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THE DAVID W. TAYLOR MODEL BASIN

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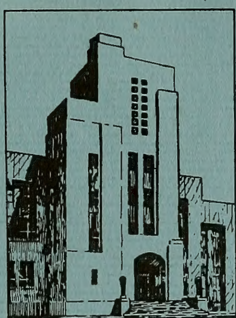
SUMMARY REPORT ON THE DEVELOPMENT OF A HOT-WIRE TURBULENCE-SENSING ELEMENT FOR USE IN WATER

by

R.G. Stevens, A. Borden, and P.E. Strausser



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ABSTRACT

A summary is given of the work done since 1946 at the Taylor Model Basin to develop a hot-wire turbulence-sensing element for use in water and of some of the uses to which the wire has been put. Recent efforts to determine the causes of wire instability and to eliminate them are described. As a result it was determined that these wires should be heated with an alternating carrier current and that the exposure of dissimilar metals in the probe assembly should be eliminated. With these precautions the wire could be stabilized in well-filtered water. In ordinary water, instability from the accumulation of dirt and surface film on the wire could not be controlled except by removing the wire frequently for cleaning. It appears that the only satisfactory solution to this problem lies in the development of a dynamic calibration technique. Theoretical expressions for the sensitivity and frequency response of a coated hot wire are included.

INTRODUCTION

Since 1946 experimenters at the David Taylor Model Basin and elsewhere have attempted to apply the principles of hot-wire anemometry to turbulence measurements in water. Although many hydrodynamic problems can be simulated in wind tunnels and studied with conventional hot-wire methods, there are a few important problems, particularly where surface effects are important, which are not amenable to this procedure. Although the techniques for the use of a hot-wire turbulence-sensing element in air are now well developed and widely used, some very serious difficulties arise when efforts are made to adapt this instrument for use in water.

It is the purpose of this report to review the efforts of various investigators at the Model Basin who have contributed to the development of a hot-wire element for use in water, to discuss the problems and difficulties involved and to report on current investigations. M.S. Macovsky and W.L. Stracke developed the first element and made a few quantitative turbulence measurements with it. The wire has been used by Macovsky and J.P. Breslin in qualitative experiments in turbulence detection. Mr. Stracke worked out a method for a dynamic calibration of the element and made preliminary experiments for developing the technique. Recent experimental investigations to develop a more stable wire have been carried out by R.G. Stevens and P.E. Strausser. Dr. Borden has made theoretical studies of the sensitivity and frequency response of hot wires on which a surface film has formed.

EARLY DEVELOPMENT OF THE HOT WIRE FOR USE IN WATER AND ITS APPLICATION

Beginning in 1946 Macovsky and Stracke developed a constant-current, hot-wire, turbulence-sensing element for use in water.[1,2] The element was heated with a direct current and was used in a conventional constant-current hot-wire circuit which had been developed at the National Bureau of Standards.[3] Most of the effort at the Taylor Model Basin was expended in selecting wire material and in developing methods of fabricating the probe and a technique for making turbulence measurements. In addition, the hot-wire element, as originally developed, has been used with varying degrees of success in quantitative turbulence measurements and has been used very successfully for qualitative measurements and for turbulence detection.

The choice of a wire material depends not only on favorable electrical properties but also on its ability to withstand the corrosive action of water and the relatively large hydrodynamic forces. The most suitable material was determined to be tungsten. Probes fabricated from 0.3-mil tungsten wire, about ¼ in. long, had a resistance of from 5 to 10 ohms and could be given a temperature elevation of 15F with a heating current of about 120 milliamperes. Such wires did not corrode and were able to withstand water speeds up to 20 knots without failing.

In fabricating the probe the wires were carefully copper plated, leaving a gap of the desired length for the sensitive portion. Then the plated portions were soldered across the tips of the metal supports. Finally, the supports were painted with insulating material to reduce electrolysis. Details of the fabrication technique are reported in References 1 and 2.

The major obstacle in obtaining accurate turbulence measurements with a hot wire is the instability of the wire resistance caused by the accumulation of gas bubbles, dirt, and a surface film on the wire. This contamination starts as soon as the wire comes into contact with the water. If the resistance fluctuations arising from changes in the convective cooling of the flow are to be measured quantitatively, all measurements must be made with a freshly cleaned wire a few seconds after it has been placed in the flow. The measuring technique developed by Macovsky and Stracke consisted of removing the wire before each measurement, cleaning it with a camel's hair brush which had been dipped in acid, positioning the probe again, and quickly taking a reading. The heating current in the wire was automatically turned on and off by means of a microswitch as the probe was swung into and out of the water. To check a reading it was necessary to repeat the whole process. Thus the reliability of the turbulence measurements depended a great deal on the patience and dexterity of the investigator. With care, measurements could be repeated.

The foregoing technique was used in the 1/22-scale model of the Taylor Model Basin circulating water channel[1] to repeat some of the classic wind-tunnel experiments of free-stream turbulence behind grids and cylinders. In the first experiment the hot-wire sensing element was mounted at various distances downstream from a grid and quantitative measurements of

[1]References are listed on page 14.

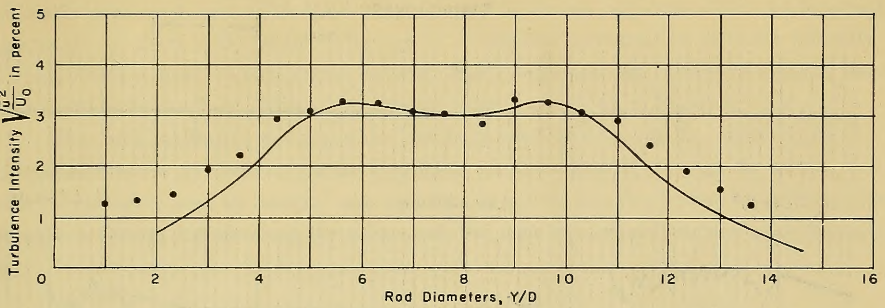

Figure 1 - Distribution of Intensity of Turbulence 91 Diameters Downstream from 3/32-inch Rod

The solid line is due to Townsend ($R_e = 850$); the points are TMB hot-wire data ($R_e = 1050$)

turbulence intensity and correlation were made. Although the wake intensities are very sensitive to the magnitude of the background turbulence, the intensity measurements made in the TMB model circulating water channel are of the same magnitude as those obtained in the wind tunnel at the National Bureau of Standards.[2,4] The validity of the correlation data obtained in the TMB facility is uncertain owing to experimental difficulties.

In the second experiment the sensing element was mounted downstream from a rod mounted horizontally across the water channel. As seen in Figure 1, the data obtained from wake traverses behind the cylinder are in good agreement with Townsend's data,[5] if allowance is made for the rather high level of background turbulence in the water channel (about 1 percent).

Preliminary measurements were also made of the decay of turbulence in the TMB towing basin after the passage of a full-form ship model.[1] Although it was difficult to make quantitative measurements under such conditions, it was estimated that after a waiting period of 10 minutes between runs the turbulence level in the basin had decayed to such an extent that it would not affect the resistance measurements.

Although quantitative turbulence measurements in water were difficult and sometimes of doubtful accuracy, the hot wire has been used with great success for qualitative measurements. After the wire has been submerged in water for a few minutes it accumulates a film at a slower rate and it becomes a useful instrument for detecting turbulence where a calibration is not required.

A useful qualitative application of the hot wire was made in an experimental study of various methods of artificially stimulating turbulence in the boundary layer of a tanker model.[1,6] For the purpose of mapping out regions of laminar, transitional, and turbulent flows,

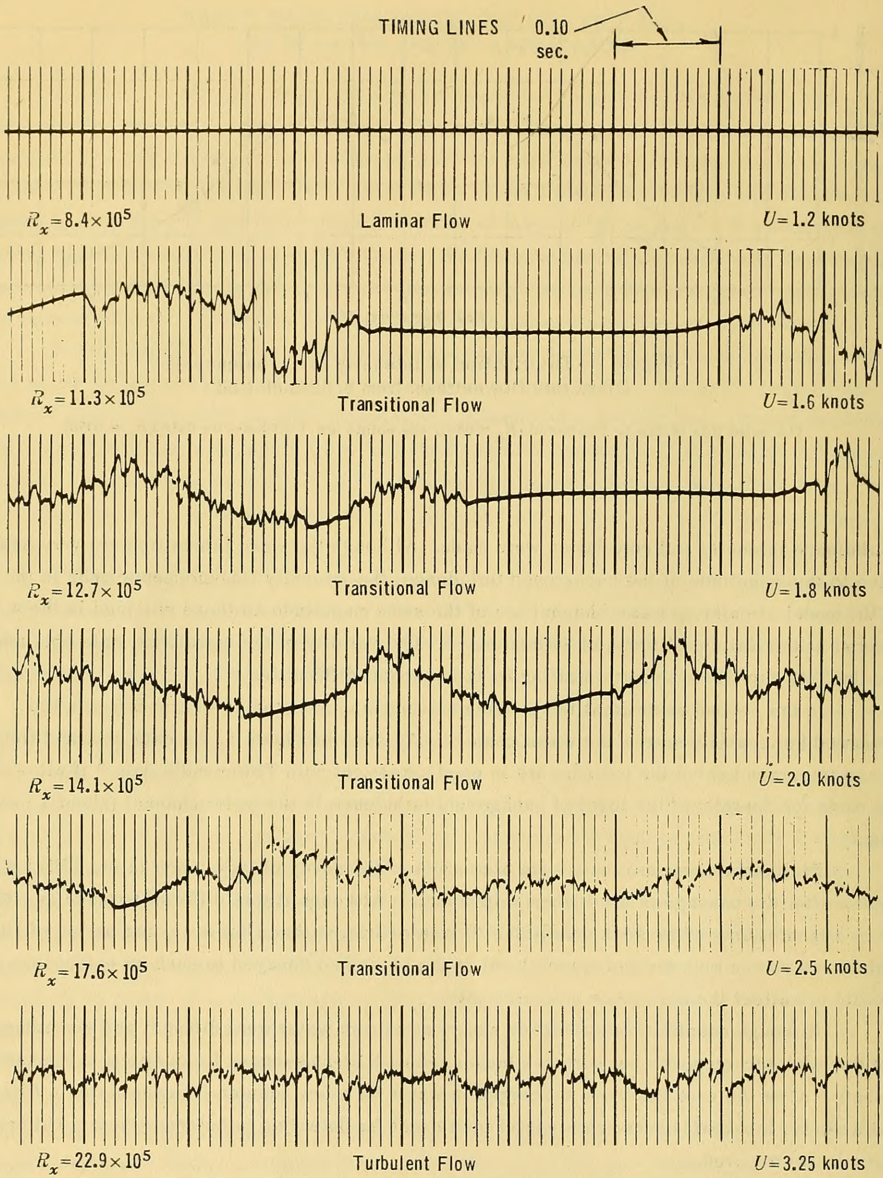

Figure 2 - Oscillogram Records from a Hot-wire Sensing Element
Showing Turbulence in a Boundary Layer

These records show how the hot-wire sensing element gives qualitative detection of turbulence.

removable turbulence-sensing elements were mounted at various positions within the boundary layer on the forebody of the model. Although no information was obtained as to the intensity or scale of turbulence, the oscillogram records clearly delineated the regions of laminar, transitional, and turbulent flow. Typical oscillogram records are shown in Figure 2.

The same qualitative technique has also been used to determine the spanwise phase configuration of vortex shedding behind a cylinder towed horizontally through the water. Following a procedure used by Roshko[7] one element was placed at a fixed point behind the cylinder while a second one traversed the wake along the same horizontal line parallel to the cylinder.

RECENT EXPERIMENTAL INVESTIGATIONS TO IMPROVE WIRE STABILITY

The inherent instabilities of the hot wire as it was developed by Macovsky and Stracke precluded its extensive use for quantitative turbulence measurements in water. Early in 1954, however, interest in obtaining a practical instrument for quantitative turbulence measurements was revived and work on the hot wire was resumed at TMB and also at the Iowa Institute of Hydraulic Research.[8] Efforts at both laboratories were directed toward obtaining a hot-wire instrument which would be as easy to operate in water as in air.

It was discovered independently at both laboratories that much of the wire instability could be eliminated by the use of an alternating heating current. The bubbles which formed on the wire when it was heated with a direct current were largely a result of electrolytic dissociation of the water. As the bubbles formed and broke away erratic changes were produced in the rate at which the wire was cooled by the flow. With an alternating heating current of several thousand cycles per second, however, the bubble formation and the resulting resistance instability were eliminated. Even in highly aerated water bubble formation was no problem.

Even with the elimination of bubble formation enough instability remained to make calibrations uncertain. In order to track down these other instabilities the hot wire was mounted in an a-c bridge circuit and resistance changes could be observed as the bridge became unbalanced. A diagram of the circuit is shown in Figure 3. The heating current was supplied by a power oscillator and the bridge unbalance was observed on an oscillograph. It was necessary to use isolation transformers on the input and output of the bridge to avoid ground loops.

In the preliminary experiments the sensing element was fabricated of 0.3-mil tungsten wire using the same techniques previously developed by Macovsky and Stracke. After all ground loops and electrical pickup had been eliminated an instability persisted which was finally attributed to a galvanic action between the dissimilar metals used in the probe supports, solder, and plating on the wires. Consequently, the old technique of soldering copper-plated tungsten wires to the probe tips was abandoned and unplated tungsten wires were welded directly to the probe holders. The joints and probe holders were painted with a good

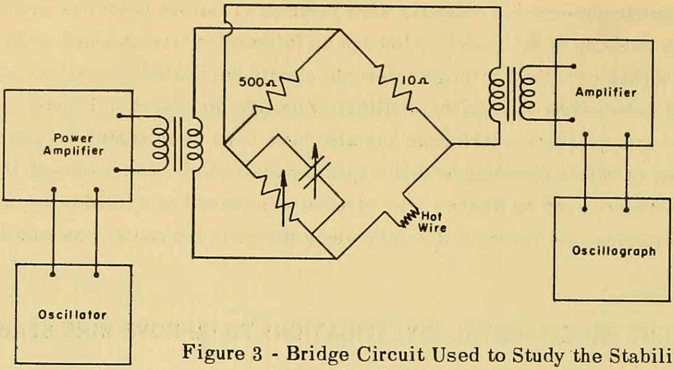

Figure 3 - Bridge Circuit Used to Study the Stability of a Hot Wire in Water

quality insulating material* to cover all dissimilar metals. It was almost impossible to effectively coat the plated portions of the wires if the old technique of mounting the wire was used. Ideally the same metal should be used throughout and the wires should be welded in place. At present, however, the technique for welding tungsten wire to tungsten has not been developed. It may prove worthwhile to reconsider other wire materials which would be easier to weld. For example, platinum or certain nickel alloys might be suitable.

If all the above mentioned precautions are taken it is possible to obtain a wire which is stable for a reasonably long time in well-filtered water. In ordinary water found in test facilities, however, an instability develops as the wire accumulates dirt and hair-like fibers from the water. Dr. Hubbard has found that the film formation is slower in highly turbulent water and is retarded by shaping the wires in a V.[8] In slowly moving streams as in the TMB channel the angle of the wire did not seem to delay the dirt accumulation. Part of the dirt could be swept away by a small stream of water from a syringe,but none of these methods were adequate to maintain a wire calibration which could be relied upon for a practical length of time. It was still necessary to remove the wire at frequent intervals for a thorough cleaning. There had been, however, a large gain in stability over the direct-current wire used in the early work.

DYNAMIC CALIBRATION TECHNIQUES

As it is usually not practical to remove the wire for cleaning very often, it may be necessary to develop a dynamic method of calibration. For example, it may be feasible to superimpose on the flow a known turbulence field immediately before or after each reading. It is important, however, that the imposed turbulence be uncorrelated with the field of turbulence

*The only satisfactory insulating material on hand at TMB for this purpose was liquid Neoprene which requires several hours to dry. Faster drying materials, such as Glyptol or Tygon, were not sufficiently waterproof.

under investigation.* In this instance, if I_t^2 is the mean square of the response to the original turbulence, I_{t+T}^2 the response with the addition of the superimposed field, the signal from the superimposed field alone is

$$I_T^2 = I_{T+t}^2 - I_t^2 \qquad [1]$$

Now since the turbulence corresponding to I_T^2 is known, the turbulence of the stream may be readily obtained without knowing the wire resistance or any of the constants of the amplifier or metering circuits. More important, the accumulation of dirt and surface film on the wire would be unimportant provided the time response of the wire were not seriously impaired.

Mr. Stracke worked for some time on a dynamic calibration technique in which the wire is given a known vibratory motion. The probe was mounted on a specially designed arm which could be mechanically vibrated. The wire moved in a small arc which was essentially parallel to the flow. There are a number of inherent difficulties in this vibration method which were never completely ironed out. First, it is necessary that the vibrator be well designed to eliminate spurious motions so that the displacements and amplitudes can be accurately measured. Corrections must be made for a possible sag in the wire as it moves. As strains in the wire would become excessive if the vibration frequency were too high, it is necessary to limit the frequency to about 10 cycles per second. It is also necessary for the wire, the amplifier, and associated circuits to have a flat frequency response over the turbulence range down to the vibration frequency of the mechanical oscillator. Some of these difficulties may be overcome by comparing the vibration response to the wire response in a known turbulence field, such as that behind a grid or rod. Details of the technique must still be worked out.

Another method of dynamic calibration which has been suggested is to insert a grid or cylinder a known distance ahead of the wire. Since the turbulence of the wake of these objects is already known a calibration could be obtained as before, provided the two turbulence fields are not correlated. The grid or cylinder could be swung in and out of position without disturbing the wire. The principle objection to this method of calibration is that it would be difficult to use in a confined space.

INSTRUMENTATION

Very little work has been done in developing instrumentation for use with the hot wire at the Taylor Model Basin since the early constant-current instruments were procured by Macovsky and Stracke.[3] Although the recent studies were made with a constant-current a-c bridge it would be highly desirable to use a constant-temperature circuit for turbulence measurements. The constant-temperature wire has advantages even though the frequencies of the turbulence fluctuations expected to exist in water are low enough that compensation would not be a serious problem. In flows where the velocity remains constant for only short intervals it would

*An investigation of how two such turbulent fields are correlated will be made in the TMB Low-Turbulence Wind Tunnel.

be inconvenient to have to set the temperature elevation and time compensation of the wire each time. Thus a constant-temperature instrument would be convenient for surveying wakes in the large towing basin or for making measurements in a boundary layer. There would also be no danger of burning out the wire as it is moved into regions of low-velocity flows.

Dr. Hubbard at the Iowa Institute of Hydraulic Research has developed a suitable constant-temperature instrument in which the wire element is heated with a carrier current of several thousand cycles.[8] For this reason no further effort will be expended at TMB in this direction.

SENSITIVITY AND FREQUENCY RESPONSE OF A COATED HOT-WIRE ELEMENT IN WATER

Since a hot-wire element acquires a surface film when it is used in water a theoretical study was made to determine how the sensitivity and frequency response of the wire are affected by the film.[9] As an aid in determining the magnitudes of the quantities under consideration Tables 1 and 2 were prepared which list the physical properties of several flow mediums and wire materials. Since the physical constants depend upon the precise composition of the particular sample, the reference is given in each case. In these tables the constants stand for the following quantities:

a	Radius of film on wire
b	Radius of wire
c_p	Specific heat at constant pressure
r_0	Sensitivity of wire at temperature T_0
R_0	Total resistance of wire at temperature T_0
T_0	Reference temperature
α	Temperature coefficient of resistance
κ	Thermal conductivity
ρ	Density
σ	Tensile strength of wire

When subscripts are used with these parameters, 1 refers to the wire, 2 to the coating, and 3 to the flow medium. In addition to physical constants the tables include useful combinations of these constants, some of which will be defined later. As many of these quantities include the wire diameter, the numerical values refer to a 1 mil wire and d is the wire diameter in mils.

If a hot wire is placed in a stream of fluid which is moving with a constant velocity, the relation between the rate of convective cooling and the electric power supplied to the wire is given by King's law.[15] When the wire has a film or coating King's law may be written as

TABLE 1

Useful Constants of the Flow Medium

Units	Fresh Water 20°C Ref 10	Sea Water 20°C Ref 10	Air 0°C Ref 11
κ_3 cal (cm sec °C)$^{-1}$	1.43×10^{-3}	1.34×10^{-3}	0.533×10^{-4}
κ_3 joule (cm sec °C)$^{-1}$	5.98×10^{-3}	5.60×10^{-3}	2.23×10^{-4}
c_{p_3} cal (gm °C)$^{-1}$	1.00	0.993	0.24
ρ_3 gm cm^{-3}	1.00	1.025	1.293×10^{-3}
U_0 cm/sec	$0.0896 \frac{b}{ad}$	$0.0825 \frac{b}{ad}$	$10.76 \frac{b}{ad}$
$U_0^{-1/2}$ (ft/sec)$^{-1/2}$	$18.4\sqrt{\frac{ad}{b}}$	$19.2\sqrt{\frac{ad}{b}}$	$1.68\sqrt{\frac{ad}{b}}$

TABLE 2

Useful Constants of Wire Materials

Units	Platinum Ref 12	Pt-Ir Ref 13	Tungsten Ref 12	Nickel Ref 12
σ 1000 lb in.$^{-2}$	35	145	500	46
α (°C)$^{-1}$	0.0035	0.00085	0.0045^7	0.0069
r_0 10^{-6} ohm-cm	11.4	32.9	5.5	6.84
T_0 °C	20	20	20	20
ρ_1 gm cm^{-3}	21.45	21.6	19.3	8.9
c_{p_1} cal (gm °C)$^{-1}$	0.0314	0.032	0.032	0.112
κ_1 cal (cm sec °C)$^{-1}$	0.165	0.042	0.48	0.22
R_0/l ohm cm^{-1}	$2.25\, d^{-2}$	$6.50\, d^{-2}$	$1.077\, d^{-2}$	$1.35\, d^{-2}$
$\kappa_2 l/\alpha R_0$ (amp)^2 *	$0.759\, d^2$	$1.048\, d^2$	$1.223\, d^2$	$0.644\, d^2$
m (amp)^2 sec *	$0.0108\, d^4$	$0.0149\, d^4$	$0.0173\, d^4$	$0.00913\, d^4$

*Numerical values given here for $\kappa_2 l/\alpha R_0$ and m are based on a flow medium of fresh water.

$$I^2 R_w = \kappa_3 l (T_a - T_e)\left(\sqrt{\frac{U}{U_0}} + 1\right) \qquad [2]$$

where

$$U_0 = \frac{\kappa_3}{2\pi a\, \rho_3 c_{p_3}} \qquad [3]$$

In these equations and in the derivations to follow

- I is the heating current,
- R_w is the average wire resistance,
- l is the wire length,
- T_a is the temperature at film surface,
- T_b is the temperature at wire surface,
- T_e is the ambient temperature of fluid,
- T_w is the average temperature of wire, and
- U is the flow velocity.

The wire resistance is related to the average temperature of the wire T_w by the equation

$$R_w = R_0[1 + \alpha(T_w - T_0)] \qquad [4]$$

It will be convenient to represent the temperature elevation of the wire by an overheating ratio a_w defined as

$$a_w = \frac{R_w - R_e}{R_e} = \frac{\alpha R_0 (T_w - T_e)}{R_e} \qquad [5]$$

where R_e is the wire resistance at the temperature T_e. Even though the temperature elevation of the wire may be large, the temperature elevation at the surface of the film may be much lower. Therefore it will be convenient to define an effective overheating ratio as

$$a_s = \frac{\alpha R_0 (T_a - T_e)}{R_e}$$

Then King's equation may be written in terms of a_s and a_w

$$I^2 = \frac{a_s}{1+a_w} \frac{\kappa_3 l}{\alpha R_0}\left(\sqrt{\frac{U}{U_0}} + 1\right)$$

From Reference 9 it can be shown that the steady-state temperatures at the inner and outer surfaces of the coating are related by the equation

$$T_b - T_e = (T_a - T_e)\left[1 + \frac{\kappa_3}{2\pi\kappa_2}\left(\sqrt{\frac{U}{U_0}} + 1\right)\log\frac{a}{b}\right]$$

If the thermal conductivity of the wire κ_1 is very much larger than κ_2 the temperature is nearly uniform within the wire and T_w may be substituted for T_b. For this approximation

$$a_s = \frac{a_w}{1 + \frac{\kappa_3}{2\pi\kappa_2}\left(\sqrt{\frac{U}{U_0}} + 1\right)\log\frac{a}{b}}$$

It is clear that a film on a wire will impair its sensitivity, particularly at high velocities. If $I^2\alpha R_0/\kappa_3 l$ is plotted against $\sqrt{U/U_0}$ for the same value of a_w but for different film thicknesses, the family of curves shown in Figure 4 is obtained. Only the curve for no film is linear. As the velocity becomes infinite the different curves approach the asymptotic values

$$I^2 \frac{\alpha R_0}{\kappa_3 l} = \frac{a_w}{1+a_w} \frac{2\pi\kappa_2}{\kappa_3 \log a/b}$$

The larger the coating ratio a/b and the lower its thermal conductivity, the more quickly the curves flatten off and the less sensitive the wire becomes. All the curves would be linear if it were possible to keep the ratio $a_s/(1 + a_w)$ constant instead of a_w.

The sensitivity of the wire in responding to a change in velocity U or a change in ambient temperature T_e is obtained by differentiating King's equation with respect to U and T_e. Then the response of a constant-current wire becomes

$$\frac{\Delta R_w}{R_w} = -\frac{a_s}{1+\sqrt{U_0/U}} \frac{\Delta U}{2U} + \frac{\alpha \Delta T_e}{1+\alpha \Delta T_e}$$

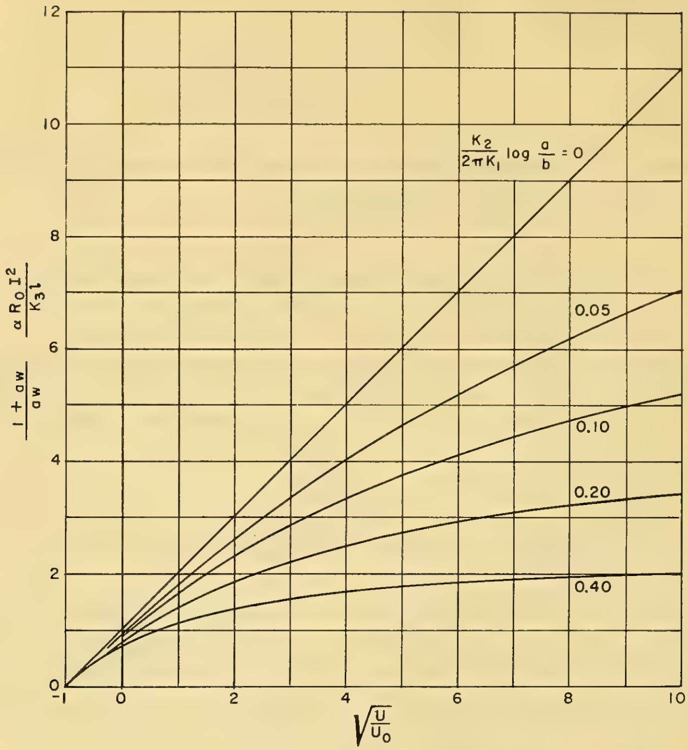

Figure 4 - Effect of a Surface Film on the Sensitivity of a Hot Wire

The response of a constant-temperature wire becomes

$$\frac{\Delta I}{I} = \frac{1}{2a_w} \left[\frac{a_s}{1 + \sqrt{\frac{U_0}{U}}} \frac{\Delta U}{U} - \frac{\alpha \Delta T_e}{1 + \alpha \Delta T_e} \right]$$

If a_s is small in these equations the wire may be just as sensitive to temperature fluctuations as to velocity fluctuations. In the towing tanks at TMB there is sometimes a temperature difference of about 10 F over a 20-ft depth, and some thermal microstructure may be expected when the water is disturbed. A hot wire must be used with caution in such facilities.

The response of a bare constant-current hot wire to a step-like change in convective cooling is given to a very good approximation by a simple exponential function

$$\Delta T_w = \Delta T_w^* \left[1 - e^{-t/M}\right]$$

where ΔT_w^* is the final temperature change produced by initiating disturbance. The time constant has been derived by Dryden and Keuthe and may be written in the form[15]

$$M = m \frac{a_w}{I^2} = \frac{\pi b^2 l \rho_1 c_{p_1}}{\alpha R_0} \frac{a_w}{I^2}$$

Values of m which depend only on constants of the wire materials are listed in Table 2.

The response of a bare constant-current hot wire to a step-like change in current input is also given by a simple exponential function. To the approximation used here, the time constant for a change in current input is the same as the time constant for a change in convective cooling.[9]

The frequency response of a system is defined as the frequency for which the response is attenuated 70.7 per cent. Furthermore, if the response of a system to a step function is given by a simple exponential function with time constant M, the frequency response is $1/2\pi M$. If a hot wire for use in water has a diameter less than one mil, it will have a frequency response of several hundred cycles. If a higher frequency response is desired, a suitable compensation circuit may be used. As the frequency response of a bare wire to a change in current is the same as that for a change in convective cooling the elements of the compensation circuit may be adjusted by applying a time-varying current input of the desired frequency to the wire.

If the wire has a coating or acquires a film the response of a constant-current wire is no longer a simple exponential function but is given by an infinite sum of exponential terms.[9] If the coating is not too thick the sum converges rapidly and an equivalent time constant may be found as the time in which the exponential portion decays to e^{-1} of its initial value. In this case the time constant for a step-like change in convective cooling is greater than the time constant for a change in current input. Therefore it would not be possible to fully correct for the time lag by adjusting the elements of the compensation circuit to obtain a good frequency response to a time-varying current input.

Even a constant-temperature wire has a time lag in responding to a change in convective cooling if the wire is coated or acquires a film.[9] If the film thickness is less than half the wire diameter the time constant under probable operating conditions is no greater than the time constant of a bare constant-current wire of the same diameter. Therefore, a thinly-coated constant-temperature hot wire should have a reasonably good frequency response when it is used in water. The simple method of setting the elements in a compensation circuit for a constant-current hot wire can not be used here, as a constant-temperature wire responds with no time lag to a change in current input.

SUMMARY AND CONCLUSIONS

As a result of research done at the Taylor Model Basin and the Iowa Institute of Hydraulic Research over the years, a hot-wire instrument for making turbulence measurements in water under controlled conditions has been developed. It is essential that the wire be heated with an alternating current to prevent electrolytic action and that only the wire metal be exposed to the water. Unless the wire supports and joints are of the same metal as the wire these must be covered with a good waterproof insulation to prevent galvanic action. With these precautions the wire is stable enough for quantitative turbulence measurements in well-filtered dust-free water.

Although the wire is stable in clean water it acquires a surface film when it is used in ordinary water such as that found in most test facilities. The rate at which the film forms depends upon the degree of contamination of the water. The usefulness of the hot-wire element for practical purposes appears to depend upon the development of a satisfactory method of dynamic calibration. Although film formation will decrease the wire sensitivity and frequency response, a coated wire may still be useful for turbulence measurements. If the wire is used in a constant-temperature circuit the decrease in frequency response should not be serious until the film thickness exceeds half the wire diameter.

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