

INFLUENCE OF TURBULENCE ON SURFACE REAERATION

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PREFACE

This interim termination report covers the period from April, 1965, through June 1, 1966, on the project "Influence of Turbulence on Surface Reaeration." This project has been sponsored in part by the U. S. Department of the Interior, Office of Water Resources Research, and the Water Resources Center, University of Illinois, as authorized under the Water Resources Research Act of 1964, Public Law 88-379. The Department of Civil Engineering, University of Illinois, also contributed to the support of this project.

Renewal of the project for f.y. 1967 had already been granted by the Water Resources Center when the principal investigator received approval to accept a temporary position under the Ford Foundation's program of Faculty Residencies in Engineering Practice. This position required him to be away from the University from June, 1966, until September, 1967. Thus, this report covers progress made before the principal investigator's departure. A proposal has been submitted for a continuation of this project during the 1967-68 academic year. If the proposal is approved, a final report will be prepared at the termination of the project.

This report covers primarily the experimental work which has been done. Most of the theoretical work is incomplete at this time and therefore will only be discussed in the final report.

Since this is an interim report, no conclusions are presented.

ABSTRACT

Some numerical methods are briefly described for determining vertical diffusion coefficients as a function of vertical coordinate in a turbulence vessel where there are no net velocities. It is planned to use this turbulence vessel and these numerical methods to study in detail the mechanics of diffusion of a substance (analogous to oxygen) which is absorbed at the free surface.

A hot-film anemometer is to be used to make direct measurement of turbulence parameters affecting the diffusion process. The anemometer has been calibrated in water which was in solid body rotation. Some of the difficulties experienced with the hot-film sensor and the corrective measures which were used are discussed. Preliminary diffusion tests have been made in the turbulence vessel where turbulence is generated by vertically oscillating screens made of expanded metal. Some values of the vertical diffusion coefficient have been calculated from the data for two of these preliminary runs.

Plans call for making more detailed diffusion studies and for making direct turbulence measurements in studying surface reaeration.

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1) INTRODUCTION

The rivers and estuaries of our country are serving as a disposal place for large amounts of municipal and industrial waste materials. Often, someone downstream from a disposal point wishes to use the water which has been contaminated. The amount of self-purification of the water as it flows is one of the controlling factors on the amount of pollutant which can be put into a natural waterway or on the use which can be made of the water downstream. Often dissolved oxygen is required to be present in the water for this purification process to take place. One significant source of dissolved oxygen is surface reaeration, that is, the natural phenomenon of the water's absorbing oxygen from the atmosphere.

Reaeration has been studied at least since 1925 when the pioneer work of Streeter and Phelps was reported (1). Since that time work on this problem has continued both in the field and in the laboratory with some of the more recent work reported in references 2 through 10. A review of much of this work is presented in ref. 7. In spite of all this work, there is still no generally applicable method to predict reaeration rates from mean flow parameters (e.g., velocity, area, stream slope, bed roughness, etc.). Before such a method can be produced, it seems essential to understand the fluid mechanisms which influence reaeration. It has been recognized, at least since Streeter and Phelps's work, that the turbulence which is present in the water is one of the factors influencing reaeration rates. To the writers' knowledge, no one has yet sought to observe in detail what happens to a substance which is absorbed at the free surface of turbulent water or to measure the turbulence itself and correlate turbulence characteristics

with observed reaeration rates. It seems beneficial to study the mechanisms which influence reaeration so that they can serve as a basis for seeking a relation between mean flow parameters and reaeration rates.

Thus, the objectives of this research are (1) to study the details of the downward transport (diffusion) of a substance which has been absorbed at the free surface of turbulent water and (2) to measure directly the turbulence characteristics near the free surface of turbulent water.

The most significant part of the downward diffusion of dissolved oxygen in turbulent water is that which occurs in the few millimeters just below the water surface. To the writers' knowledge, there is no sensor which is physically small enough to allow the resolution needed in measuring dissolved oxygen concentrations in this small region. Since small temperature sensors are available, heat is being used as a tracer to study the diffusion downward from a free surface. A situation analogous to that for oxygen absorption is created for the laboratory study. In a vessel where turbulence is artificially generated in water, the air over the water is heated above the water temperature. This temperature difference causes heat to be absorbed by the water at the free surface and diffused downward just as it occurs with oxygen in the reaeration process. The sides and bottom of the vessel are insulated to prevent heat loss. Temperatures are measured in the water as a function of time and distance below the free surface. This detailed temperature data will be used to study the diffusion characteristics. Some data has been obtained on temperature profiles (section 4.3) and some preliminary analysis of this data has been done. It is anticipated that more data will be collected and that more detailed analysis of the data will be undertaken.

It is planned to use a constant temperature hot-film anemometer to measure turbulence directly in the region immediately below the free surface. The anemometer has been calibrated as discussed in section 3.2 but no turbulence measurements have been made.

2) SOME METHODS FOR DETERMINING THE DIFFUSION COEFFICIENT

2.1) General Equation

For the case of a conservative substance which is absorbed at the free surface of turbulent water and diffused downward in the absence of any net velocities, the equation for the conservation of that substance may be written (ref. 11, p. 627-9) as

$$\frac{\partial c}{\partial t} = \frac{\partial}{\partial y} \left(e_y \frac{\partial c}{\partial y} \right) \quad 2.1$$

where c is the concentration of the substance (turbulent fluctuations having been averaged out), e_y is the vertical diffusivity for the substance under consideration, y is the vertical coordinate measured positively upward from the bottom of the water, and t is time. In this expression, e_y is considered to be a function of y . If c is measured as a function of y and t , this data may be used to calculate the eddy diffusivity and thereby gain some insight into the characteristics of the turbulence which is present.

2.2) Finite Difference Method

Eqn. 2.1 may be viewed as an equation in y - t space, and this space may be divided into a grid as shown in fig. 2.1, with a constant Δy and Δt

between the grid points. If e_y is assumed to be constant over the small range of $2\Delta y$, eqn. 2.1 may be written in approximate (finite difference) form using values of c at the grid points:

$$\frac{c_{i,j+1} - c_{i,j}}{\Delta t} = e_y \frac{c_{i+1,j} - 2c_{i,j} + c_{i-1,j}}{(\Delta y)^2} \quad 2.2$$

In this expression, the subscripts i and j refer, respectively, to the values of y and t at which c is to be evaluated. A forward difference was used to represent $\partial c / \partial t$, and a forward then a backward difference to represent $\partial^2 c / \partial y^2$. Measured concentrations may be used in eqn. 2.2 to solve for e_y . This method may be used under any conditions for which eqn. 2.1 is valid, provided the assumptions stated above are acceptable. The larger Δy and Δt are, the less accurate is the finite difference approximation for the derivatives. The smaller Δy and Δt are, the more data has to be collected.

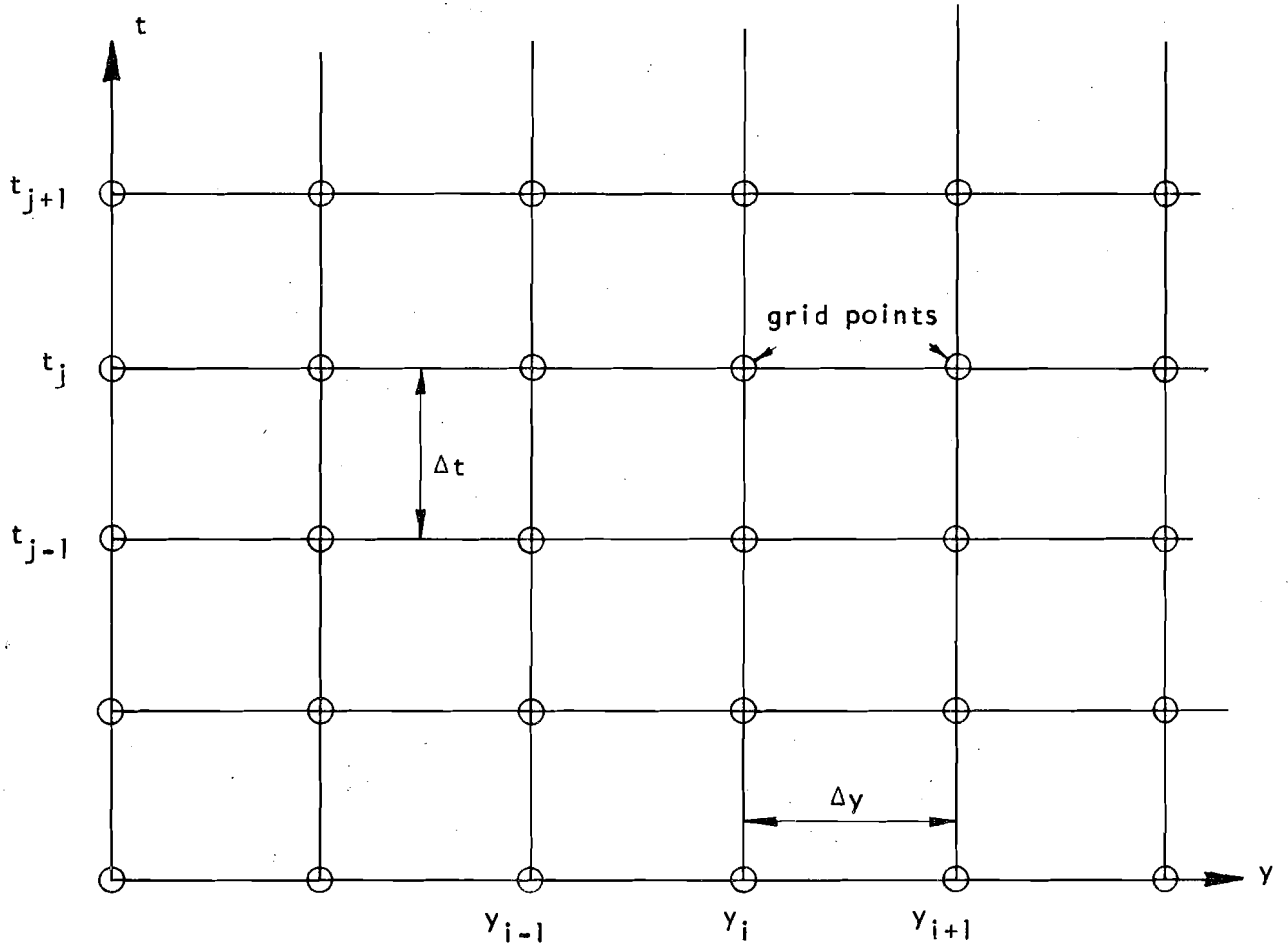


Fig. 2.1: Finite difference grid in y-t space

2.3) Integration Method

2.3.1) General

Eqn. 2.1 may be integrated with respect to y from zero to y_1 to give

$$\int_0^{y_1} \frac{\partial c}{\partial t} dy = \left(e_y \frac{\partial c}{\partial y} \right)_{y=y_1} - \left(e_y \frac{\partial c}{\partial y} \right)_{y=0} \quad 2.3$$

This expression implies that a fixed time is used to evaluate the various terms. If conditions are such that none of the diffusing substance can be transported across the bottom, then the last term in eqn. 2.3 must be zero since it represents the flux of the substance at $y=0$ (ref 11, p. 629).

Thus,

$$\left(e_y\right)_{y=y_1} = \frac{\int_0^{y_1} \frac{\partial c}{\partial t} dy}{\left(\frac{\partial c}{\partial y}\right)_{y=y_1}} \quad 2.4$$

By evaluating $\partial c/\partial t$ from the data for the chosen, fixed time, then integrating this with respect to y , e_y may be calculated. The finite difference method may be used to evaluate the derivatives and numerical integration probably will be needed to perform the integration indicated.

$$2.3.2) \quad \underline{c(y,t) = f(y) + g(t)}$$

Consider the case of

$$c(y,t) = f(y) + g(t) \quad 2.5$$

where f is a function of y only and g is a function of t only. Eqn. 2.5 implies that c is a function of both y and t , but that $\partial c/\partial y$ (i.e., the rate of change of c with respect to y) is a function of y only. This situation might arise, for example, where the surface concentration changes with time but where the diffusion is rapid enough so that the concentration for any y changes at the same rate as the surface. Substitution of eqn. 2.5 into 2.1

gives

$$g'(t) = \frac{d}{dy} \left(e_y f'(y) \right)$$

Since this equation states that a function of t only (the left-hand side, LHS) is equal to a function of y only (RHS), then each function must be equal to a constant (say A):

$$g'(t) = A \tag{2.6}$$

$$\frac{d}{dy} \left(e_y f'(y) \right) = A \tag{2.7}$$

Integrating eqn. 2.6 shows that $g(t)$ is, at most, a linear function of t , i.e., $g(t) = At + B$, where B is a constant of integration. This implies that the concentration at the surface or at any other y (say y_1) must increase linearly with time since

$$c(y_1, t) = f(y_1) + At + B$$

The rate of increase of c at any y_1 can be used to evaluate the constant A . With $\partial c / \partial t = g'(t) = A$ and with the last term in eqn. 2.3 equal to zero as before, the numerator of equation 2.4 can be integrated so that

$$(e_y)_{y=y_1} = \frac{Ay_1}{\left(\frac{\partial c}{\partial y} \right)_{y=y_1}} \tag{2.8}$$

Under these conditions, it is necessary to use the finite difference scheme only to evaluate $\partial c/\partial y$.

2.3.3) Steady State

If the data indicates that a steady state (i.e., $\partial c/\partial t = 0$) exists before equilibrium (i.e., $c = \text{constant}$) has been reached, then continuity of the diffusing substance requires that some of the substance must be moving across some other boundary in addition to the free surface. In this case, the last term on the RHS of eqn. 2.3 probably would not be zero and eqn. 2.4 would not be valid. However, the LHS of eqn. 2.1 would be zero and eqn. 2.1 could be integrated once with respect to y giving

$$e_y \frac{dc}{dy} = b \quad 2.9$$

where b is a constant. If e_y and dc/dy are known at some y , b can be found. The gradient at other values of y (i.e., dc/dy) can then be used to evaluate e_y as a function of y . The constant b is proportional to the vertical flux of the diffusing substance. The exact relation between the constant in eqn. 2.9 and the vertical flux depends on the way in which the concentration c is defined. (See ref. 11, Chap. 20.)

It is anticipated that one or more of these methods will be used to analyze the concentration data which is collected. Thus, it will be possible to obtain numerical values of the diffusion coefficient and to study the downward diffusion of a substance which is absorbed at the free surface.

3) TURBULENCE MEASUREMENTS BY HOT-FILM ANEMOMETRY

Anemometry techniques have been employed for making high frequency velocity measurements in fluid flows. Anemometry will be used in this re-aeration study to measure characteristics of turbulence produced by oscillating screens in a water-filled tank where surface absorption and downward diffusion are being investigated. The anemometer gives essentially instantaneous, point velocity readings in the form of a continuous output voltage. Operations on this continuous voltage signal will give turbulence measures such as an RMS value of the velocity fluctuations.

3.1) Equipment

The anemometer used in these experiments is the Heat Flux System Model 1010 manufactured by Thermo-Systems Incorporated of Minneapolis, Minnesota. This system is a constant temperature anemometer which may be used with either hot-film or hot-wire sensors. The sensor used has been a Thermo-Systems' hot-film sensor (NT-26-QW-10). This is a 0.001" diameter quartz coated platinum-film sensor with a sensitive length of 0.020".

The sensor has a temperature coefficient of approximately 0.014 ohms/°C. The anemometer maintains the sensor at a constant temperature (hotter than the surrounding fluid temperature) by supplying varying electrical power to the sensor. As the cooler fluid flows past the sensor, heat is transferred away from the sensor and more power is required to keep the sensor heated to the given constant temperature. The amount of power required to maintain the sensor at the given temperature under a certain set of flow conditions is a measure of velocity past the sensor. As can be seen

from the anemometry circuit (fig. 3.1), the sensor is one leg of a Wheatstone bridge. Under normal operating conditions the bridge will be at Balance for only one flow condition. For all other flow conditions the bridge must operate slightly off balance in order for there to be a signal from the bridge.

3.2) Calibration

3.2.1) Principle

It was assumed that the calibration obtained from measurement of a steady-state velocity with a low turbulence level would also be valid for instantaneous velocity measurements in a more turbulent state of flow. The steady-state velocity for calibration was achieved by rotating a water-filled circular tank about its center until the fluid was rotating as a solid body.

3.2.2) Equipment

a) Calibration Tank: The rotating circular tank is a stainless steel tank 18" in diameter and 6" deep. A 5/8" diameter stainless steel shaft is connected to the inside of the tank at its center as shown in the schematic diagram of the anemometer calibration tank (fig. 3.2). The 5/8" diameter shaft is rotated by a 1/2" horizontal shaft through a right angle (6:1) gear and pinion. The 1/2" shaft is belt-driven by a 1/8 horsepower (at 1725 RPM) Bodine shunt wound D.C. motor used in conjunction with a Minarik SH53 speed controller. The 1/2" shaft may also be rotated by the speed controller and the same type motor with an integral 40:1 gear

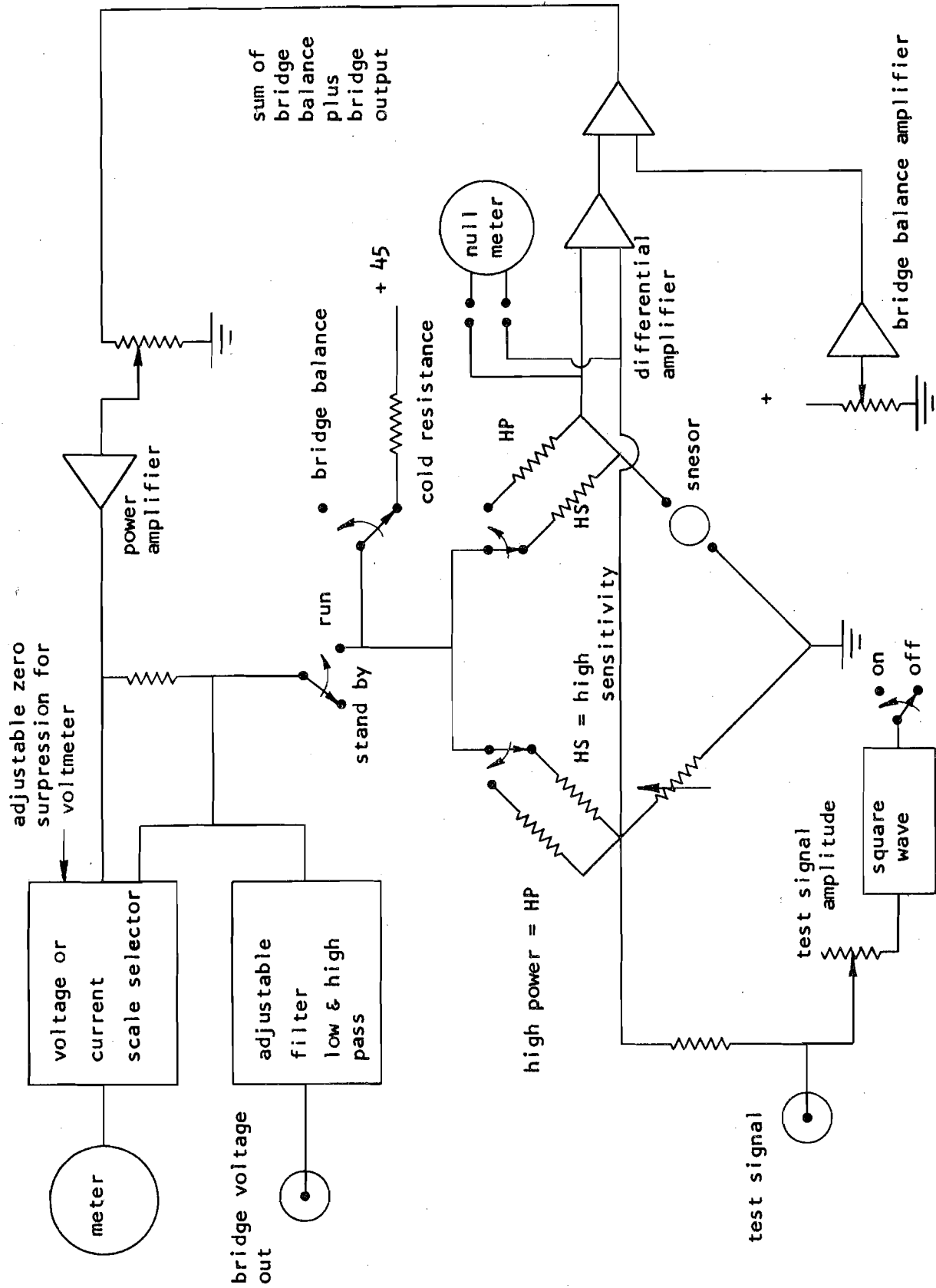


Fig. 3.1 - Anemometry Circuit

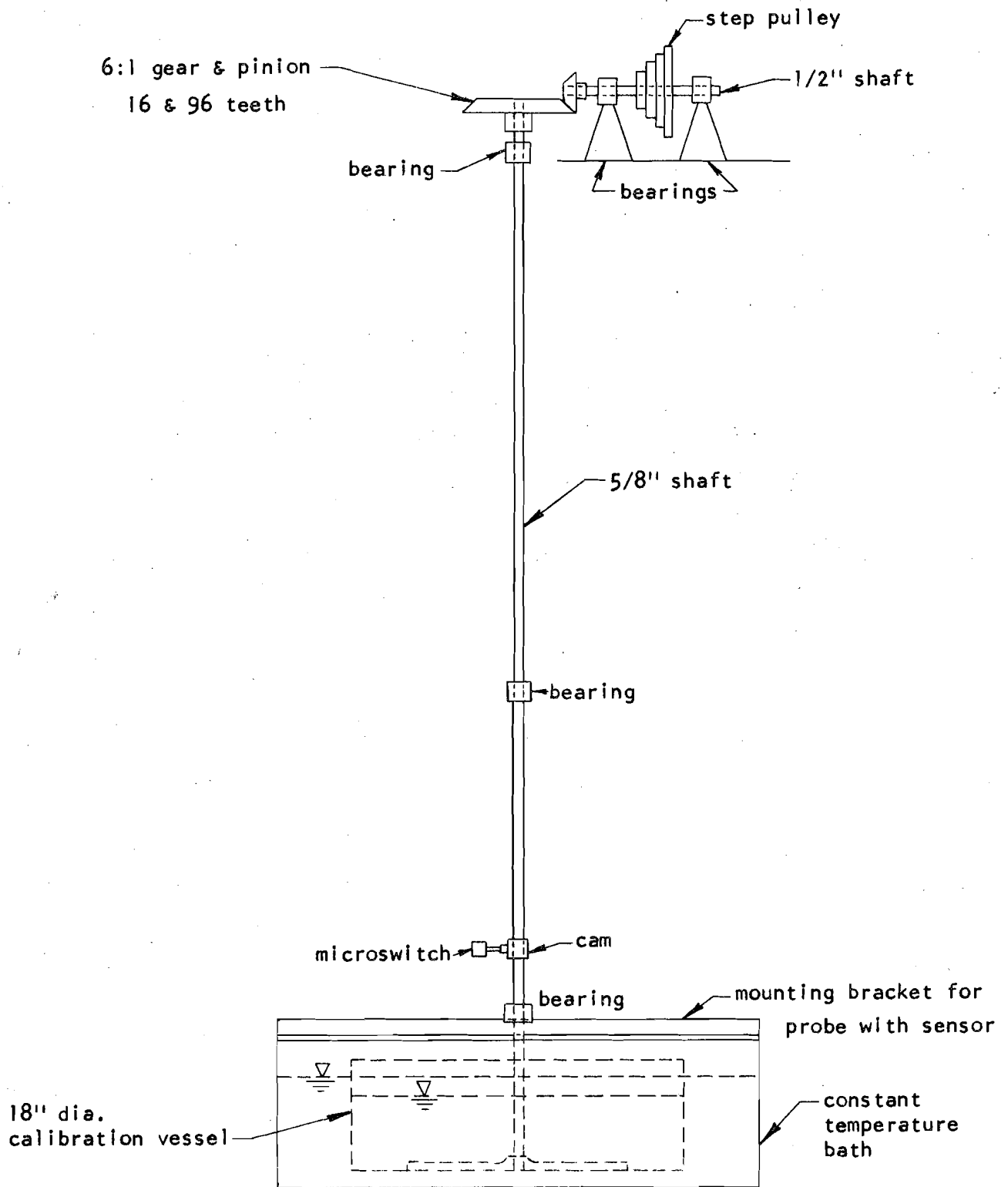


Fig. 3.2 - Schematic diagram of anemometer calibration tank

reduction. These two motors and a 2, 3, 4, 5" step pulley on the 1/2" horizontal shaft give the circular tank a continuous RPM range from 0.15 to 288. The minimum and maximum radii at which the sensor can be placed for calibration are 0.22' and 0.71'. Thus, a velocity range of 0.0035 ft/sec to 21 ft/sec is possible.

b) Constant Temperature Bath: A 3/4" plywood box (26" x 26" x 9" deep) fitted with a 28 gauge galvanized liner serves as a constant temperature bath for the rotating circular tank. The circular tank rotates while partly submerged in the constant temperature bath. A 1/8" plexiglass sheet is used to cover the temperature bath as well as the circular tank. A Yellow Springs Instrument Company Thermistor Controller (#2165) used in conjunction with a 2175-1 Thermistor Probe controls two 250-watt knife-type immersion heaters to maintain the temperature bath and the water in the circular tank at a constant temperature.

3.2.3) Calibration Procedure

The initial step in the calibration procedure was to clean and rinse, very thoroughly, all equipment which might contaminate the water in the calibration tank. The calibration tank, temperature bath, and plexiglass cover were then put in place. Water was added to the temperature bath until the water surface was within 1" of the top of the circular tank. The 1/8 horsepower motor, without the 40:1 gear reduction, was used to rotate the calibration vessel and thereby circulate the water in the bath while the two 250-watt heaters were used to bring the water in the temperature bath to the environment temperature (25.0°C). While the water in the temperature bath

was being brought to 25.0°C, distilled water in a 5 gallon jar was being heated to 25.0°C by inserting one 250-watt knife-type immersion heater into the jar. The distilled water was then poured into the circular tank to about a 4" depth. The motor with the 40:1 gear reduction was then used to rotate the circular tank since calibration was to be run at the lower end of the tank's RPM range. Thermo-Systems' N25-12 miniature probe, with the hot-film sensor, was attached to the mounting brackets at a given radius. The sensor was installed about 1" from the bottom of the circular tank with its 0.02"-sensitive length aligned along a tank radius. The distance from the center of the tank to the middle of the sensor was measured. A cam on the 5/8" vertical drive shaft was adjusted to a point where it would momentarily close a micro-switch each quarter-revolution. The micro-switch operated a Redington Electric Counter (2-1006) and the counter and an electric timer were turned on and off at the same time by a common switch. This was the system used for RPM measurement.

The anemometer unit was then turned on and allowed to stabilize, which took about five minutes. From the time since the water was first poured into the circular tank until this point, the water temperature was periodically checked and the temperature controller adjusted to maintain the water at 25.0°C. Sensor resistance at the environment temperature (25.0°C) was measured. An "overheat ratio" $\left(\frac{R}{R_e}\right)$ of 1.1 was used in the calibrations. This gave an operating temperature of 67.7°C for the sensor. The sensor resistance is related to the sensor operating temperature by a temperature coefficient of resistance (ρ) as follows:

$$R = R_e \left(1 + \rho (t_s - t_e) \right)$$

where:

R_e = cold resistance = resistance of sensor at environment temperature

R = operating resistance of sensor

t_s = operating temperature of sensor

t_e = sensor's environmental temperature

ρ = temperature coefficient for sensitive element of hot-film (0.00234/°C for Thermo-Systems' film sensors)

If vaporization of the water is to be prevented, the operating temperature can not be above 100°C. This places a limit on the sensitivity which can be obtained in water measurements.

Calibration was completed by correlating the anemometer bridge voltage with a velocity past the sensor.

At each velocity the bridge was adjusted to a balanced condition (i.e., the signal voltage originated entirely from the bridge balance amplifier). As previously mentioned, the bridge will be at least slightly off balance during turbulence measurements. Thus, the calibration which was obtained with the bridge balanced at each velocity was compared with measurements made with the bridge unbalanced. These results are presented in section 3.2.5.

3.2.4) Operating Problems and Solutions

a) The Effect of Gas Bubbles and Other Foreign Particles:

The initial attempts at calibration of water velocity against bridge voltage

were not encouraging. Bridge voltage, at a given velocity, was not a constant but rather seemed to be a function of how long the sensor had been in the calibration tank. At first it appeared that dirt accumulation on the sensor, especially lint type fibers, was entirely responsible for this change in bridge voltage with time although the water used for calibration had been filtered. Also the calibration vessel was covered and an enclosure was built around the entire experimental apparatus so that only filtered air could enter the area. All of these precautions did not completely eliminate the problem of drift in the output voltage. Some calibrations were attempted by cleaning the sensor intermittently by brushing it, while submerged, with a small camel hair brush. Calibration curves established this way were reliable but brushing of the sensor was awkward in the calibration tank and undesirable, even if possible, during experiments.

Under closer inspection of the sensor while in operation, very small gas bubbles were observed to be accumulating on the sensor. The hot-film was evidently bringing the water's dissolved gases out of solution. It was then decided to use distilled and deionized water in the tank. The water was used shortly after it came from the still while it was yet low in dissolved gases. This essentially eliminated the necessity for cleaning the sensor during a calibration and it is felt that the same will be true during the experiments.

Accumulation of dissolved gases and dirt (usually lint fibers) affects the hot film's velocity calibration. In general, it was observed that if both lint fibers and dissolved gases are present in the water into which the film is placed, the dissolved gases will have a more adverse effect upon the calibration at the lower velocities and the dirt, at the higher velocities. The distinction between higher and lower velocities is

not a clear cut one but, in this study, it appeared to be at about 0.4 ft/sec.

The effects due to dirt and gas bubbles were separated by observing the sensor appearance and the bridge voltage reaction at different velocities. At low velocities, accumulation of bubbles on the sensor was apparent and when these bubbles were noticed, the bridge voltage started increasing more or less continuously by as much as one volt in 15 seconds. These bubbles appear to increase the effective diameter of the sensor and thereby increase the rate of heat transfer. At higher velocities, accumulation of lint fibers on the film caused the bridge voltage to decrease in jumps. The lint fibers appear to insulate the film and lessen the heat transfer. At the higher velocities it seems logical that the gas bubbles would have a more difficult time clinging to the film while the lint fibers would simply loop around the film.

b) Sensor Cold Resistance Change: The cold resistance of a hot-film sensor may change for at least two basic reasons: either (1) the sensor's environmental temperature may change or (2) the sensor's physical characteristics may change (e.g., the quartz coating may wear through or crack and corrosion or other chemical effects may then cause the cold resistance to change). Thermo-Systems' instruction manual for the Heat Flux System Model 1010 gives several procedures for correcting the calibration if the sensor's cold resistance changes between a calibration and a test run. Compensating circuits are also available to maintain a constant overheat ($t_s - t_e$) but another correction may still have to be applied if t_e changes enough to cause a significant change in fluid properties. When the cold resistance changes during a calibration or test, corrections are much harder to apply.

The changes due to the physical characteristics of the sensor are the most important in these experiments since environmental temperature is controlled by temperature baths. A change in cold resistance from 10.39 to 10.49 ohms has been observed during calibration in a constant temperature environment. If an overheat ratio of 1.1 were set at the beginning of a test using the initial cold resistance, the change in resistance would cause the sensor's operating temperature to change from 67.7°C to 59.2°C. This is about a 20% change in the overheat for water at 25.0°C.

The calibration results indicate that if the sensor resistance changes between calibrations, a constant overheat ratio will give the same calibration curve. (See fig. 3.3.)

3.2.5) Results of Calibration

The calibration curve for one sensor was run with the bridge at balance for every velocity (fig. 3.3). This balancing at each flow velocity was done by adjusting the output from the bridge balance amplifier at each flow velocity until the null meter indicated the bridge to be at balance. It is not possible to have the bridge always at balance in turbulence measurement and it is generally recommended that the sensor be balanced at about the average velocity when making measurements in turbulent flows. In calibration no. 5 (table 3-1), the difference between the steady-state velocity readings (i.e., bridge voltages) at balanced and unbalanced conditions was observed. The errors shown for the reading in the unbalanced condition are relatively large. However, the turbulent fluctuations in velocity are normally only a few percent of the average velocity (at which the bridge may be balanced). Thus, the degree of unbalance in turbulence measurements

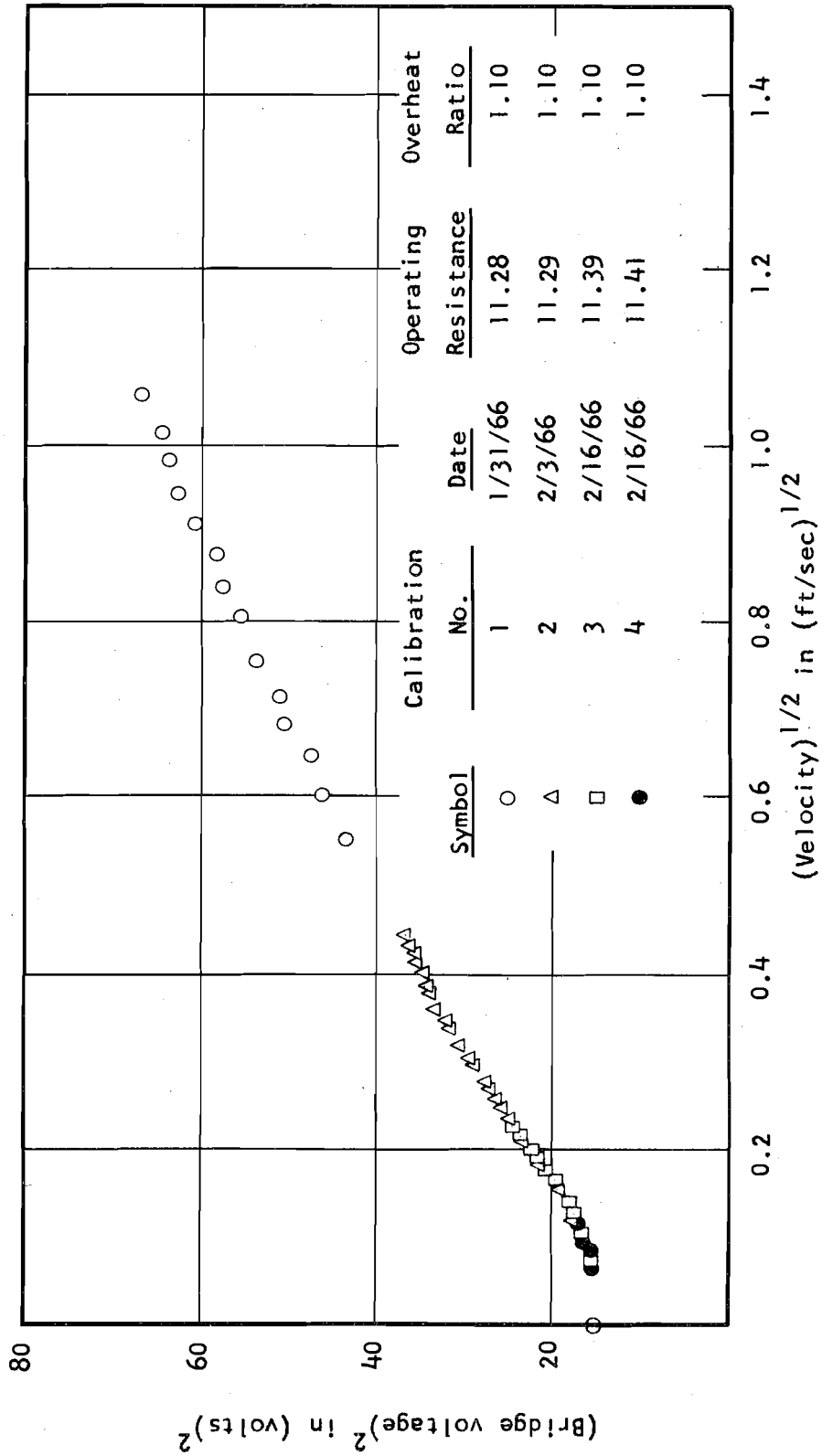


Fig. 3.3 - Anemometer calibration

should be much less than those used in obtaining the data in table 3-1.

Table 3-1. Comparison of balanced and unbalanced calibration of anemometer system.

Steady-State Velocity (FPS)	Balanced only at Velocity = 0.00 (FPS)		Balanced only at Velocity = 0.0358 (FPS)		Balanced only at Velocity = 0.127 (FPS)		Balanced only at Velocity = 0.180 (FPS)	
	V_1^*	% Error ^{**}	V_1^*	% Error ^{**}	V_1^*	% Error [*]	V_1^*	% Error ^{**}
0.0187	0.0177	-5.3	0.0204	+9.1	0.0204	+9.1	0.0219	+17.1
0.0358	0.0346	-3.3	0.0358	0.0	0.0373	+4.2	0.0372	+3.9
0.111	0.108	-2.7	---	---	---	---	---	---
0.127	0.123	-3.1	---	---	0.127	0.0	0.132	+3.9
0.180	0.175	-2.8	---	---	---	---	0.180	0.0

V_1^* = Velocity read from the calibration curve for balanced conditions using the signal (B_v) for the given unbalanced conditions.

% Error^{**} = Percent error between the actual steady-state velocity and V_1^* .

4) TURBULENCE TANK STUDIES

4.1) Equipment

4.1.1) Turbulence Tank

The turbulence tank is a 20" x 12" x 12" deep vessel in which stainless steel screens are oscillated vertically to produce turbulence. The six screens (flattened expanded metal, 1/2" no. 16) have a vertical spacing of 1" and are driven by four 5/16" rods. (See fig. 4.1.) The tank is a product of Jewel Aquarium Company of Chicago. It consists of a metal frame with

Step pulley
& flywheel
on 1/2" shaft
behind rotating
disk

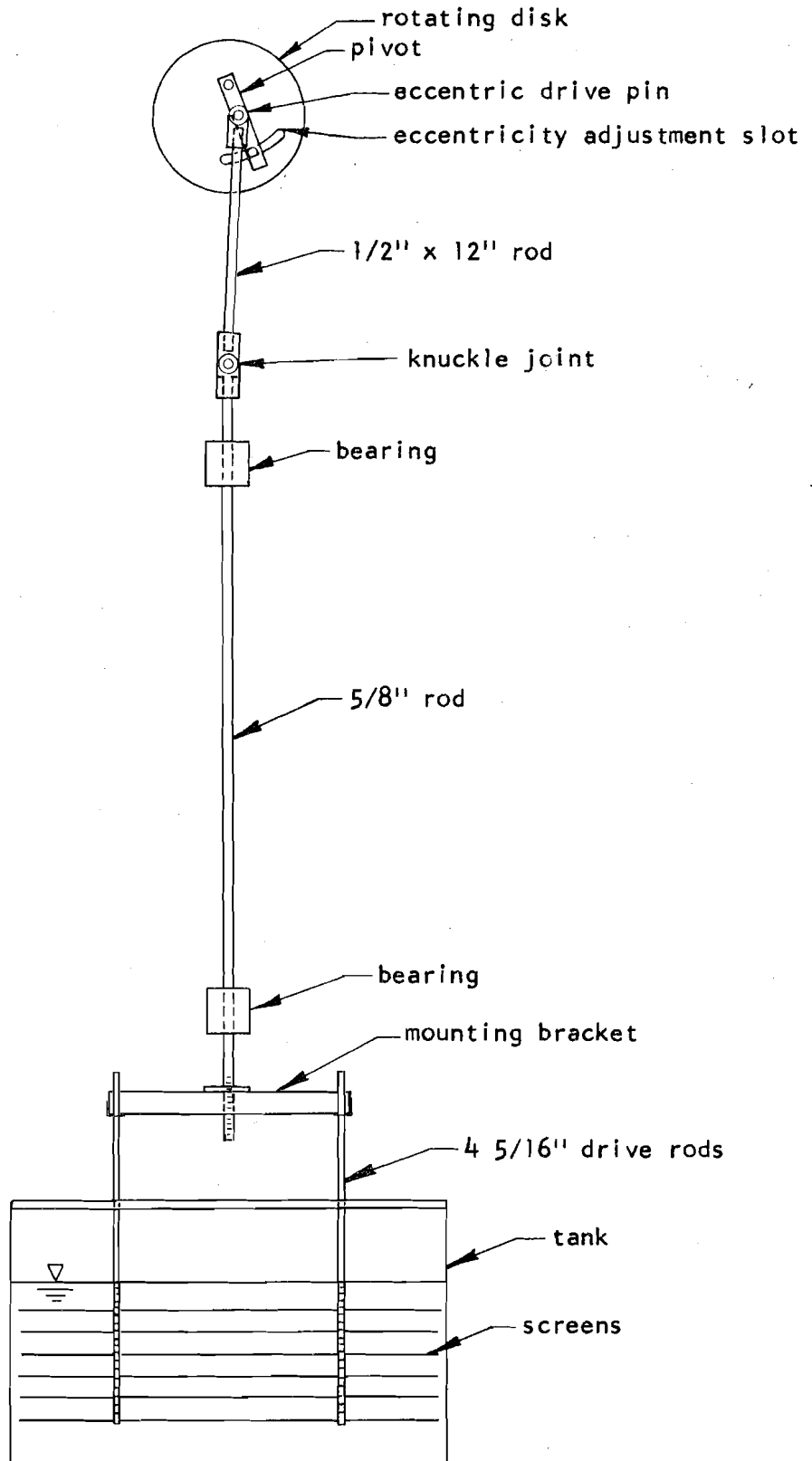


Fig. 4.1 - Schematic diagram of turbulence tank

1/8" glass walls and a 1/4" glass bottom.

The screens are fastened with nuts and washers to the four 5/16" threaded stainless steel rods, which extend through the screen openings. The top screen has a nut and washer only on its lower side. A clear Hysol epoxy cement was used to fasten the nut and washer to the screen. This arrangement allows the top screen to come close to the water surface without having a nut on top of the screen which would break the water surface. Each stainless steel rod is threaded 5-1/4" for the screen attachments and 6" for adjustment at the mounting bracket. The top screen is tightened against the end of each rod's threads.

a) Variability: The same two motors which are used to drive the anemometer calibration vessel (section 3.2.2) provide the power to oscillate the screens. By using either a 1" or 2" V-belt pulley on the motor to drive a 2, 3, 4, 5" step pulley, a continuous screen speed adjustment from 1 to 1725 RPM is possible. The anticipated range of operation is from 50 to 400 RPM.

The term "stroke" will refer to the distance between the extremes of the vertical screen movement. A slot in the rotating disk permits continuous stroke adjustment from zero to 1-7/8". Experiments at a 7/16" stroke have been run thus far.

The "screen distance" was measured from the water surface to the upper surface of the top screen at the top of its motion. This "screen distance" is dependent upon the stroke and the water depth. The screen distance can be changed from a previous setting by adjustment of the rods in the mounting bracket slots or by adding or withdrawing some water. The latter method was usually used.

b) Air Space Temperature Control: The turbulence tank has a 3/8" plexiglass cover. The air space over the water is heated above both the water temperature and the room temperature by the use of two 100-watt silicone-rubber-embedded heating tapes. A Yellow Springs Instrument Company Thermistor Controller (model 63RA) used in conjunction with a 2175-1 Thermistor Probe controls the heaters to maintain the air space at a constant temperature.

c) Tank Insulation: The turbulence tank sits in an open plywood box (26" x 38" x 10" deep) which is used to keep four thicknesses of insulation (Ward's Glass Fiber 3") in place around the sides of the tank and one thickness beneath. The average thickness of the insulation around the sides of the tank was 8". The insulation is used to lessen heat exchange between the water and sources other than the heated air space above the water surface.

4.1.2) Temperature Measurement

In this study heat is being used as a tracer to investigate the mechanics of diffusion downward from a free surface of turbulent water. In order to do this, a temperature measuring device which will give "instantaneous, point" temperature measurements is necessary.

a) Equipment: The temperature sensor is a 0.014"-dia., glass-coated, bead thermistor (Fenwal Electronics, Framingham, Massachusetts, no. GC32J1). It was mounted at the end of an 18"-long plexiglass tube (O.D. = 1/4" and I.D. = 1/16").

As shown in fig. 4.2, the sensor is one leg of a Wheatstone bridge. The bridge is connected to a Sanborn recorder (model 140) and is a.c. excited. The 0.018 microfarad capacitance in the top leg of the bridge provides capacitive balance for the system. Voltage across the sensor was restricted to less than 30 millivolts in order to keep the sensor from heating more than 0.01°C above its surroundings. An ammeter (\pm 50 milliamps) is used to indicate when the bridge is balanced. The ammeter circuit has a coarse and fine switch which refers to the sensitivity of the circuit.

Usual operation of the temperature measuring device is to balance the bridge with the thermistor at a known temperature using the 1000 ohm potentiometer and then to lock this potentiometer. Temperature measurement is accomplished using the 100 ohm potentiometer to bring the bridge back to balance as the resistance of the thermistor changes due to temperature changes. The 100 ohm fixed resistor can be added to the circuit to give a total variation of 200 ohms in one leg of the bridge. This allows temperature measurement over a range of 3.7°C from the balance point.

b) Calibration of Temperature Measuring Device: The device was calibrated over the temperature range of 25.00°C to 28.50°C. A four-liter beaker, insulated on the bottom and sides, was used as a temperature calibration tank. A 250-watt knife-type heater was placed in the beaker and connected to a Variac for temperature control. A rheostat-controlled stirrer was used for circulation of the water within the beaker. Water temperature was measured with a calorimeter thermometer (ASTM 56c) which was marked directly to 0.02°C.

The temperature probe was inserted into the beaker keeping the sensor away from the glass walls and the water surface. With the Sanborn recorder in the "coarse" setting and the resistance in the leg opposite the sensor initially set at 2200 ohms, the 1000 ohm potentiometer was adjusted to

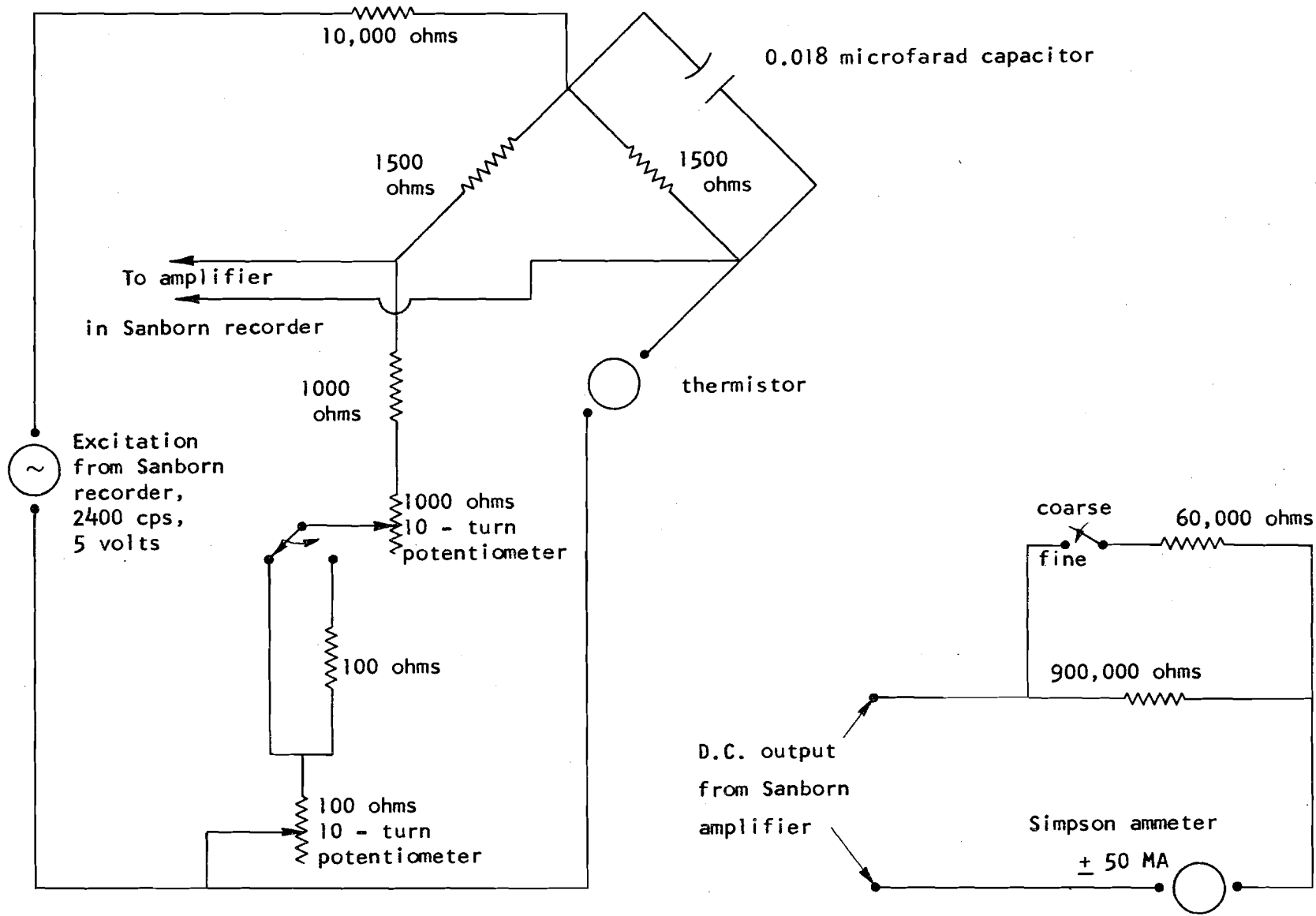


Fig. 4.2 - Circuitry for temperature measurement

balance (i.e., the point of maximum deflection to the right on the milliammeter) and locked. This balancing was done with the beaker water temperature at 25.00°C. The water temperature was measured with the calorimeter thermometer bulb within 1/4" of the thermistor sensor. The Sanborn recorder was then switched to its "fine" setting and its zero knob was used to set the milliammeter at midscale. Calibration was then completed by changing the water temperature in increments and by bringing the milliammeter back to its reference point (i.e., the bridge back to balance) by adjusting the 100 ohm potentiometer with the 100 ohm resistor switched into or out of the bridge leg as required. In this manner, a calibration of temperature versus resistance was obtained (fig. 4.3).

The data for the calibration curve was taken on two different days with one day's lapse in between. The time interval over which each day's data was taken was about 4-1/2 hours. A plot of water temperature versus the sum of the 100 ohm potentiometer setting and the fixed 100 ohm resistor (either zero or 100) revealed that the data could be represented by two straight lines with a slope break occurring at 26.75°C. Envelope lines drawn on the graph show that the data falls within $\pm 0.05^\circ\text{C}$ of the straight lines established for calibration. (See fig. 4.3.)

4.2) Evaluation of Secondary Mechanisms of Heat Transfer to the Water

Since heat was being used as a tracer to measure diffusion rates, it was necessary to investigate possible heat losses from the turbulence tank.

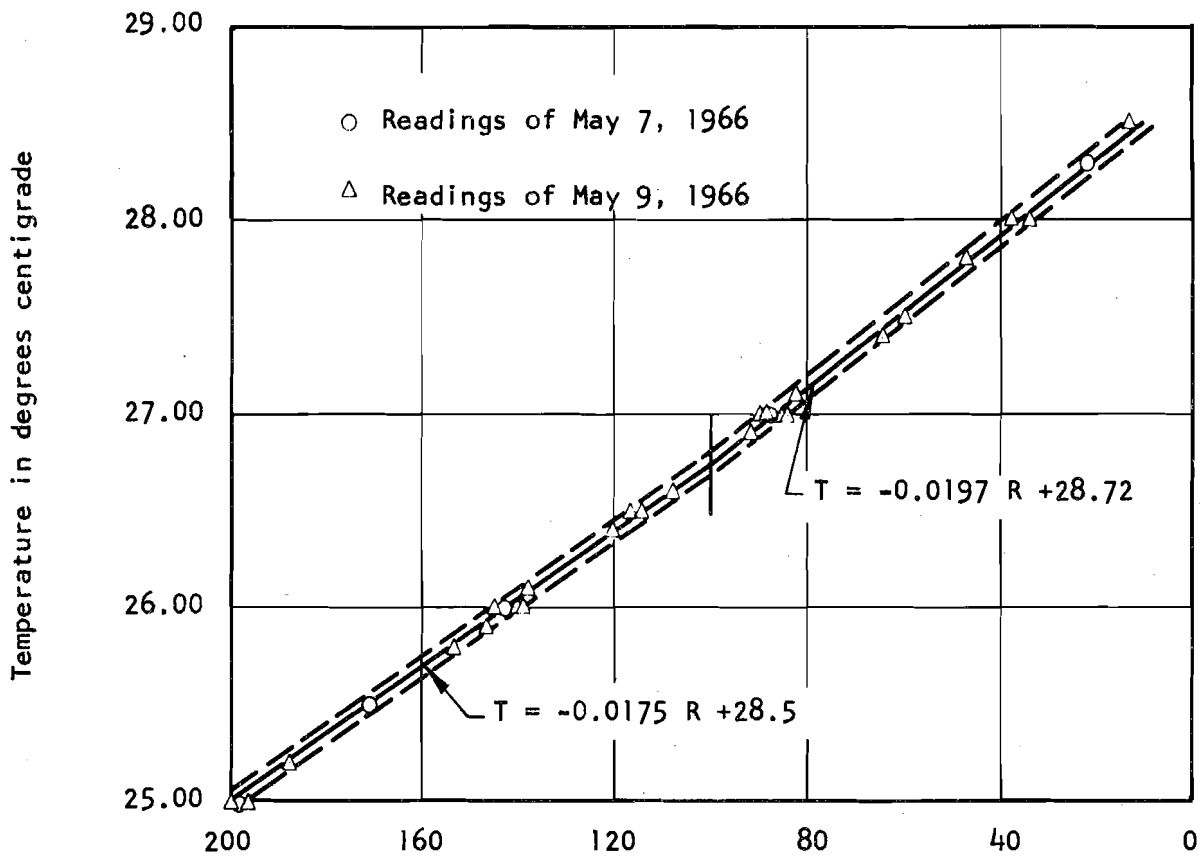


Fig. 4.3 - Calibration of thermistor

4.2.1) Heat Transfer Through the Turbulence Tank's Glass Walls

The bottom of the tank was insulated with one thickness of Ward's 3" fiberglass insulation and the sides, with four thicknesses of the insulation. Assuming that the tank has 7" of water in it and that a 10°C temperature difference exists between the water and the room air, the rate of heat loss at steady-state diffusion through the insulation would give a temperature change in the water of approximately 0.04°C/hr. In this calculation it was assumed that the glass walls were at the water temperature. Normally the temperature difference between the water and room air was less than 10°C, and the heating rate for the water was much more than 0.04°C/hr. Thus, it was concluded that this is a negligible source of heat transfer.

4.2.2) Heat Transfer Down the Turbulence Tank's Glass Walls and the 5/16" Stainless Steel Drive Rods

Analytical solutions to these heat transfer problems were attempted but the solutions required several questionable assumptions. Thus, experimental techniques to determine these effects were tried.

The air space inside the tank was heated to 45°C. A 3/4" plywood board was floated on the water surface to reduce the amount of heat transfer at this surface. The board had a 45° chamfer around it to enable the glass walls to heat just as they would if the board were not present. The point of the chamfer met and fit snugly against the glass walls at the water surface. The screens were oscillated at 245 RPM with a stroke of 1/2" and a screen distance of 1/8". The experiment indicated that, with 7" water depth and a 20°C temperature difference between the water and the heated air space,

heating of the water due to the heat transfer down the glass walls and stainless steel rods was at the rate of about $0.2^{\circ}\text{C}/\text{hr}$. This figure takes account of calculated transfer through the plywood and to the environment. A similar experiment with a plexiglass cover on the water surface indicated a negative heat transfer down the walls and rods. It is planned to check this possible source of error more thoroughly. For the time being, this is assumed to be a negligible source of error since the heating rates during the experiments were of the order of $1^{\circ}\text{C}/\text{hr}$.

4.3) Experiments to Determine Diffusion Coefficients

4.3.1) Procedure

Water was added to the turbulence tank and heated to about 25.0°C while the temperature measuring device was balanced at 25.0°C in the temperature calibration setup and the temperature calibration curve was checked at a few temperatures. Bronze wire mesh (18 x 14) extending $1/2''$ inward from the glass walls at the water surface was installed around the inside of the tank. This mesh was to dampen the surface waves. Stroke, RPM, and water depth measurements were taken in the tank. The screens were stopped and the air space was heated to a given temperature. Three thermometers were extended through the plexiglass cover at distributed points to measure the air space temperature. The temperature probe was mounted in a point gauge above the plexiglass cover at about the middle of the tank's length and $3-1/4''$ in from one side. When the air space reached the desired temperature, the point gauge was used to locate the water surface and the screens were again started. Measurements of temperature at given depths and times were then taken. The air space tempera-

ture was checked periodically. At the experiment's end, the temperature probe was again placed in the temperature calibration tank and the calibration curve was checked. The calibration checks at the beginning and end of each run showed that the thermistor gave readings within $\pm 0.05^\circ\text{C}$ of the calibration curve.

4.3.2) Experimental Measurements

Experimental measurements have been made in the turbulence tank with different screen distances, RPM, and air space temperatures over a range of water temperatures as shown below:

Run No.	Stroke (inches)	Screen Distance (inches)	RPM	Air Space Temperature $^\circ\text{C}$	Water Temperature Range Due to Surface Heating, $^\circ\text{C}$
1	7/16	1/8	210	38	25.8 - 27.0
2	7/16	1/8	200	36	25.3 - 26.0
3	7/16	3/8	208	42	25.9 - 26.4
4	7/16	3/8	200	42	26.0 - 27.0
5	7/16	7/8	200	41	25.4 - 26.2
6	7/16	7/8	100	41	25.4 - 26.2

The data for runs 5 and 6 is shown in fig. 4.4 and 4.5 respectively. The last two experiments have been repeated and fairly consistent results have been obtained. The temperatures at the water surface are always the least reliable and the least consistent.

From the experimental data taken thus far, it appears that the temperature versus time data for various depths gives a set of parallel straight

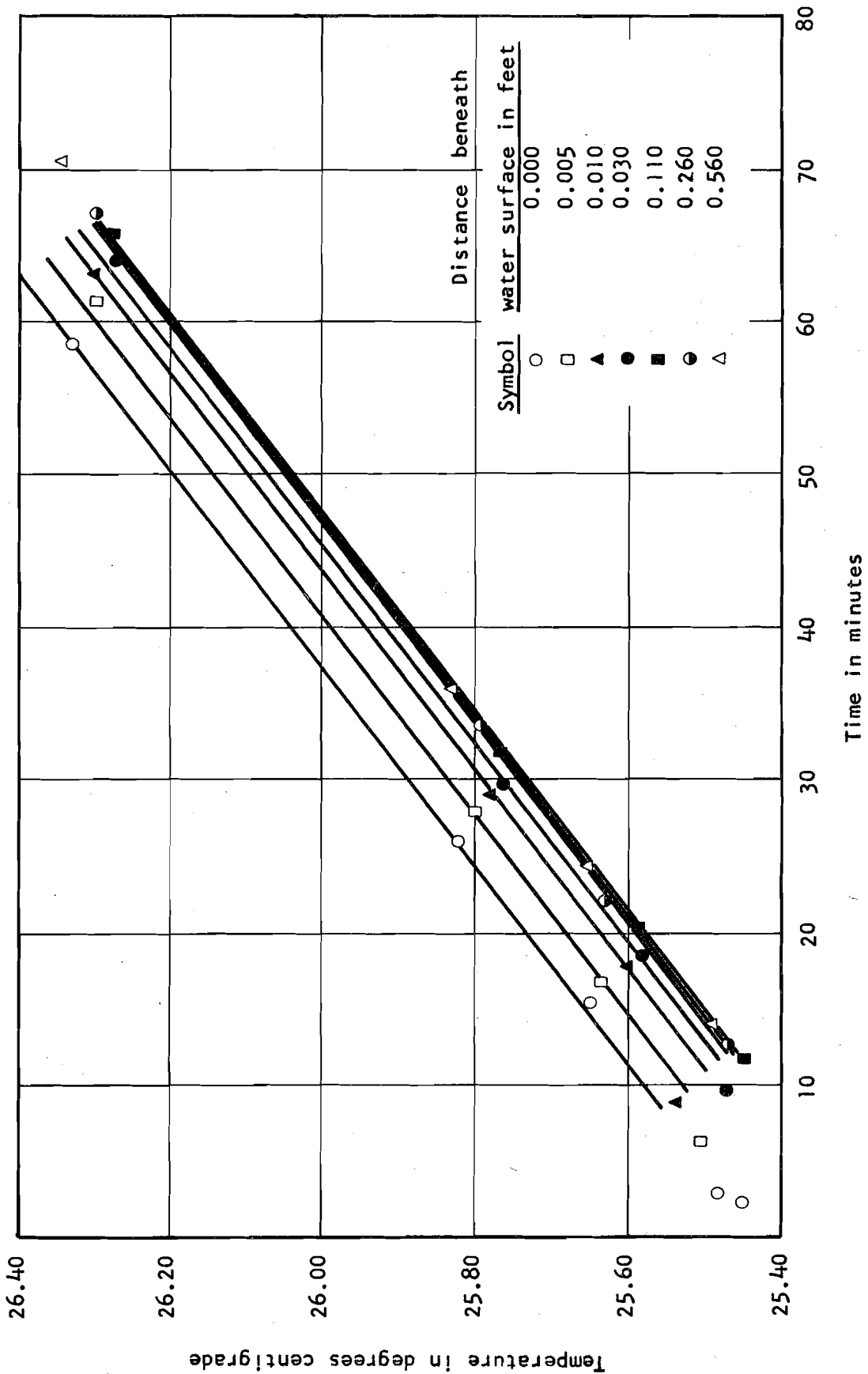


Fig. 4.4 - Temperature data - run 5

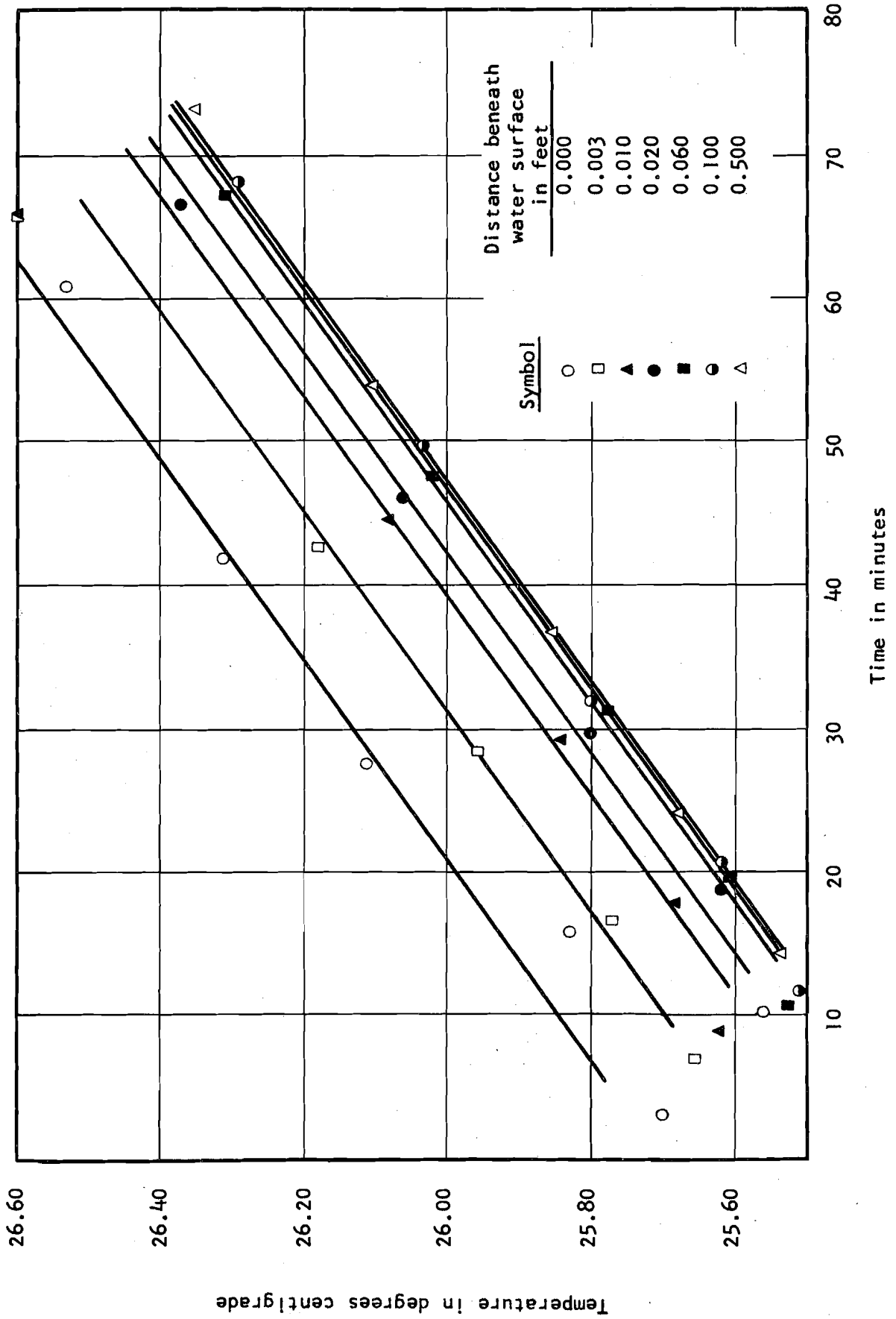


Fig. 4.5 - Temperature data - run 6

lines, that is, the heating rates ($^{\circ}\text{C}/\text{time}$) are the same at all depths at a given time and are approximately constant for a given run. The existence of this linear and parallel relation indicates that $\partial c/\partial y$ is not a function of time. Thus, at each instant in time, the diffusion behaves essentially as a steady-state process for the temperature which exists at the water surface for that instant. This, in turn, indicates that the downward diffusion of heat is rapid enough to provide effectively instantaneous response to temperature changes at the free surface. For lower turbulence levels in the water, this linear and parallel relationship might not exist.

Using eqn. 2.8, with the water temperature taken as the concentration, diffusion coefficients were computed from runs 5 and 6 with the coefficients for run 5 ranging from $2.56 \times 10^{-4} \text{ ft}^2/\text{min}$ near the free surface to $4.64 \text{ ft}^2/\text{min}$ in the region occupied by the screens. For run 6 the range was $4.47 \times 10^{-5} \text{ ft}^2/\text{min}$ to $0.572 \text{ ft}^2/\text{min}$. The molecular heat diffusivity is about $1 \times 10^{-4} \text{ ft}^2/\text{hr}$ (ref. 11, p. 248). Precise experimental values of the diffusion coefficient are hard to determine for these preliminary runs since not enough data was collected to allow accurate determination of the gradients needed. (See section 2.) It is planned to take more complete data in future tests so that a better evaluation of the diffusion coefficient can be made.

Fig. 4.6 shows the vertical profile of temperature for runs 5 and 6. These profiles were plotted by reading points off the straight lines drawn in fig. 4.4 and 4.5.

Temperature in degrees centigrade

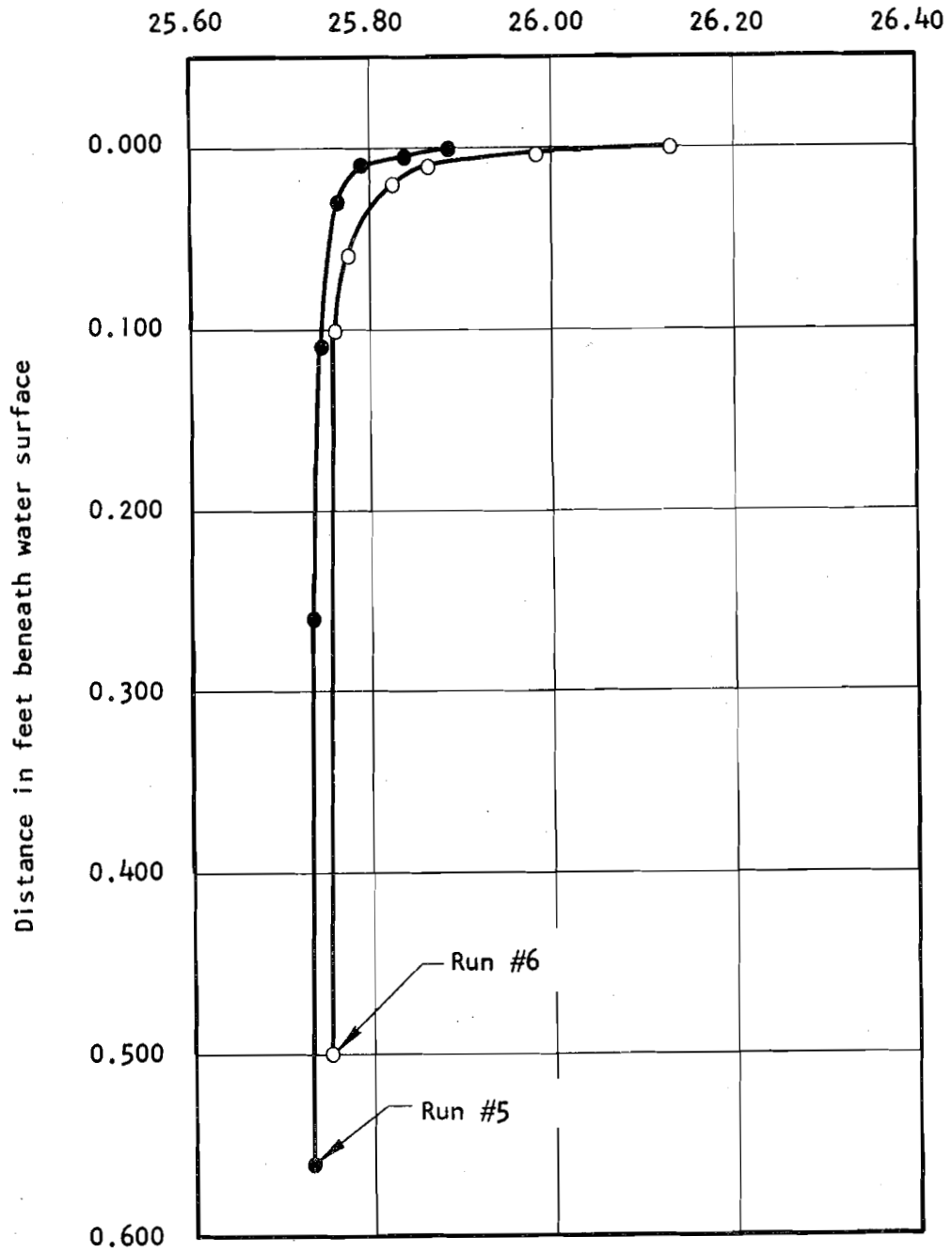


Fig. 4.6 - Temperature profiles at 30 minutes - runs 5 and 6

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LIST OF SYMBOLS

<u>Symbol</u>	<u>Definition</u>	<u>Dimension</u>
A	constant	
B	constant	
B_v	anemometer bridge voltage	
b	constant	
c	concentration	
e_y	vertical diffusivity	L^2/T
FPS	feet per second	L/T
f	function of y	
g	function of t	
i	subscript indicating value of y at which quantity is to be evaluated	
j	subscript indicating value of t at which quantity is to be evaluated	
RPM	revolutions per minute	
R	operating resistance of hot-film sensor at t_s	
R_e	resistance of hot-film sensor at t_e	
t	time	T
t_e	temperature of environment in which hot-film sensor operates	
t_s	operating temperature of hot-film sensor	
y	vertical coordinate measured upward from bottom of tank	L

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