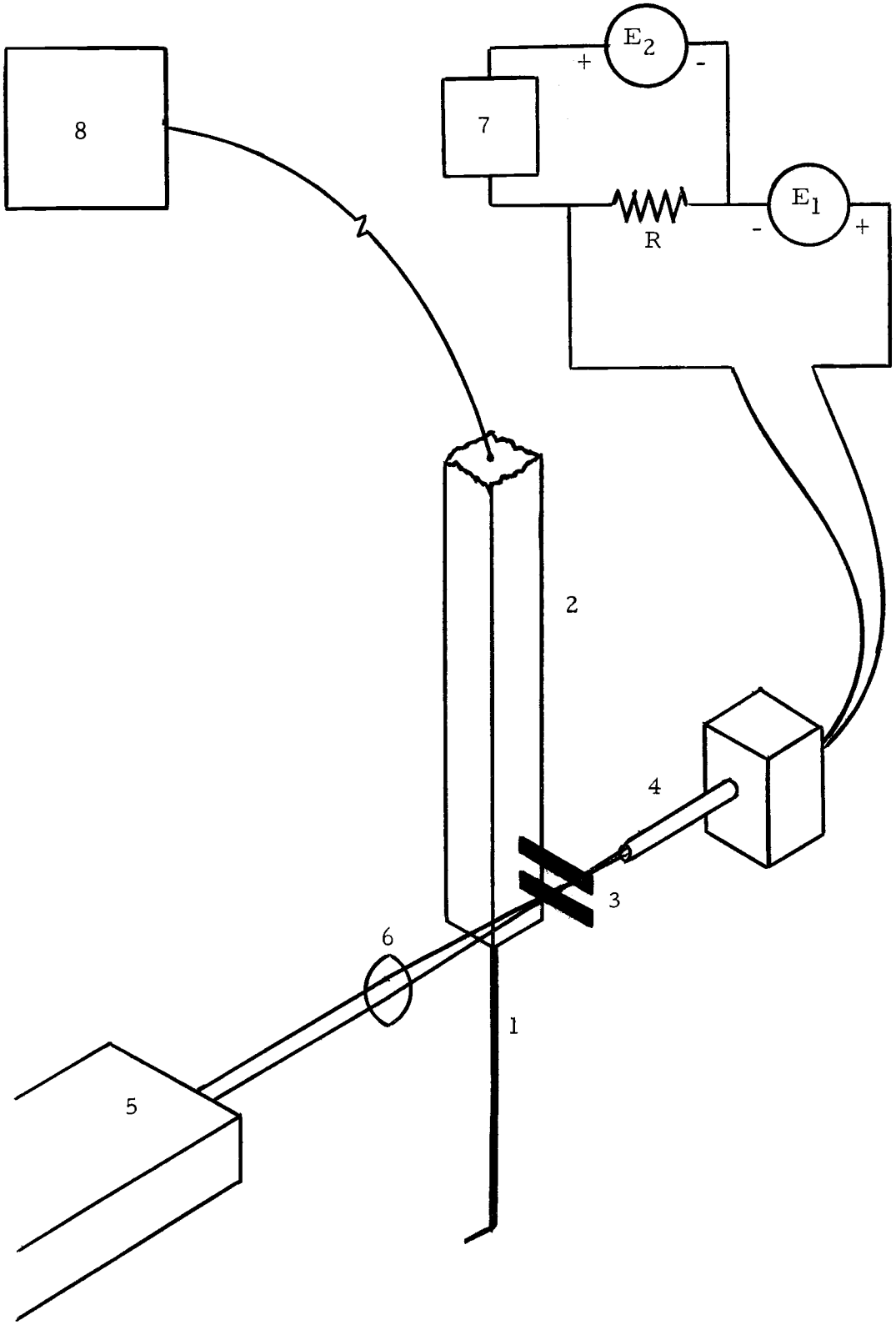

Figure 6. Electro mechanical shematic of velocity measurement system

in resistance of the photocell [4]. This photocell resistance was in series with the resistance R and the voltage E_1. Thus the series circuit was used to produce a rapidly changing voltage, which was used to start and stop the digital timer[6] [7]. The voltage supply E_2 was used to lower the signal into the timer so that the voltage change was from plus to minus. The digital timer was operated in the period mode and was capable of measuring the time elapsed over a single period. The period as observed by the timer was as shown in Figure 7. Thus, the timer began counting when the first knife edge crossed

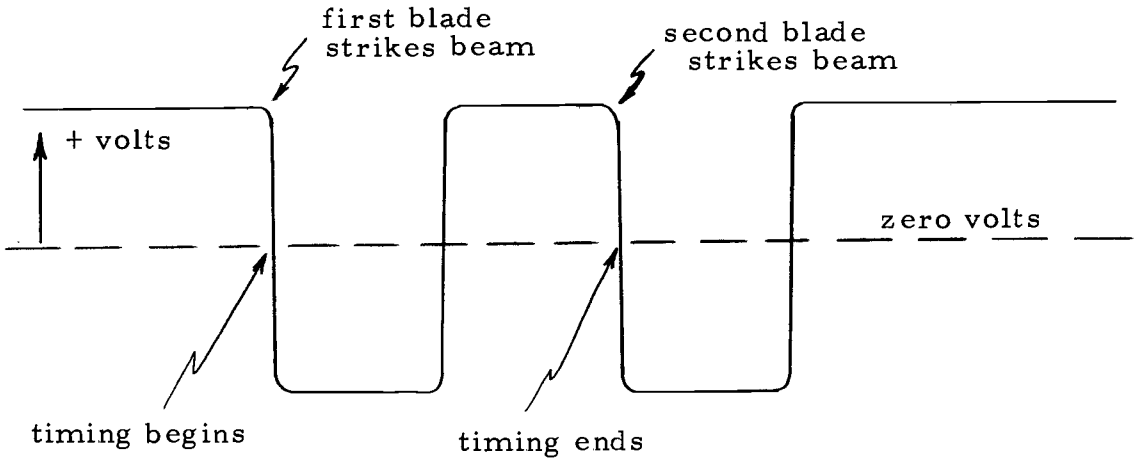

Figure 7. Voltage signal into timer

[6] Monsanto model 100B counter-timer

the beam and ended counting when the second knife edge crossed the light beam. Since the distance between the leading edges of the blades was known, the velocity was calculated by dividing this distance by the elapsed time. The values for the components of the circuit of Figure 7 were

R = 1000 kilo-ohms,

R (photocell) = 150 kilo-ohms (with light),

R (photocell) = 3000 kilo-ohms (without light),

E_1 = 6 volts,

and E_2 = 3 volts.

This method proved to be a very dependable way to measure the probe velocity, provided that the digital timer operated satisfactory.

The original plan for velocity measurement was to use a microswitch as the gate to start and stop the timer. A third method of velocity measurement was developed to determine which of the two methods, the microswitch method or the laser-photocell method, was more reliable and would be better to use. The method consisted of photographing the falling bar with the shutter of a camera open for two flashes of a strobotach. The time between two flashes was known, and the distance the bar fell during that time could be taken from the photograph. It was found that due to the inertia of the switch mechanism there was an error in the measurement proportional to the velocity of the probe when using the microswitch method. At the higher

velocities the method tended to predict a lower velocity than actually occurred (five percent low at five cm/sec).

Because the laser-photocell system proved to be accurate over the velocity range desired, it was chosen over the microswitch method. Actually, because this work describes the changes in performance of the hot film probes, the measurement accuracy was not critical, so long as any errors were consistent for every calibration. However the calibration system described here is being used for the calibration of probes whose subsequent use is the measurement of velocity profiles resulting from natural convection heat transfer to mercury. The laser-photocell method of measurement is a valuable addition to this continuing heat transfer research.

Voltage Measurement System

The voltage output from the anemometer was fed simultaneously to an integrating digital voltmeter[7], an oscilloscope[8], and an XY recorder[9]. The oscilloscope and XY recorder were not used continuously but were observed when their display was desired. The voltmeter, as it was used for these calibrations, averaged the voltage over a fixed 16.6 ms time period, regardless of the probe velocity. The voltage

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[7] Vidar model 500 integrating digital voltmeter.

[8] Tektronix model 5110 oscilloscope.

[9] EAI model 1030 variplotter.

integration was started manually when the first knife blade cut the light beam. This is the same as saying the integration of the voltage began when the timer began timing.

The voltmeter is presently being modified to begin integration when the first knife blade triggers the timer and to end integration when the second knife blade stops the timer. With this modification, the voltage measured is then the average voltage over the entire time of velocity measurement. This time may be considerably greater than 16.6 ms for the slowest velocities. Because the system was designed to drop the probe at a fairly constant rate over 25 cm, it is felt that the velocity was sufficiently constant over the 5.3 mm interval of velocity measurement. Thus the fixed 16.6 ms integration time introduced little error into the voltage measurement. To illustrate that the velocity was not constant over the full 25 cm drop, an XY recorder plot of the anemometer output is shown below in Figure 8.

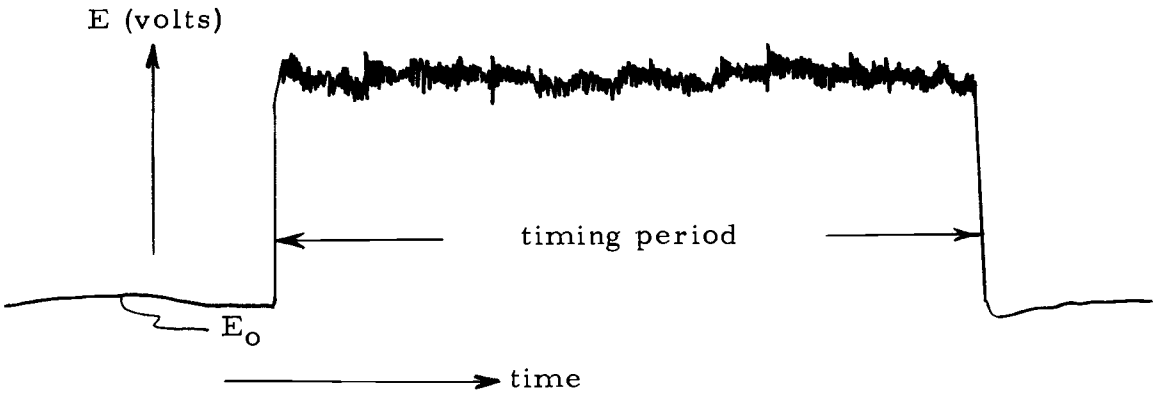

Figure 8. XY Recording of a typical anemometer output during calibration

The rest voltage was relatively flat with some randomness to it. The sudden jump in voltage was due to the release of the probe as it began its descent through the mercury. The high frequency noise in the output was assumed to be a result of mechanical vibrations in the velocity generation system. The sudden drop in rest voltage output was associated with the sudden termination of the probe's descent.

Mercury

The mercury was contained in a stainless steel tank 30 by 30 cm square and 41 cm high. The total weight of the mercury was about 500 kg. This large amount was determined by the requirements of the natural convection heat transfer experiments planned, not by the requirements of the probe calibration. Certainly, if the container was required only for probe calibration, its size could be significantly reduced.

The purity of the mercury throughout the experiments appeared excellent. It is difficult to measure the purity of mercury quantitatively, primarily because it is necessary in most uses to have impurities below one ppm, which indicates that mercury is potentially a very pure metal. The best qualitative test of mercury purity is to examine visually the mercury surface. If the mercury surface remains shiny and mirror-like after several days of exposure to the air, it can be said that the mercury is pure to at least one ppm of base

metals. If there is a larger quantity of base metals the surface will soon develop a very unsightly brown film, composed of oxides of base metals. The sight test does not indicate the impurity levels of noble metals within the mercury. Reference (2) is a good summary on the purity of mercury for the interested reader. Reference (1) is an interesting account of many aspects of mercury, including the history of mercury.

The mercury used in the work reported here was cleaned by a sequence of steps which seemed to be very satisfactory, as well as safe and economical.

The first step was to filter the mercury through white qualitative filter paper with a small hole at the bottom of the cone. The paper absorbed water and oil, and most of the visible oxide particles would not pass through the hole. For this reason the mercury would appear quite clean after filtering, but in a short while the base metals at the surface would oxidize, resulting in the normal oxide film. Thus the filter did not eliminate unoxidized base metals.

The mercury was filtered into three one liter glass bottles, and the second step of the cleaning was then to bubble air through the mercury for 24 hours. The laboratory air first passed through a cyclone filter and then through a line pressure regulator before passing out an aquarium air stone immersed in the mercury. The purpose of the air was to oxidize all of the base metals within the mercury. The air

exiting the mercury bottle was then passed into an empty glass bottle and then into a hood. A mercury vapor meter, monitoring the air going into the hood, showed no sign of mercury vapor in the air stream, indicating that any mercury vapor condensed on the walls of the empty glass bottle.

The third step was to let the mercury stand with no disturbances for 24 hours, and then siphon all but the top two cm into a clean bottle. The standing period was to allow the base metal oxides to float to the mercury surface. The clean mercury was sucked out from the bottle via a small glass tube, pushed down to about one cm from the bottom of the bottle. The suction was continued until the mercury level was about one cm from the glass tube end. Thus, the majority of the base metal oxides remained in the bottle, and the new bottle contained purer mercury.

Because impurities tend to collect at free (non wetted) surfaces, the author believes that some oxides creep down the side of the suction tube and are deposited into the cleaned mercury. Therefore, after the stainless steel mercury container was filled with the cleaned mercury, and after a wait of several days, the mercury surface showed signs of base metal oxides. The great advantage of the cleaning method was that the mercury had been thoroughly bubbled with air. This meant that nearly all of the base metal impurities had been oxidized and were on the surface. It was a simple matter to use a small

suction device to skim the surface free of the impurities, and throughout the experiments there appeared to be no surface film occurring from impurities within the mercury.

Much has been written on the harmful effects to the body of mercury vapor. Reference (3) is a very good, and brief, discussion of the problems involved. During the experiments presented here, every reasonable precaution was taken to prevent mercurialism. It is interesting to note however that a tentative analysis of the author's hair showed a mercury level over twice the normal amount. This was after a year of work with mercury.

EXPERIMENTAL PROCEDURES

Calibration Procedure

The procedures for calibration were varied as experience indicated throughout the experiments. The basic sequence of steps was:

1. Set the needle valve to the desired velocity setting,
2. Measure the rest voltage (E_o) by resetting the digital voltmeter,
3. Manually lift the bar-probe combination 25 cm and release,
4. Manually reset the digital voltmeter when the first blade struck the laser beam, giving the run voltage (E) for that velocity,
5. Monitor the elapsed time on the counter, giving the means to calculate the velocity.

These steps were then repeated for each datum desired.

The time required to complete these steps was varied considerably with no apparent change in resulting calibrations. For the first few runs, one minute was allowed after every movement of the probe. This was to allow time for disturbances in the mercury to dampen out. It was soon found that the entire sequence of steps could be completed in less than one minute without apparent difficulties or change in calibration.

The oscilloscope and XY recorder were only observed if their output was desired for some reason. The XY recorder was most useful to obtain the trend of the anemometer voltage, particularly the rest voltage. About ten seconds after the probe reached the end of its descent the voltage appeared to steady down to its normal rest voltage output, and the recorder showed this well. Observations of these plots were the first indication that the calibration could be speeded up.

All calibrations were performed at room temperature. The laboratory did have slight periodic temperature changes, but the mercury bath was not significantly affected by these changes. The initial calibrations included a measurement of the rest resistance at each velocity setting, but it was soon found that this resistance remained very constant throughout a given calibration. Thus the probe resistance was checked a few times to make certain it did not change, and the resistance measurement at each velocity was eliminated.

For all calibrations the velocity range was about .1 to 5 cm/sec and the number of velocity settings for each calibration ranged between 20 and 50, depending on the particular test.

Data Reduction and Analysis

The data available from a typical calibration were stored in a digital computer[10] and later reduced into voltage change and probe

[10] CDC 3300 Digital computer.

velocity. It is helpful to recall that the measurements taken during calibration were

1. Rest voltage (E_o),
2. Run voltage (E),
3. Elapsed time (ET).

Because the knife blade separation was constant and known, the velocity for each drop was easily calculated from V = S/ET, where S is the distance between the leading edges of each blade.

It is helpful to recall the need for calibrating a probe. Essentially a calibration is required to allow a voltage measurement to be converted to a value of fluid velocity. Thus in a practical use of a hot film anemometer, the probe is inserted into a flow, the voltage across the sensor is measured, and the flow velocity is then obtained from a calibration curve or equation. This procedure is opposite from the calibration where the velocity is the independent variable and the voltage is the dependent variable. A specific velocity is generated and the measured voltage corresponding to that velocity is obtained.

The experimenter must decide in what form to correlate his data, and the decision depends on the use of the resulting calibration equation. If the probe is to be used to measure velocities, the velocity should definitely be known as a function of voltage. If the calibration is to be compared to other calibrations or to previous analytical approximations the usual approach is an equation relating voltage to a

function of velocity. The best approach for obvious reasons is to reduce the variables to dimensionless numbers. In particular a correlation of the form Nu = f(Pe) or Nu = F(Re) is sought.

The data from this experimental program were reduced into the form of V = f(E) because this equation allows the best subsequent use of the calibration for velocity measurement. One calibration was reduced into the form Nu = f(Pe) in the event that the reader wishes to compare these calibrations with one of his own. A good correlation was found to be

$$Nu = .646 + .447\ Pe - .255\ Pe^2.$$

The reader is cautioned that this correlation was obtained from values of Pe less than unity. Because the results of this work are dependent upon calibration changes of each probe, independent of any others, this reduction to dimensionless parameters was not an important consideration. The author believes that each probe should be calibrated when possible, which eliminates the use of dimensionless correlations as a practical means of probe calibration.

After reduction into columns of $E - E_o$ and V, each calibration was statistically analysed using the canned program *SIPS available from the university's teletypes. The data were fitted to a second order equation of the form

$$V = C_1 + C_2(E - E_o) + C_3(E - E_o)^2 \qquad (10)$$

by the least squares method. Higher order equations were tried but were found to improve the correlation by insignificant amounts.

It was also necessary to compare any two calibrations of the same probe to determine if some change in a parameter had changed the calibration. Because the velocity increment was not exactly the same for any two calibrations, this was not a typical statistical problem. (The velocities were not made the same due to the nature of the calibration system.) The method adopted to compare calibrations was the F test, with the F statistic calculated by the extra sum of squares method. The procedure was to combine the two calibrations of interest into a restricted model and obtain a regression equation of the form of equation (10). Thus, the data from the two calibrations are added together to form what can be considered a third calibration. The F statistic was then calculated from

$$F = \frac{\dfrac{RSS_r - (RSS_i + RSS_j)}{df_r - (df_i + df_j)}}{\dfrac{RSS_i + RSS_j}{df_i + df_j}}, \qquad (11)$$

where RSS = residual sum of squares from the analysis of variance of the regression, df = degrees of freedom, and the subscripts r, i, j denote the restricted, i^{th}, and j^{th} models respectively. Since all regression equations were of the form of equation (10), df = N - 3, where N is the sample size used to generate the equation. If RSS_i and RSS_j

are calculated from the same set of data, then $RSS_i + RSS_j = RSS_r$, which results in F = 0. If the calibrations i and j are significantly different, then $RSS_r >> RSS_i + RSS_j$, and F will have a high value. Tables of the F statistic are available in most regression analysis books. The F statistic calculated by equation (11) was compared to the 90% confidence interval from the table, for the appropriate degrees of freedom. If the calculated value of F was greater than the appropriate value from the table, then there was greater than 90% confidence that the calibration i was different than the calibration j.

For a given probe, the F statistic was calculated for every possible combination of i and j. (The one exception was i = j, which would yield F = 0 everytime.) Thus if a probe was calibrated M times, (M - 1)! F statistics were calculated.

Visual examination of plots of the calibrations was used as another method of determining a change in calibration. While this lacks a quantitative comparison, it is a simple and effective way to examine the data and find significant changes in the calibration.

Application of Metallic Films

Because Hoff (13, 14) had found metallic coatings over the sensor to be beneficial, it was decided to test the effect of various thin metallic films to see if they would be helpful additions to the research program. The candidate metals are those which are wetted by

mercury. Hoff tried both copper and gold. Another possibility is silver. Two possibilities not examined in this work are Columbium and Haynes 25 which are discussed in Reference (25). If the theory is correct, these films would reduce the thermal contact resistance between the sensor and the mercury.

Wetting is a quantitative concept generally defined by the contact angle between a bead of the fluid of interest placed on the surface of interest. It is thus helpful to think in terms of degrees of wetting rather than simply whether a surface has been wetted or has not been wetted. Thus, silver, gold, and copper are strongly wetted by mercury, glass is not wetted by mercury, and nickel is partially wetted by mercury. The degree of wetting is strongly dependent on the surface condition of the material. Mercury which has wetted the inside of a tube has a concave meniscus, while mercury in a glass tube, for instance, has a convex meniscus. Usually wetting is discussed in terms of three phases, but it has been used in the anemometer literature to describe the contact between the sensor and the mercury, in the absence of the third phase, normally air. This seems acceptable as a descriptive concept, even if it is not the standard use of the term.

As a first attempt to obtain metallic coated sensors, two probes were sent to Marc Hoff, Grumman Aircraft Engineering Corp., Bethpage, New York, for the application of a thin gold film by vapor deposition. These probes were plated gratis by Mr. Hoff, but

unfortunately they were absent from the experiment for over six months. The technique used is described by Hoff (13). Although vapor deposition of gold is quite common throughout the country, there are unique problems associated with the geometry of the sensor and the probe body which preclude a simple procedure. Two companies were approached on a contract basis but wanted several hundred dollars to apply the gold films. For these reasons it was felt that the best solution was to examine the performance of the two sensors plated by Hoff. If the vapor deposited gold was then found to be a valuable addition, a more permanent supply would be obtained.

The performance of the probes coated with vapor deposited gold as well as all of the metal plated probes, are given later in the thesis. Suffice it to say that it was found that the vapor deposited coatings were perhaps not worth the difficulties of obtaining them. A search then began for an adequate method to plate chemically a metal onto the quartz coated sensor. Chemical plating has a great advantage over vapor deposition in that a uniform coating is a natural consequence of the procedure. One disadvantage might be that the metal does not adhere to the quartz as well as the vapor deposited metal.

The first coatings were of silver and were applied by a professional glass blower. The method was identical to the chemical plating of silver onto glassware for decorative ornaments and scientific apparatus. Although on large pieces of glass the silver appeared

as an extremely smooth surface, the coated sensor appeared through the microscope to be quite rough, with even small areas not coated. The estimated mean thickness of the silver film was five micrometers.

An important feature of a metallic film on the sensor is that it must last long enough to take measurements and calibrate the probe. Because silver and gold surfaces are wetted very well by mercury it is natural to assume that a thin film would soon be lost by amalgamation into the mercury. For this reason it is puzzling why Hoff obtained good results for many hours after insertion of the gold probes (he does not specify how many hours), unless the advantage of the gold remained after the actual coating was gone.

Heinisch (10) used a heated nickel plate in mercury for a long time with no apparent nickel amalgamation. On the basis of this, nickel coatings were applied in an attempt to obtain a probe which would at least present a semiwetting surface to the mercury but would remain on the sensor for a long period of time. (A further motivation for obtaining a nickel coating was that gold could be easily coated onto the nickel, whereas it could not be chemically plated directly to the quartz.) The nickel coating was applied by catalytic deposition of nickel. The basic steps are given in Reference (20). Briefly, the surface is first sensitized with a stannous chloride-hydrochloric acid solution. It is then rinsed with water, sensitized with a palladium chloride solution, rinsed with water, and finally plated by immersing

into a nickel chloride solution at 95°C. Many attempts at plating the nickel were required before a successful coating was obtained. It was found by accident that the beaker containing the nickel solution must be plated along with the sensor. This means that the beaker was sensitized along with the sensor, and when the actual nickel plating began, the nickel was deposited on the beaker as well as on the sensor. The success of the plating was very dependent on the cleanliness of the whole system and the thoroughness of the water rinse. It was found that the best coatings were obtained if the beaker was placed in an ultrasonic field (generated by an ultrasonic cleaner) and the sensor then soaked in the beaker. The resulting nickel coatings, after the procedure was refined, were quite easy to apply and appeared to be quite uniform in thickness. They were estimated by microscope measurements to be five micrometers thick. The nickel surface appeared quite smooth, but not as smooth as the standard sputtered quartz film. Microscope magnification was typically 50 to 100X.

Gold coatings were easily applied to a sensor if it had first been plated with nickel. A commercial gold cyanide solution[11] was used as per the instructions. The resulting gold coatings were similar to the silver coatings in roughness, although the gold did appear to coat the sensor completely. The gold thickness was estimated at three

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[11] Engelhard Industries, Chemical division, Newark, N. J.

micrometers. Thus, these probes had a combined metal coating of about eight micrometers. All metal thicknesses were felt to be known to no better than 25% of the actual average thickness.

TESTS AND RESULTS

Effect of Overheat Ratio

Several overheat ratios (OHR) were examined to determine what the optimum value would be. The regression lines of these calibrations are shown in Figure 9. As the sensor operating temperature increased (increasing OHR), the sensitivity of the probe increased, which was the anticipated trend. This is a desirable feature, because a greater change in output voltage for a given change in velocity gives a more accurate measurement. There is a tradeoff however, because a greater operating temperature causes a greater disturbance to the flow due to increased natural convection flow from the sensor. An additional disadvantage to higher operating temperature is a decrease in the life expectancy of the probe.

In general, it is a difficult problem to determine the optimum OHR because of the lack of quantitative values placed on the significant variables. This is often the case when faced with optimizing a certain variable of a system.

Table 1 presents a statistical summary of the calibrations shown in Figure 9. There does not appear to be an obvious trend in the standard deviation of the rest voltage or the residual sum of squares about the regression line with OHR. It was hoped that a trend towards better performance could be found, allowing a reason for choosing a

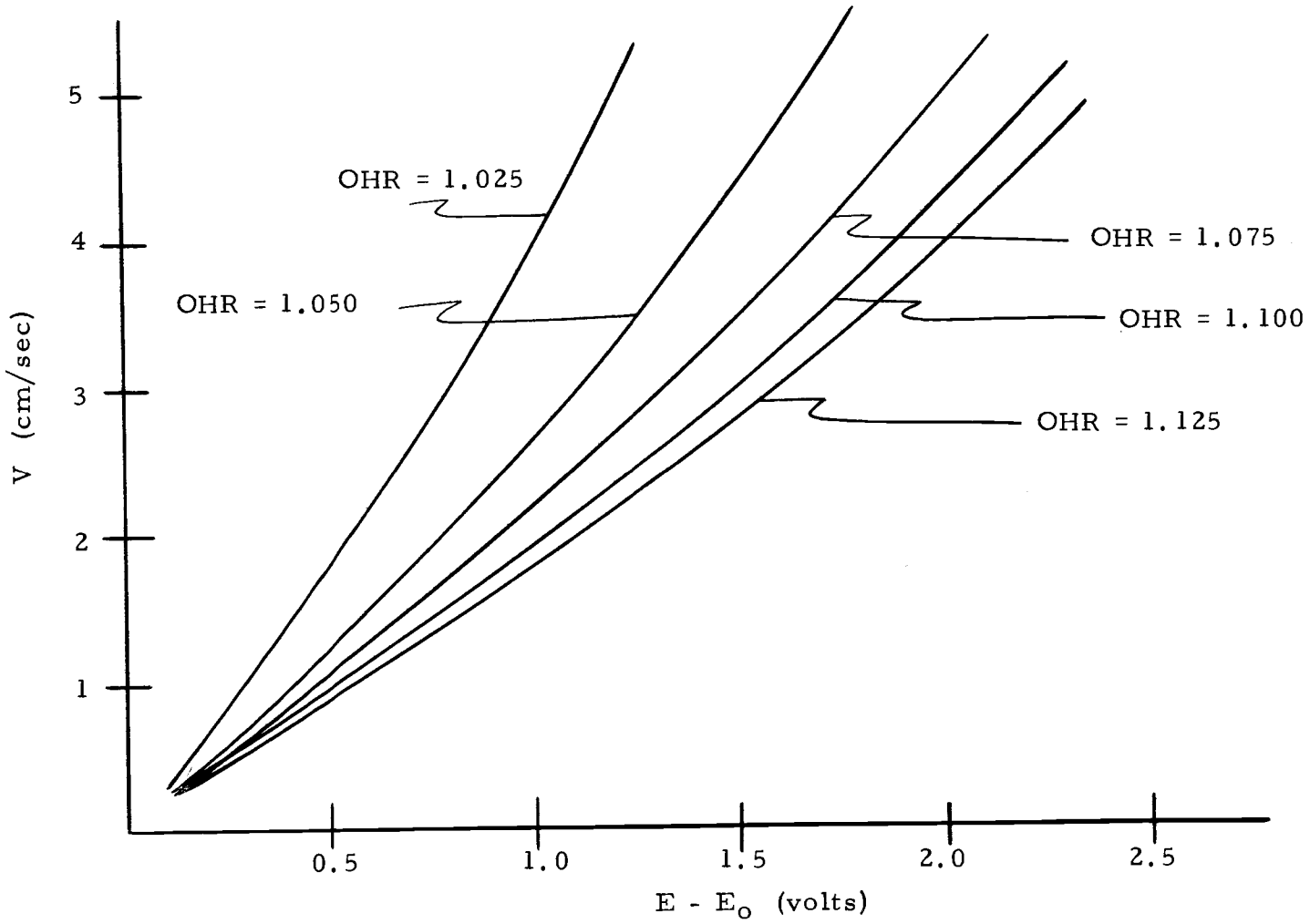

Figure 9. Effect of overheat on calibration

particular OHR. It was finally decided to use an OHR of 1.1 primarily because White (28) found this to be satisfactory for laminar natural convection velocity measurements and there seemed to be no reason to change. It is felt by the author that the general conclusions of this thesis would be obtained by a research program repeating the work with a different OHR.

Table 1. Summary of variable overheat ratio calibrations.

Calibration			Rest Voltage		Regression	
Probe	OHR	Samp. Size	Ave. E_o	St. Dev.	R^2	Res. S. S.
2Q	1.025	35	6.456	.0153	.9893	.2310
"	1.050	"	9.208	.0134	.9972	.1731
"	1.070	"	11.414	.0169	.9971	.1561
"	1.100	"	13.145	.0250	.9966	.1870
"	1.125	"	14.740	.0214	.9977	.1480

Examination of Rest Voltages

Once the overheat was selected, the logical step was to operate a probe and determine the effects of various parameters on its performance. Because calibration involves reduction of data before one can see the results, it is difficult to draw conclusions or see trends in performance during calibration. However, the rest voltage was a signal which was obtained directly from the digital voltmeter or the XY recorder. Therefore, as a beginning approach to the problem, it

was decided to examine the behavior of the rest voltage signal, enabling a more direct indication of the effect of various parameters on anemometer performance.

The first examination of the rest voltage signal was simply the analysis of the effect of surface fluids and sensor cleaning agents. If the probe was inserted into the mercury through a water cover, the rest voltage would begin at a low level and steadily climb to a steady state level after a few minutes. Figure 10 shows this trend. The anemometer was switched to run (resulting in the heating of the sensor) for the first time after insertion through the water layer. This climb to a steady level was experienced for every insertion through a water layer, and for the same probe, the resulting steady state level was

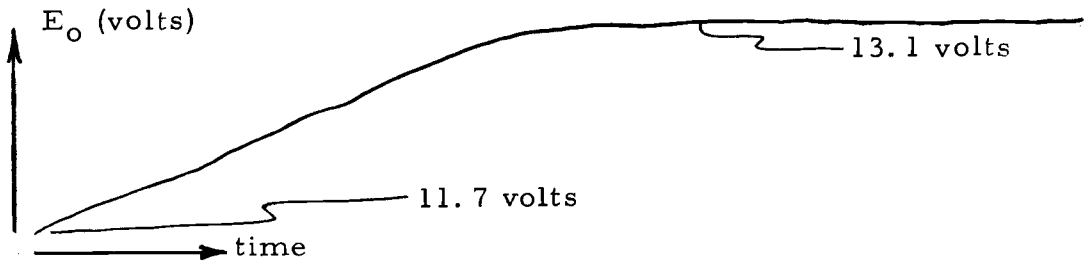

Figure 10. Plot of rest voltage after insertion through water

very close to the same after each insertion. Furthermore, if the probe was inserted into the mercury with no cover fluid (the

air-mercury interface discussed in the following section) there was no transient state after switching to run, and the level of the rest voltage was very close to that of the steady state level after insertion through the water.

The transient rest voltage phenomenon immediately after insertion through water was experienced in every one of the ten times the procedure was repeated. (Three different probes were used.) The author feels that a film of water exists around the probe after insertion, and it is gradually eliminated by the natural convective flow about the heated sensor. Thus, the preliminary conclusion was that after this short removal time, a probe inserted through a water layer would perform similar to the same probe inserted from the air into the mercury. Admittedly, there is no indication that the same rest voltage implies that the calibration would be the same, however, the results of this work never contradicted this assumption. In other words, if the rest voltage remained at the same average value, the calibration did not change significantly. This intuitively makes sense if the operation of the anemometer is considered. The anemometer output is dependent on the heat transfer from the sensor. If we thus examine one velocity (zero in the rest voltage case) and the voltage there is the same, it seems reasonable that the other voltages over the range of velocities would likewise remain unchanged. This concept is suggested to apply only to the comparison of voltages of a single probe, although

the concept might possibly be valid for probes of equal diameter and manufacturer.

Sensor cleaning agents were examined by simply contaminating a sensor with oil and metallic oxides, cleaning it with the agent of interest, and monitoring the rest voltage. Two methods of cleaning were used, namely jet spray of the cleaning fluid onto the sensor and insertion of the sensor into the cleaning fluid undergoing ultrasonic vibrations. The cleaning fluids used were Freon[12], 2,2,4-trimethylpentane, alcohol, dishwashing soap, and water. With no cleaning, the rest voltage after sensor contamination was 10.3 volts. Spray cleaning with alcohol or water failed to increase the rest voltage. Ultrasonic cleaning with alcohol raised the voltage to 13.1 v, but the water remained ineffective. The Freon and 2,2,4-trimethylpentane appeared to eliminate all contamination both by jet spray and ultrasonic cleaning, raising the rest voltage to 13.1 v. The dishwashing soap actually further reduced the rest voltage, causing the anemometer output to go below ten volts. A previous test showed that acetone destroyed the sensor in a relatively short time. The conclusion of the test was that either Freon or 2,2,4-trimethylpentane would be satisfactory cleaning agents. Later the possibility was raised that Freon caused cracks in the quartz layer because of the high temperature gradients caused by a very fast evaporative rate. This occurred

[12]Miller-Stephenson Chem. Co., L.A., Calif. Freon TF-MS180.

to the author when a probe shorted to the mercury immediately after cleaning with Freon. However, many probes were used successfully after cleaning with Freon. Because electrical shorting between the mercury and the heating element of the sensor was a major cause of probe failure, it appears that the slower evaporating 2, 2, 4-trimethylpentane may be the safest of the two successful cleaning agents.

The final rest voltage test was the examination of the long term variation of the rest voltage in air, water, and mercury. The sensor was placed into a beaker containing the appropriate fluid, and this beaker was surrounded by ice water, contained in a well insulated bath. Figure 11 shows a schematic of the system. The ice water was used to create isothermal beaker walls, because during a run the anemometer would be continually giving energy to the system and if the temperature of the system changed, the overheat ratio would not remain constant at 1.1. (The power dissipation in the rest condition was about 0.5 watt.)

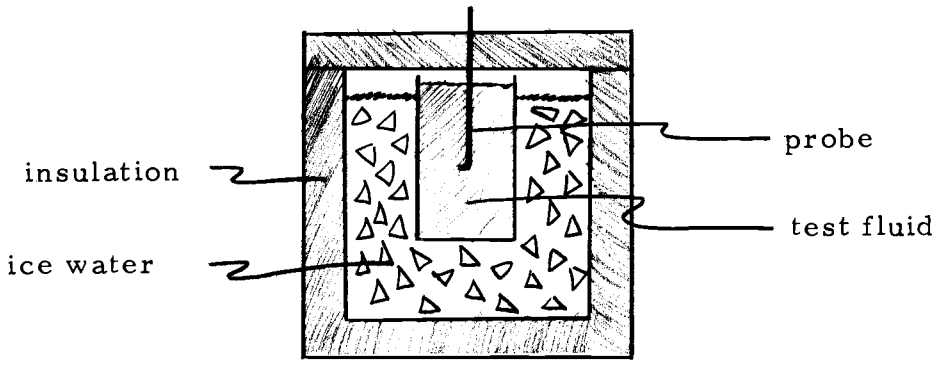

Figure 11. Insulated ice water bath for rest voltage measurements.

The procedure was to insert the probe into the test fluid and monitor the rest voltage every minute for eight hours. It was decided to monitor the voltage at night to have the most disturbance-free environment. A time lapse movie camera was placed in front of the digital voltmeter and took a picture of the anemometer output every minute. The data were then stored in the computer by visually examining the movie film frame by frame. The same OHR of 1.1 was used for each test fluid. Because of the large amounts of data, no attempt has been made to plot it here. Instead, the summary of the results are given in Table 2. From this table we see that the rest voltage in mercury was on the order of three times as large as the rest voltage in water, and on the order of 12 times as large as the rest voltage in air. Furthermore, although the average variation about the average rest voltage was over three times as large in mercury as in water, the ratio of the average variation to the average rest voltage was approximately the same for both mercury and water.

Table 2. Rest voltage with time summary for water, mercury, and air.

Test fluid	Sample Size	Time Period	Ave. E_o	St. Dev.
Water	480	8 hr.	4.427	.00193
Mercury	"	"	13.729	.00650
Air	"	"	1.098	.000000279

The rest voltage tests described in this section gave some indication of hot film anemometer performance in mercury. The next three sections discuss the calibration results and conclude the experiments performed during this research.

Effect of Reimmersion

The survey of the literature indicates that a probe will probably change calibration with each insertion into the mercury. The probable explanation of this phenomenon is that the thermal contact resistance at the sensor-mercury interface changes with each insertion. This section presents under what conditions this change in calibration is likely to occur.

Practical experiments with mercury require a protective cover to prevent poisonous mercury vapor from escaping into the laboratory. For an open container of mercury, the easiest solution is to cover the mercury with a thin layer of nontoxic liquid. The most common liquid is water. Hill (11) and White (28) used mineral oil. To insert the probe into the mercury an experimenter must either pass the sensor through the cover fluid or remove the cover fluid for the short time required to immerse the probe. A small suction device can remove most visual traces of the fluid but there is some question as to whether the fluid film will have been completely removed. Hill and White used an air jet directed perpendicular to the mercury surface

to blow the oil away and insert the sensor. The author feels that this approach will not prevent some deposition of oil onto the sensor.

Two probes were used to investigate the effect on calibration of probe reimmersion. There were four possibilities for any given immersion. These are defined in the next four paragraphs, following which the performance of the probes will be presented.

One possibility was an air-mercury interface immersion in which the cleaned sensor was passed directly from the environment into the mercury. A five cm O-ring was placed on the mercury surface and the water cover was sucked out of this ring. (This was done to prevent having to remove the water from all of the 625 square cm of exposed mercury surface.) A hair dryer was then used to evaporate any remaining liquid water. A mercury vapor meter showed no increase of mercury in the surrounding air, indicating this to be a safe technique if the dryer is turned down quite low.

The normal conditions, with water as the cover fluid, constituted the system during a water-mercury interface immersion. Distilled water was used at all times, and it was kept free of contaminants from the air primarily by frequent replacement. The water was replaced by fresh water prior to every insertion.

The third possibility for an immersion was the application of a thin film of mineral oil directly onto the sensing element with subsequent immersion through an air-mercury interface. This procedure

was adopted rather than applying the mineral oil to the mercury surface because of the danger of the oil's presence negating the other experiments. The author feels that the best way to eliminate the oil once it has been poured over the mercury is to filter the mercury through paper filters. This is a slow process if 500 kg of mercury are involved! It seems likely that the large buoyant force on the oil surrounding the sensor after immersion reduces the film to the same thickness regardless of the method by which the oil was applied. Thus, a drop of oil applied to the sensor before immersion should not be different from passing the sensor through an oil cover film.

The fourth immersion possibility was to pass the probe through a contaminated mercury surface. This will be termed an oxide-mercury interface. The surface was prepared by sucking off the water and applying a film of base metal oxides saved from the mercury cleaning process. The resulting surface was thus similar to the appearance of mercury when it has a sufficient amount of impurities for oxidation at the surface. Instead of the extremely shiny qualities of very clean mercury, one is presented with a very dull and dirty looking surface. Because the underlying mercury was free of oxidizing metals, the base metal oxide film was easily removed by skimming the surface, returning the system to its previous shiny state.

Probe 3Q[13] was calibrated nine times over a period of eleven days. The regression lines of these nine calibrations are shown in Figure 12. Each line represents 50 data points. The raw data were not plotted to minimize confusion. As is discerned from the figure, seven of the lines are very close together and are difficult to distinguish from each other. The basic procedure for each of these calibrations was to insert the probe through the desired surface condition, switch the anemometer to the run mode for one hour, calibrate the probe, extract and clean the probe with Freon, and reimmerse for calibration again. The exact plan was not followed in every case, because some performance aspects of the probe were examined after some of the calibrations. In every case the probe was calibrated one hour after immersion, thus making the surface condition the only known variable in the experiment. (The exception is sensor run time, which must inevitably be increasing throughout the experiment.) Table 3 indicates the surface description for each calibration, as well as the pertinent statistical data. The F statistic was computed for each calibration, and the result was that the only two calibrations which could be proved to be different were 3Q6 and 3Q9, representing oxide-mercury and oil-mercury interfaces respectively.

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[13] The symbol Q indicates that the exterior coating of the sensor was quartz. Other possibilities would be N(nickel), or G (gold).

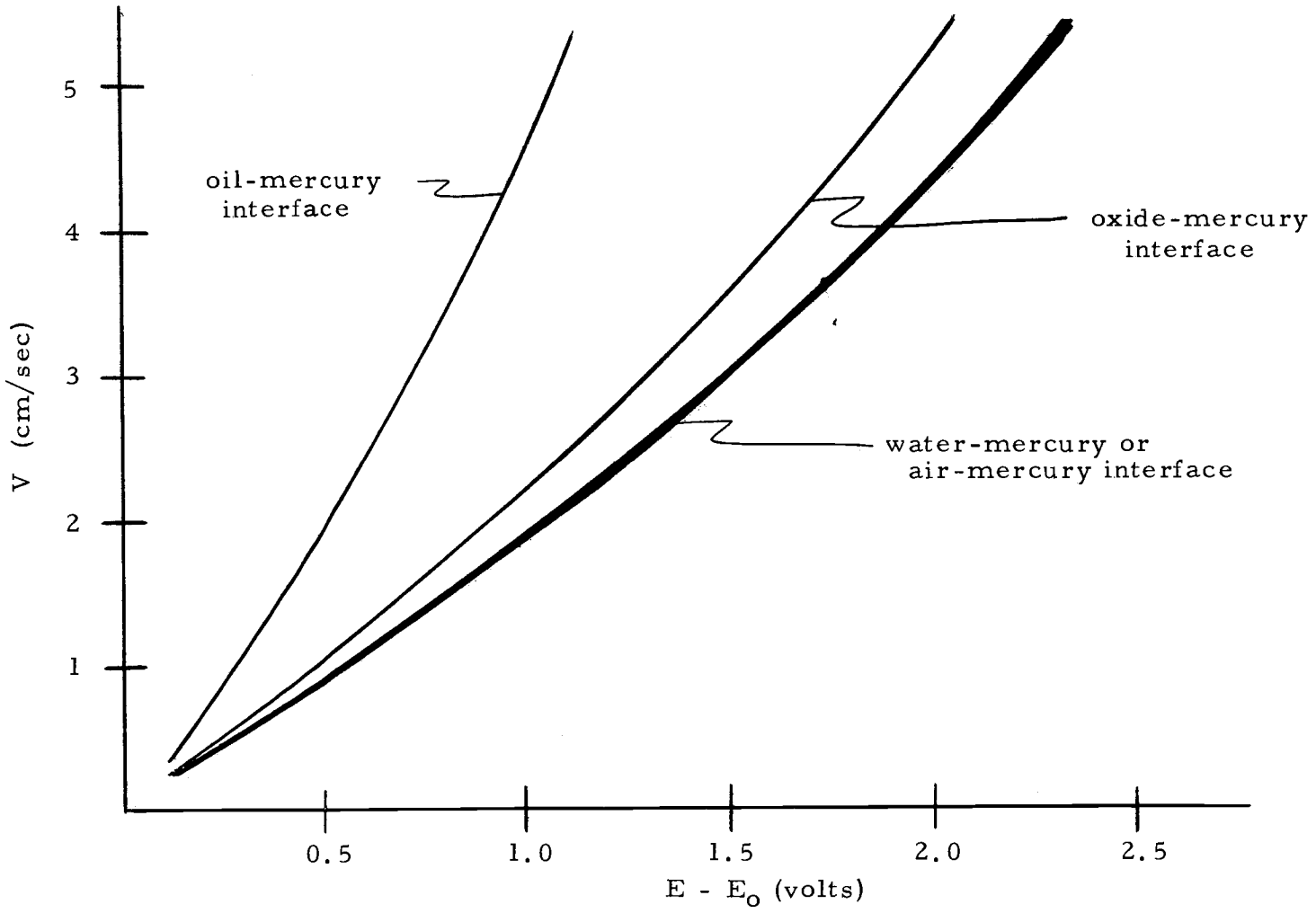

Figure 12. Effect of reimmersion on calibration

Table 3. Summary of reimmersion calibrations.

Calibration			Rest Voltage		Regression	
Probe	Inter-face	Samp. size	Ave. E_o	St. Dev.	R^2	Res. S. S.
3Q	Air-Hg	50	13.106	.0193	.9945	.3800
"	Air-Hg	"	13.071	.0080	.9979	.1791
"	Air-Hg	"	13.046	.0092	.9981	.1639
"	H_2O-Hg	"	13.169	.0232	.9978	.2602
"	Oxide-Hg	"	12.476	.0258	.9963	.3010
"	H_2O-Hg	"	13.142	.0286	.9966	.3300
"	H_2O-Hg	"	13.149	.0282	.9953	.3410
"	Oil-Hg	"	10.381	.0271	.9889	.2940

The important result of this test was that the probe calibration did not change significantly with reimmersion through either an air-mercury interface or a water-mercury interface. This is a contradiction to the results of previous investigators and is believed to be the result of the cleanliness of the mercury surface. Furthermore, the residual sum of squares for each regression appeared somewhat variable from one run to another, but they did not indicate that the oxide film or the oil film resulted in more scatter in the data. This partially eliminates contaminants as a major reason for anemometer output randomness.

The complete results of the testing of probe 4Q are given in the next section, but one aspect will be mentioned here. Probe 4Q was calibrated eight times over a period of twenty days. The probe was

immersed through an air-mercury interface and calibrated seven times. It was then extracted, cleaned, and reimmersed through a water-mercury interface. The calibration did not change. The F statistic for calibration seven compared to calibration eight was .735. The corresponding value for the 90% confidence interval is 2.80.

Thus, although only two probes were used, a total of ten immersions were examined. Eight of these immersions were through a clean surface, either a water-mercury or an air-mercury interface. The calibration for these eight immersions did not change significantly. If a mineral oil or oxide film were applied to the sensor, there was a reduction in the sensor heat transfer, with a corresponding loss in sensitivity.

Tests for Calibration Drift with Time

It was decided to test anemometer performance with time simply by calibrating each probe until it failed or until the test was felt to be complete. Three probes were used for these tests, but probe failure of the first two occurred before useful data were obtained. The procedure was to immerse the probe, switch to run, and begin calibration within one half hour after immersion. Subsequent calibrations were then taken approximately every two days. Each probe was given ten hours of run time each day. Approximately two hours of each ten could be counted as forced flow past the sensor. The other eight hours

were with the anemometer in the run mode, but with the probe in a stationary position. This means that the sensor was a constant temperature above the bulk mercury temperature, with resulting buoyant forces creating fluid flow, but the probe was not being continually dropped through the mercury.

The first probe tested failed during the third calibration. The calibration did not visually change between the first and the second calibration. The failure was due to an electrical short between the mercury and the platinum heating element, presumably through a small crack or pinhole in the quartz insulation. The performance of this probe during failure was seen in a total of six probes during the full course of the experiments presented in this thesis. The first signs of failure would be a step change in voltage output. Usually any change in grounding or instrumentation would further change the anemometer voltage, and finally the voltage output would deteriorate to large magnitude random variations rendering the probe completely useless. It is interesting to note that the short circuit could be proved with a resistance meter by placing one lead into the mercury and the other lead into the inside of the BNC connector of the probe. The resistance would typically be infinite when the first signs of trouble started, but would inevitably be zero when the probe had become useless. This apparently indicates that the electrical path to the heating element was intermittent at first, or perhaps only existed when the

sensor was heated, but after some time the crack would have grown and become a permanent leak through the insulation.

The second probe tested failed during the first calibration, with the same shorting characteristics as described above.

The third probe performed adequately for a total of 200 hours over a period of 20 days. The probe was immersed through an air-mercury interface and calibrated approximately every other day. Eight formal calibrations were recorded over this 20 day span, although as mentioned, the run time on the sensor was ten hours every day, regardless of whether a formal calibration was made. After the seventh calibration the probe was extracted from the mercury vessel, cleaned with Freon, and immersed through a water-mercury interface. After one day (run time of ten hours) the probe was calibrated.

Figure 13 shows the data from the first and the last calibration of this probe (calibrations 4Q1 and 4Q8). Either of these calibrations was typical of the other six calibrations. The statistical summary of the eight calibrations of probe 4Q is given in Table 4. The F statistic for any combination of the calibrations is indicated in Table 5. Of the F statistics shown, none are above 2.80, indicating that there is no statistical basis for believing that the calibration changed significantly during the 20 day period. From a physical standpoint, the calibrations appeared to fall on top of each other.

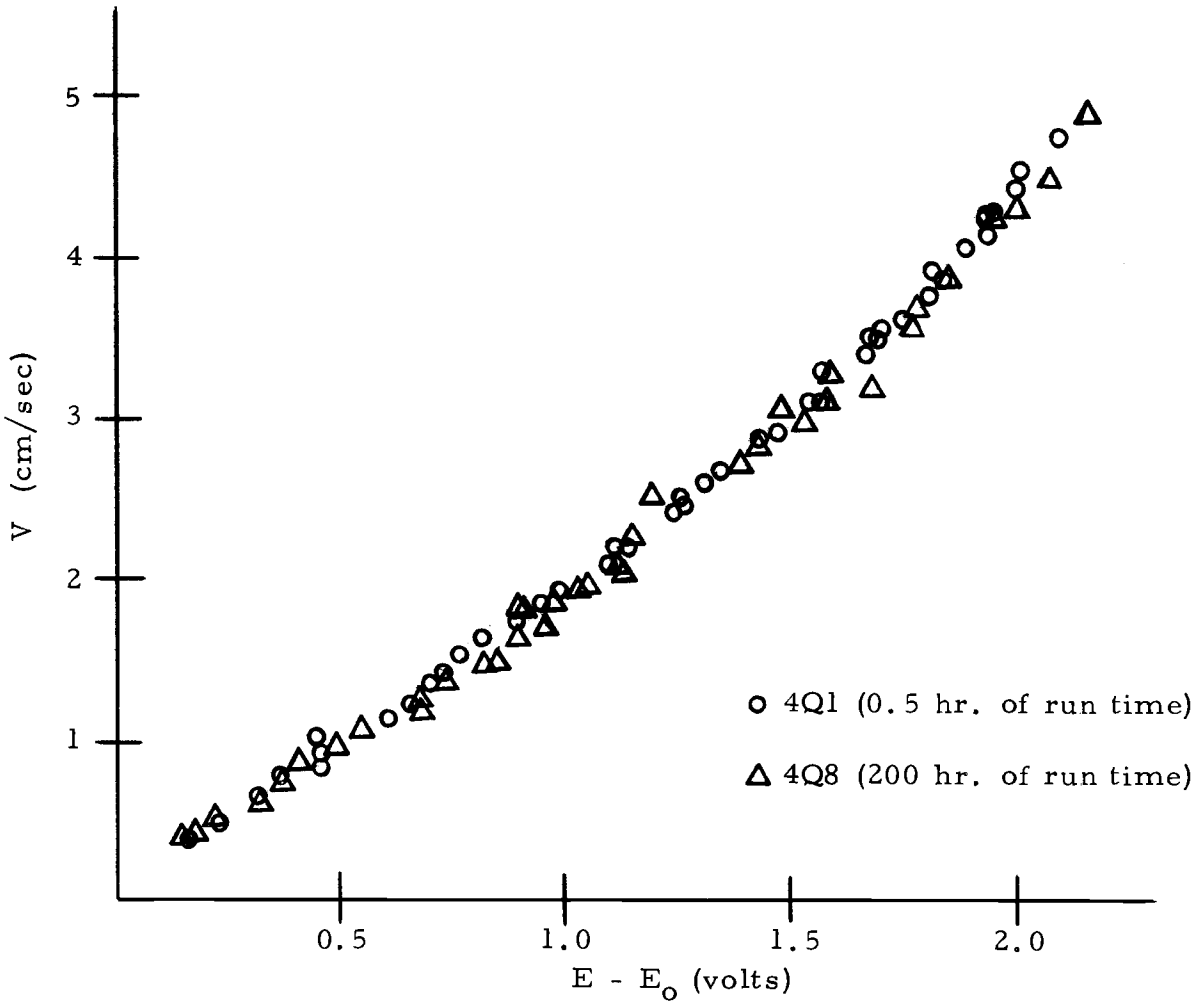

Figure 13. Plot of data of first and last calibration of probe 4Q

Table 4. Summary of drift calibrations.

Calibration			Rest Voltage		Regression	
Probe (No.)	Inter-face	Samp. Size	Ave. E_o	St. Dev.	R^2	Res. S. S.
4Q1	Air-Hg	47	13.926	.0148	.9982	.1282
4Q2	"	47	13.940	.0126	.9978	.1781
4Q3	"	41	13.967	.0104	.9964	.2020
4Q4	"	43	13.968	.0213	.9964	.2155
4Q5	"	41	13.968	.0306	.9968	.1802
4Q6	"	38	13.982	.0024	.9986	.0664
4Q7	"	36	13.967	.0132	.9979	.1491
4Q8	H_2O-Hg	39	13.900	.0168	.9919	.1080

Table 5. F statistic for drift tests (probe 4Q).

	Calibration							
	1	2	3	4	5	6	7	8
1	-	.553	1.247	1.914	1.596	1.357	1.769	.973
2	-	-	1.804	1.497	1.205	1.423	1.732	1.201
3	-	-	-	1.314	.488	.131	.128	.438
4	-	-	-	-	.531	1.312	1.939	.768
5	-	-	-	-	-	.300	1.170	.447
6	-	-	-	-	-	-	.789	.988
7	-	-	-	-	-	-	-	.735
8	-	-	-	-	-	-	-	-

The results of the nine calibrations of the reimmersion tests (the calibrations of probe 3Q discussed in the preceding section) further support the no drift with time hypothesis. Recall that for the clean immersions the subsequent calibrations remained constant. Obviously, total run time increased with each calibration, and therefore the calibration did not change with time. The estimated run time on probe 3Q was 50 hours.

It is perhaps an oversight by the author that an external velocity field of some kind was not generated during the drift test during the periods between calibrations. It seems, however, that the flow velocities of interest in this work are so small that flow induced wear will be negligible over any reasonable time period. The hypothesis is then that drift would be a result of contamination accumulation, a condition that would probably result simply from the chemical properties of the mercury and the quartz surface, while the probe was in the run mode.

Effect of Metallic Sensor Coatings

Probes with exterior coatings of gold, silver, or nickel were operated in an attempt to reduce the random variations in the anemometer output. The application of these films is discussed in the metallic coatings section of this thesis.

The first probes examined with metallic coatings were the two from Mr. Hoff. These probes had thin vapor-deposited films of gold

applied around the quartz insulation. The first probe failed about one half way through the first calibration. The failure was the result of an electrical short between the mercury and the heating element of the sensor. The probe's performance appeared to be an improvement over that of a standard quartz probe but it was difficult to decide quantitatively how good because only 20 data points were obtained before probe failure. The heat transfer was perhaps slightly higher than that of a standard quartz coated probe. The rest voltages demonstrated a standard deviation about their mean of .086, a number lower than most of the calibrations presented so far, but not the lowest experienced (see calibration 4Q6). The author feels that only one calibration of 20 points is just to small to evaluate adequately the performance of the probe.

The second and last probe sent by Hoff was calibrated and examined for over a week. There was no behavior of the probe which gave any indication that it had been gold plated. The performance was in every way typical of the performance of a standard quartz coated probe. This was a great disappointment, because it leaves in question whether or not the vapor deposition of gold is a desirable addition. Attempts to obtain a film by vapor deposition from other sources failed, and it was decided not to approach Mr. Hoff again. The tentative conclusion, both from this work and the work of White (28),

indicate that the gold plating is not as desirable an addition as was first believed.

Two probes were chemically coated with silver and immersed into the mercury. The silver films were eliminated almost immediately by the mercury, and as a result, the silver coatings were judged worthless as a means of reducing the anemometer voltage variations.

The gold films which were applied to the nickel probes also proved worthless. It was only a few seconds after immersion in the mercury before the gold layer was eliminated. This is possibly because of poor adherence of the gold to the nickel, but it seems more likely that the mercury simply was able to eliminate the gold by amalgamation, regardless of the quality of the gold-nickel contact.

This left the nickel probes as the best possibility for reduction of voltage variation by means of metallic coatings. Two standard quartz coated probes were calibrated one half hour after immersion through an air-mercury interface. Their performance was normal. The probes were then plated by the catalytic deposition of nickel, the method described in the Application of Metallic Films section. The first probe (designated as probe 5N) was immersed through an air-mercury interface and calibrated one half hour after immersion. The performance of the probe was remarkably improved over the calibration prior to the application of the nickel. The rest voltage was very stable. It was decided to calibrate the probe periodically to determine

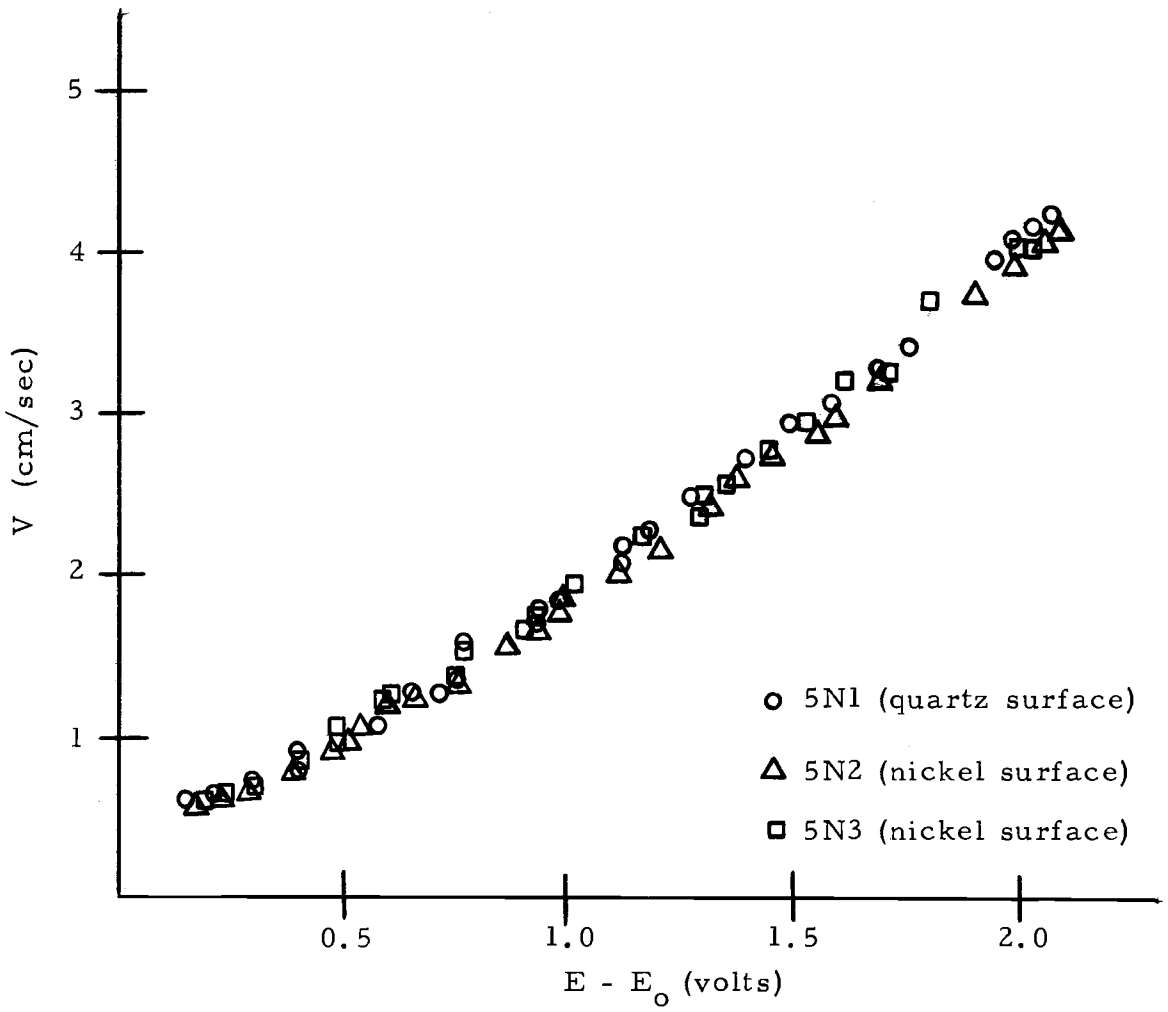

Figure 14. Calibrations of probe 5N, with and without nickel

how long the nickel coating would improve the probes performance, but the next calibration, eight hours after immersion into the mercury, showed a reversion to the performance of the probe before the nickel was applied. Subsequent calibrations failed to show improvement. The data for the first three calibrations are shown in Figure 14. It is difficult to see the effect of the nickel in Figure 14, but Figure 15, which indicates the rest voltage variation for the probe before and after the nickel coating, dramatically shows the improvement. To indicate the effect on the total performance of the probe, Table 6 summarizes the statistics of the calibrations of probes 5N and 6N.

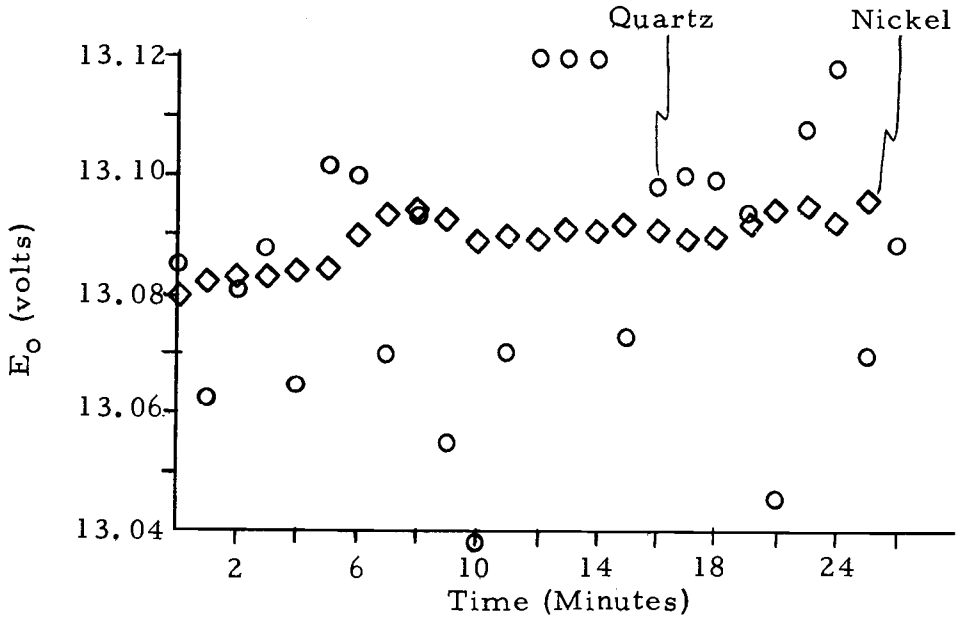

Figure 15. Rest voltage variation of calibrations 5N1 and 5N2.

To determine if the phenomena observed would be reproduced, the second probe, designated as probe 6N and previously calibrated before the application of the nickel coating, was calibrated one half

hour after immersion through an air-mercury interface. The

Table 6. Summary of metallic coating calibrations.

Calibration			Rest Voltage		Regression	
Probe (No.)	Met. Film	Samp. Size	Ave. E_o	St. Dev.	R^2	Res. S. S.
5N1	Quartz	29	13.082	.0214	.9975	.1000
5N2	Nickel	26	13.091	.00451	.9991	.0323
5N3	Nickel	25	13.087	.0259	.9988	.0772
6N1	Quartz	21	13.850	.0243	.9969	.0735
6N2	Nickel	23	13.862	.0052	.9980	.0372
6N3	Nickel	20	13.918	.0334	.9914	.0789

performance of the probe with the nickel on it was again greatly improved over the performance of the probe prior to the nickel plate. It was then decided to monitor the rest voltage while waiting for the next calibration. It was difficult to determine just when the output began to revert back to the normal variation of a quartz probe, because the change was gradual, but within five hours the effects of the nickel had apparently worn off, and the subsequent calibration indicated that the probe had reverted to its performance prior to the application of the nickel film. Figure 16 shows the first three calibrations of probe 6N, and Figure 17 shows the rest voltage variation of the first two calibrations. Table 6 gives the statistical summary of the first three calibrations.

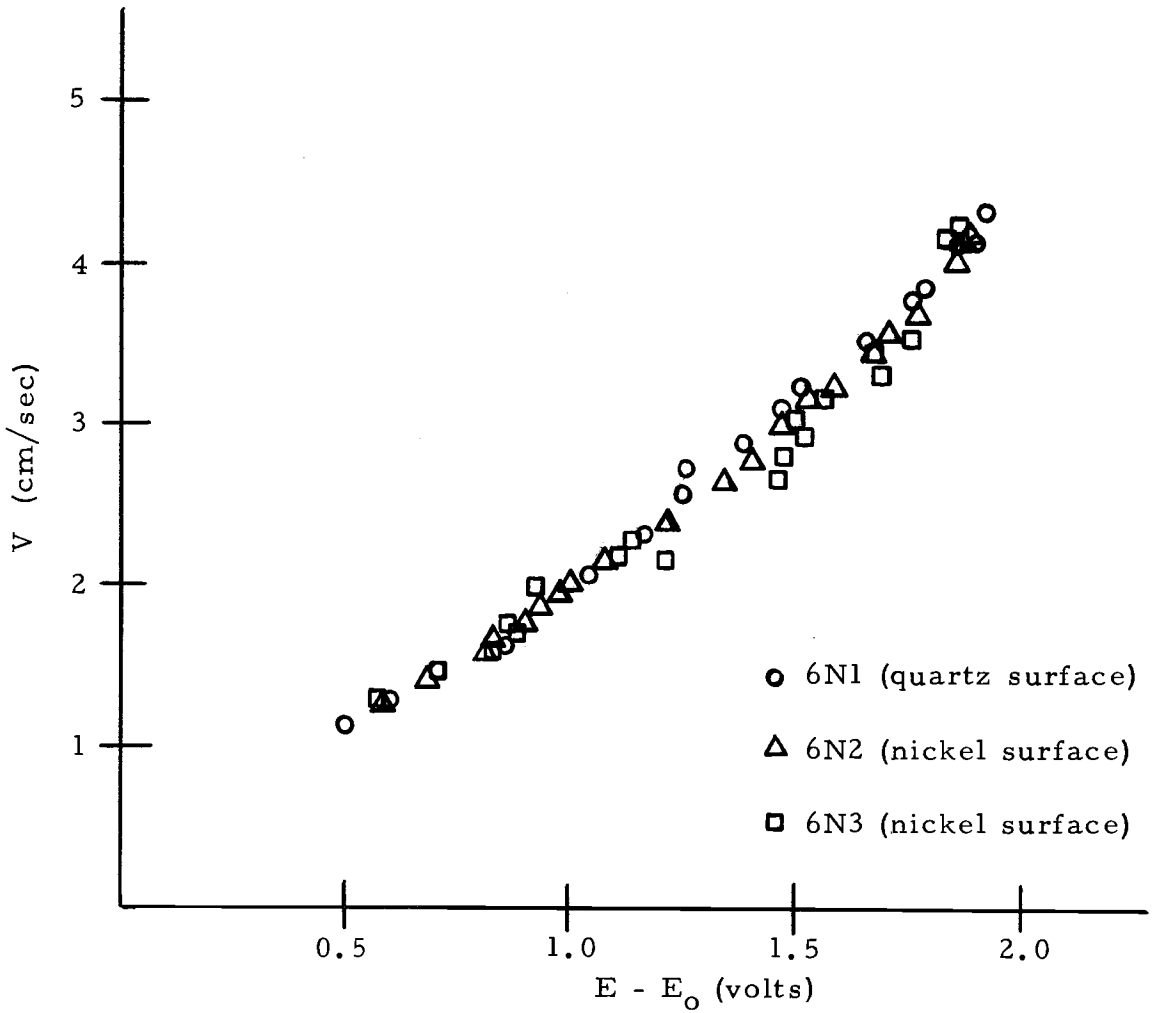

Figure 16. Calibrations of probe 6N, with and without nickel

Figures 15 and 17 clearly show that the rest voltage variation was reduced shortly after the application of the nickel, and Table 6 shows the effect of this reduction on the total calibration. It is helpful to recall that the data reduction procedure was to measure the rest voltage, create the velocity field and measure the velocity voltage, then substract these two to obtain the voltage change ($E - E_o$). Therefore even if the velocity voltage variation was not improved, one would expect a better calibration simply by reducing the uncertainty of the rest voltage measurements. Table 6 indicates that the uncertainty of the total calibration (indicated by the residual sum of squares) was reduced by approximately three times by the addition of the nickel layer. Unfortunately, this improvement was short lived and therefore is of little direct practical importance.

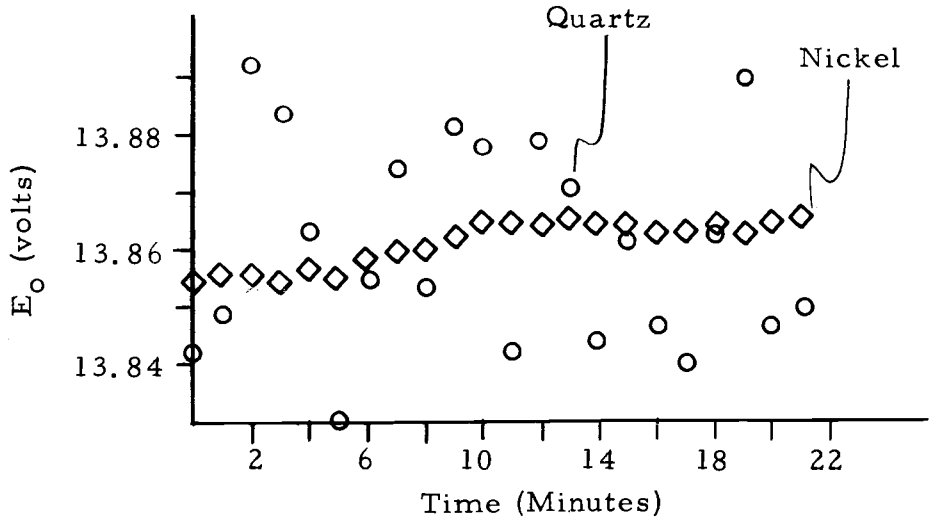

Figure 17. Rest voltage variation of calibrations 6N1 and 6N2

This partial confirmation of Hoff's conclusion that a metal film is an aid in anemometer measurements in mercury points directly to the sensor-mercury interface as the origin of random voltage fluctuations. Although no large increase in heat transfer was experienced, there was still proof that the random fluctuations were related to an interaction phenomenon at the sensor-mercury interface. The author does not fully understand the means by which the nickel reduced these fluctuations, because the nickel coating remained for several days after insertion. The nickel probes were extracted and reimmersed several times, but the reduction in voltage fluctuations experienced immediately after the application of the nickel was never reproduced.

DISCUSSION OF RESULTS

Tables 1, 3, 4, and 6 summarize the majority of the calibrations performed during this work. These represent 28 calibrations, ranging from a low of 20 data points to a high of 50 data points.

Random Voltage Variation

One striking feature of the calibrations was the apparent change in output randomness when no parameters were consciously changed. For example, consider Table 4, recalling that the only variable for calibrations 1-7 was time. Apparently, however, sometime between calibrations 4Q5 and 4Q6, something happened which significantly reduced both the standard deviation of the rest voltage and the residual sum of squares about the regression line. The subsequent calibration 4Q7 then seemed to revert to about the normal variation experienced during the first five calibrations.

In each of the tabular summaries there are changes in randomness not associated with some known cause, and it is important to note that these changes occurred even though the actual calibration did not change. It thus appears that any change in calibration is associated with a gross change in the total thermal resistance (recall the effect of the mineral oil on the sensor), but the change in the randomness of the signal is associated with the rate of change of the thermal contact

resistance. The logical question is why does the voltage signal variation change from calibration to calibration, and the author believes the answer involves an understanding of the complex interaction at the sensor-mercury interface. The data taken during this research were macroscopic measurements, but these data are specified by the microscopic events occurring at the sensor as the fluid flows by. The existence of some nonwetting thermal contact resistance is easy to visualize but the facts about its existence are extremely difficult to obtain. From the data given in this thesis some glimpses into the dynamic behavior of this contact resistance may be obtained, but the results are inadequate to completely predict the molecular interaction at the sensor surface.

One apparent conclusion is that this change in contact resistance is small compared to a thermal resistance from macroscopic sources. For example as an estimate we could assume that the maximum change in the thermal contact resistance would be on the order of two times the standard deviation of a typical calibration. (This is tantamount to saying that the deviation of the rest voltage from the average value is a result of the changing contact resistance.) With this assumption the change in voltage due to the change in thermal contact resistance was about .06 v. However, from Table 3, the effect of an oxide film on the mercury surface reduced the rest voltage by more than .6 v, and an oil film reduced the rest voltage by more than 2.6 v.

Uncertainty and Scatter

It is possible from the data here to estimate the average residual of all of the calibrations of the hot film probes in mercury. The sum of the residual sum of squares of the 28 calibrations is found to be 5.054 cm^2/sec^2, and the sum of the sample sizes is 1101. Dividing, and taking the square root, we obtain the average amount that a particular datum varies from its regression line as .0677 cm/sec. A plot of the 90% confidence intervals for two of the calibrations showed a band of almost the same thickness over the complete range of voltages, and therefore the value of .0677 cm/sec is felt to be an approximate average variation from the regression line at any voltage. The confidence intervals were not obtained for every calibration.

Note that an average residual of .0677 cm/sec does not indicate the uncertainty of the calibration curve. It is possible to obtain this uncertainty by following the procedure of Reference (15). Recall that the data were reduced into the form of

$$V = f(E - E_o) .$$

Therefore, to perform the regression legitimately we assumed that the uncertainty in $E - E_o$ was negligible. The velocity in the calibration was computed from

$$V = \frac{S}{ET} ,$$

and therefore the uncertainty W_v is found, by knowing the uncertainties W_s and W_{ET}, from

$$\frac{W_v}{V} = \left(\left(\frac{W_s}{S} \right)^2 + \left(\frac{W_{ET}}{ET} \right)^2 \right)^{1/2} .$$

Choosing ± .003 cm for W_s and .0005 sec for W_{ET}, as well as the minimum value for ET, we obtain

$$\frac{W_v}{V} = 0.76\% \quad \text{(odds 20 to 1)}.$$

The principal source of the uncertainty in V is W_s, and thus a more accurate measurement of S would be the best way to reduce W_v.

Anemometer Performance Due to Shorting

If an opening in the quartz insulation occurs, there is then an electrical path between the mercury bath and the heating element, provided the opening is large enough to allow mercury to pass through it. This in itself is not enough to destroy the operation of the circuit, so long as the mercury is not grounded in some way with the anemometer output. It is apparently this failure of the quartz insulation which caused the mysterious step changes in voltage experienced by White (28). These step changes were experienced in this work (see the calibration with time section). At the first signs of a short, the probe would still perform normally, but with a different output voltage. After some time, the output would completely deteriorate, presumably

because the opening in the quartz insulation increased in size or new openings occurred.

The author feels that the concept of step changes due to openings in the insulation may be the explanation of the difference between the results of Hoff (13, 14) and this work. (See Figure 2 for the summary of Hoff's results.) It is suggested by this author that a crack or cracks in the quartz insulation of Hoff's probes resulted in a major lowering of the voltage output, and the subsequent plating of the gold bridged over these cracks, eliminating the short circuit and therefore increasing the voltage output significantly. This is a speculative comment, and has some questionable aspects, but it may at least partially explain why the metallic coatings greatly increased the voltage output for Hoff and had no such effect in this work. The author finds no explanation for the closeness of the calibration of the gold probes by Hoff to the inviscid flow solution of Grosh and Cess. The viscosity of the mercury and the finite length of the sensor both have the effect of lowering the heat transfer from the sensor below the analytical solution of Grosh and Cess. Furthermore, Hoff used equation 6 to calculate Nu, which means his value for Nu was lower than would be obtained by a more accurate expression of the form of equation 7.

Mercury Cleanliness

It is the author's suggestion that the basic differences between the results of this work and the results of previous investigators are a consequence of

1. Improved techniques of applying the quartz insulation, resulting in films considerably more pore-free than in the past (16),

and 2. Improved mercury cleanliness.

The mercury cleanliness is an interesting yet imprecise subject. It would be nice to have the mercury vessels of all of the anemometry research referenced in this thesis placed side by side, to visually examine the surface condition of the mercury. Each of the research projects started out with clean mercury, but it is amazing what only one galvanized bolt will do to the surface of the mercury. It is possible, then, that the cleanliness of the mercury used in this work, particularly the surface cleanliness, was in part responsible for the lack of drift with time and the negligible effect of reimmersion on the anemometer calibration.

Probe Longevity

The reader probably does not have an accurate concept of the average probe life of all the probes used, because the ones that

performed satisfactorily are primarily the ones which are discussed in this thesis. No attempt will be made to tabulate the history of every single probe used, but a few comments will perhaps give a qualitative summary. The probes had widely variant usable lives. Other than mechanical damage due to carelessness, the cause of failure was always due to a leakage in the quartz insulation (or conceivably a leakage through the epoxy insulation on the support needles), and in most cases, if the probe was going to develop a short circuit at all, it would do so very early in its life. Some probes had an apparent short circuit to the mercury immediately upon insertion for the first time. If a probe survived this initial period with no problems it appeared that it would last for a very long time. For some experiments it might be wise to use candidate probes for some time before using them for the actual experiment, thus weeding out the ones with a likelihood of failure.

CONCLUSIONS

The constant temperature anemometer, utilizing quartz coated hot film probes, was successfully used to measure velocities between 0.1 cm/sec and 5. cm/sec. A probe was operated 200 hours over a period of 20 days, without drift in calibration. It was found that if the mercury surface was kept clean, the calibration for a probe remained unchanged after several immersions into the mercury. Furthermore, the immersion could be through an air-mercury interface or a water-mercury interface, and so long as the surface was clean, the calibration did not change. There was no definite evidence that the immersion through the water-mercury interface would result in more random fluctuation in the voltage output than an immersion through an air-mercury interface.

Random voltage fluctuation was as significant in this work as in the previous research. Efforts to decrease the fluctuation by using metallic plated sensors were for the most part unsuccessful. Probes plated with nickel significantly decreased the fluctuation, but only for about five hours of run time. From the success of the nickel probes for a short while, it appears that random voltage fluctuations are caused primarily by a continually changing contact resistance at the sensor. Although it seems possible that a satisfactory metallic coating of some sort may exist, the conclusion of this thesis is that the

standard quartz coated hot film probe should be used to obtain velocity measurements.

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