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RESPONSE TIME CORRELATIONS FOR  
PLATINUM RESISTANCE THERMOMETERS  
IN FLOWING FLUIDS

Dhirendra K. Pandey and Robert L. Ash

OLD DOMINION UNIVERSITY RESEARCH FOUNDATION  
Norfolk, Virginia

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## FOREWORD

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## LIST OF SYMBOLS

$D_{sh}$	Sheath diameter, m
$h$	Heat transfer coefficient based on sheath diameter $D_{sh}$ , watt/m <sup>2</sup> k.
$k$	Thermal conductivity, watt/m k
MPE	Maximum Percentage Error defined as $= 100 \times \frac{(\tau_E - \tau_{predicted})}{\tau_E}$
$Pr$	Prandtl number, $\mu C_p/k$
$Re$	Reynolds number, $\frac{D_{sh} \cdot U \cdot \rho}{\mu}$
$T$	Temperature, °C
$V$	Flow velocity, m/sec
$x_1, x_2$	Gap between the sheath and the sensing element
$\mu$	Dynamic viscosity, kg/m.sec
$\rho$	Density, kg/m <sup>3</sup>
$\tau$	Time Constant, second

### Subscripts

a	Air
E	Experimental
HK	Hashemian and Kerlin
O	Oil
OA	Oil and Air
W	Water
WO	Water and Oil
WOA	Water, Oil and Air

RESPONSE TIME CORRELATIONS FOR  
PLATINUM RESISTANCE THERMOMETERS IN FLOWING FLUIDS

By

Dhirendra Kumar Pandey<sup>1</sup>, Co-Principal Investigator  
Robert L. Ash,<sup>2</sup> Principal Investigator

SUMMARY

The thermal response of two types of Platinum Resistance Thermometers (PRT's), which are being considered for use in the National Transonic Wind Tunnel Facility, were studied. Response time correlations for each PRT, in flowing water, oil and air, were established separately.

A universal correlation,  $\tau_{MOA} = 2.0 + \frac{1264.9}{h}$ , for a Hy-Cal Sensor (with a reference resistance of 100 ohm) within an error of 20% was established while the universal correlation for the Rosemount Sensor (with a reference resistance of 1000 ohm),  $\tau_{OA} = 0.122 + \frac{1105.6}{h}$ , was found with a maximum percentage error of 30%. The correlation for the Rosemount Sensor was based on air and oil data only which is certainly not sufficient to make a correlation applicable to every condition. Therefore, the correlation needs more data to be gathered in different fluids. Also, it is necessary to state that the calculation of the parameter,  $h$ , was based on the available heat transfer correlations, whose accuracies are already reported in literature uncertain within 20-30%. Therefore, the universal response constant correlations established here for the Hy-Cal and Rosemount sensors are consistent with the uncertainty in the input data and are recommended for future use in flowing liquids and gases.

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<sup>1</sup>Research Assistant Professor, Department of Mechanical Engineering and Mechanics, Old Dominion University, Norfolk, Virginia 23508.

<sup>2</sup>Chairman, Department of Mechanical Engineering, Old Dominion University, Norfolk, Virginia 23508.

## 1. INTRODUCTION

Transducer response characteristics are a critical element in the design and operation of controlled mechanical systems. Temperature transducers (thermometers) are an important class of instruments used in temperature control, and the Platinum Resistance Thermometers (PRT) class of thermometers is the subject of this investigation.

The most systematic early work on measuring the time constant of (glass bulb) thermometers was developed by Harper [1] in 1912. He observed the influence of fluid properties, convection and agitation on the time constant of the thermometer. Subsequently, the demand for accuracy has changed the design of temperature sensors. Goodwin [2] and Hornfeck [3] studied the response time and thermal lag of thermometers when they were placed in a well, and other more detailed studies of time-lag in sheathed industrial thermometers can be found in references [4-8].

Aikman et al. [5] and Looney [8] suggested the use of heat transfer coefficient to determine the effective time constant. This idea was used extensively by Kerlin et al. [9-13] in establishing a correlation of the time constant for several platinum resistance thermometers. Hashemian and Kerlin [13] have reported recently a correlation for a Rosemount Sensor of 1000 ohm\* Rosemount PRT, which was being considered for use in the National Transonic Wind Tunnel Facility (NTF) at NASA Langley Research Center. However, they had reservations about the generality of the correlation. Therefore, the object of this study was to verify or improve the estimates and characterize the response behavior of these sensors. The ultimate objective

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\*Platinum resistance thermometers are characterized typically by their reference temperature resistance value.



is to predict the response characteristics of these sensors in the wind tunnel environments of the National Transonic Facility (NTF) at NASA Langley Research Center.

The Plunge Method recommended by ASTM [17] was used in this study to determine the time constant of a Hy-Cal and Rosemount Sensor. Experimental data were analyzed and compared with previous literature. Thus, correlations to predict time constants for each PRT sensor have been established.

## 2. RESPONSE TIME CONSTANT

The behavior of a sensor can be characterized by its response to a disturbance in its surroundings. Such disturbances are a step change, a linear ramp change, or a sinusoidal oscillation. A simple and accurate method used in this study is a step change as illustrated in Figure 1. This step change may be produced by plunging the sensor from a reference medium into a moving fluid. Time constant is then defined as the time required for the sensor to register 63.2% of the temperature change. The time constant of a temperature sensor depends on the physical properties of the sensor, transport properties of the fluid and the thermal environment. The thermal environment can include effects due to convection, conduction and radiation. Turbulence intensity and distributed thermal capacities also affect the time constant.

Aikman et al. [4] and Looney [8] suggested that a single time constant approximation of the lag of temperature-sensing devices is often adequate for determining the effect of the system lag on the control loop. This single time constant has been related to the environmental conditions through an external heat transfer coefficient,  $h$ , and the suggested correlation takes the form:

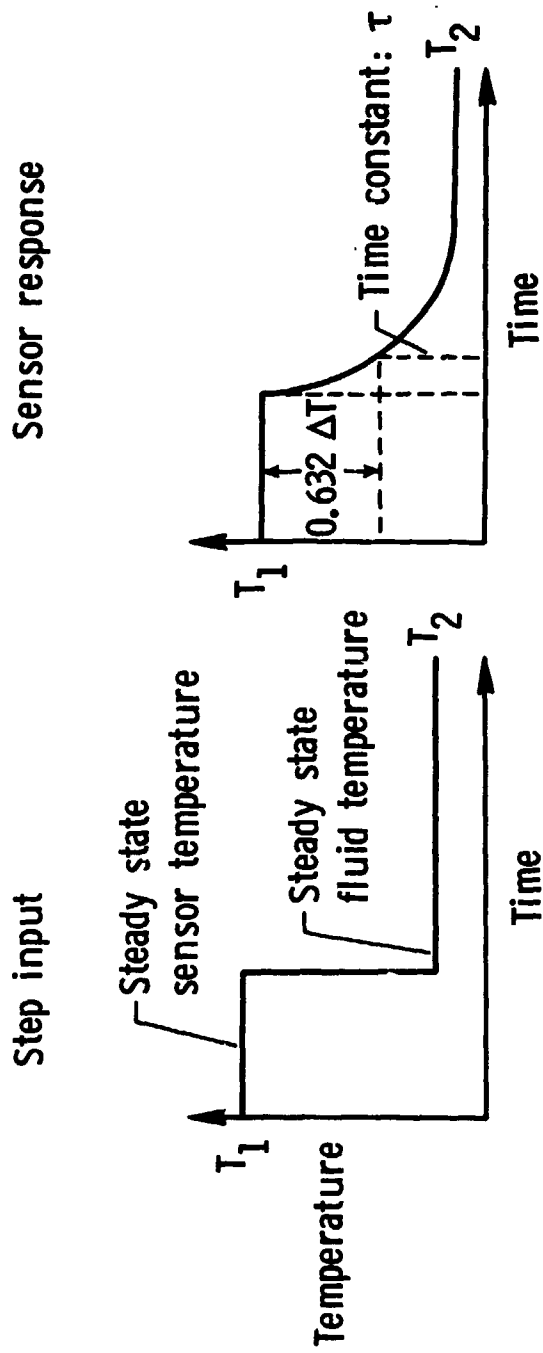


Figure L - A typical response to a step change in temperature sensor.

$$\tau = C_1 + C_2/h \quad (1)$$

where  $C_1$  and  $C_2$  are correlation constants. Recently, Kerlin et al. [9-13] have used this idea extensively in their work. They designated  $C_1$  as the internal component of the sensor time constant and  $C_2$  as the surface component of the sensor time constant. Their results were developed in terms of a lumped parameter and a distributed parameter approach for estimating  $C_1$  and  $C_2$ . For the Lumped Parameter Approach:

$$C_1 = \frac{\rho C_p r_o^2}{2k} \ln \left( \frac{r_o}{r_i} \right) \quad (2)$$

and

$$C_2 = \frac{\rho C_p r_o}{2k} \quad (3)$$

while for the Distributed Parameter Approach:

$$C_1 = \frac{0.24 \rho C_p r_o^2}{k} \quad (4)$$

and

$$C_2 = \frac{\rho C_p r_o^2}{2k} \quad (5)$$

where

$\rho$  = density of the sensor

$C_p$  = specific heat of sensor

$k$  = thermal conductivity of sensor

$r_o$  = outer radius of sensor

$r_i$  = radius at which sensing element is located inside the sensor.

Note that  $C_1$  and  $C_2$  are totally dependent on sensor properties. Process temperature may change their numerical values (due to temperature dependent properties), but, in any case,  $C_1$  and  $C_2$  should not be negative on physical grounds. The results of Hashemian and Kerlin [13] contradicted this non-negative requirement for the Rosemount they tested in that a negative value for  $C_1$  was reported. That result will be discussed later.

### 3. HEAT TRANSFER COEFFICIENT

#### 3.1 Heat Transfer Coefficient in Flowing Liquids

The accurate determination of the time constant using Equation (1) depends on the accuracy of the heat transfer coefficient estimate for the sensing element. A first order estimate of the heat transfer coefficient can be obtained by treating the sensor as an infinitely long circular cylinder in a cross flow. Numerous investigations on this topic have been reported in the literature. McAdams' [14] correlation is used widely by researchers. That correlation for water was found valid by Fand [15,16] over the Reynolds number,  $Re$ , range of  $0.1 < Re < 10^5$ . McAdams' [14] correlation can be expressed as

$$Nu = Pr^{0.3} [0.35 + .56 Re^{0.52}] \quad (6)$$

where  $Nu = \text{Nusselt Number} = \frac{h D_{sh}}{k}$

$Re = \text{Reynolds Number} = \frac{D_{sh} U \rho}{\mu}$

$$Pr = \text{Prandtl Number} = \frac{\mu C_p}{k}$$

$$h = \text{heat transfer coefficient, } \frac{\text{Watt}}{\text{m}^2\text{K}}$$

$$D_{sh} = \text{sheath diameter, m}$$

$$k = \text{thermal conductivity of fluid, } \frac{\text{Watt}}{\text{mK}}$$

$$U = \text{flow velocity, } \frac{\text{m}}{\text{sec}}$$

$$\mu = \text{Dynamic viscosity, } \frac{\text{Kg}}{\text{m sec}}$$

$$C_p = \text{Specific heat of fluid, } \frac{\text{Watt Sec}}{\text{Kg K}}$$

McAdams' correlation is found to be excellent in the Reynolds number range cited for Prandtl numbers between 6.58 and 380. However, the present work uses oil with a Prandtl number on the order of 9000 where no correlation exists in the literature. Engine oil was selected to test the response characteristic of the Rosemount because of its dielectric effects in flowing water as recommended by the manufacturer. Therefore, equation (6) must be extended to incorporate this fluid for estimation of the heat transfer coefficient.

### 3.2 Heat Transfer Coefficient In Flowing Air

The available literature on heat transfer between a cylinder placed vertically in flowing air was reviewed thoroughly. Hilpert's correlations [19] were used in this work as stated below:

$$Nu = 0.615 Re^{0.466} \quad (40 < Re < 4000)$$

and

$$Nu = 0.1745 Re^{0.618} \quad (4,000 < Re < 40,000).$$

(7)

Here the Prandtl number is 0.71.

#### 4. DESCRIPTION OF THE SENSORS

Two Platinum Resistance Thermometers (PRT's) of different designs were tested in this study and are shown schematically in Figure 2. One is a Hy-Cal Sensor (100 ohm reference resistance) with sheath diameter,  $D_{sh} = 0.635$  cm (Figure 2a), while the other is a Rosemount Sensor (1000 ohm reference resistance) with sheath diameter,  $D_{sh} = 0.834$  cm (Figure 2b). It should also be noted that the PRT's in this study had different internal sensor geometries and the different element/shroud dimensions result in different flows around the sensing element. Both PRT's were designed for direct immersion (wet type - no thermal well) with the sheath of each PRT perforated at the sensing end to allow fluid flow around the sensor. The specifications of these sensors are summarized in Table 1.

#### 5. EXPERIMENTAL APPARATUS

The purpose of this experiment is to obtain the time constants ( $\tau$ ) of Platinum Resistance Thermometers (PRT's) by using the Plunge method as described in reference [17]. Subsection 5.1 details the apparatus for the measurement of time constants for PRT's in flowing liquids while Subsection 5.2 explains the instruments used in flowing air.

##### 5.1 Response Time Testing for PRT in Flowing Liquids

The schematic diagram of the Plunge Method which was used to obtain the time constants for the PRT's is shown in Figure 3. A photograph of this set up is also given in Figure 4. The experimental apparatus consisted of a mechanical system and an electronics system.

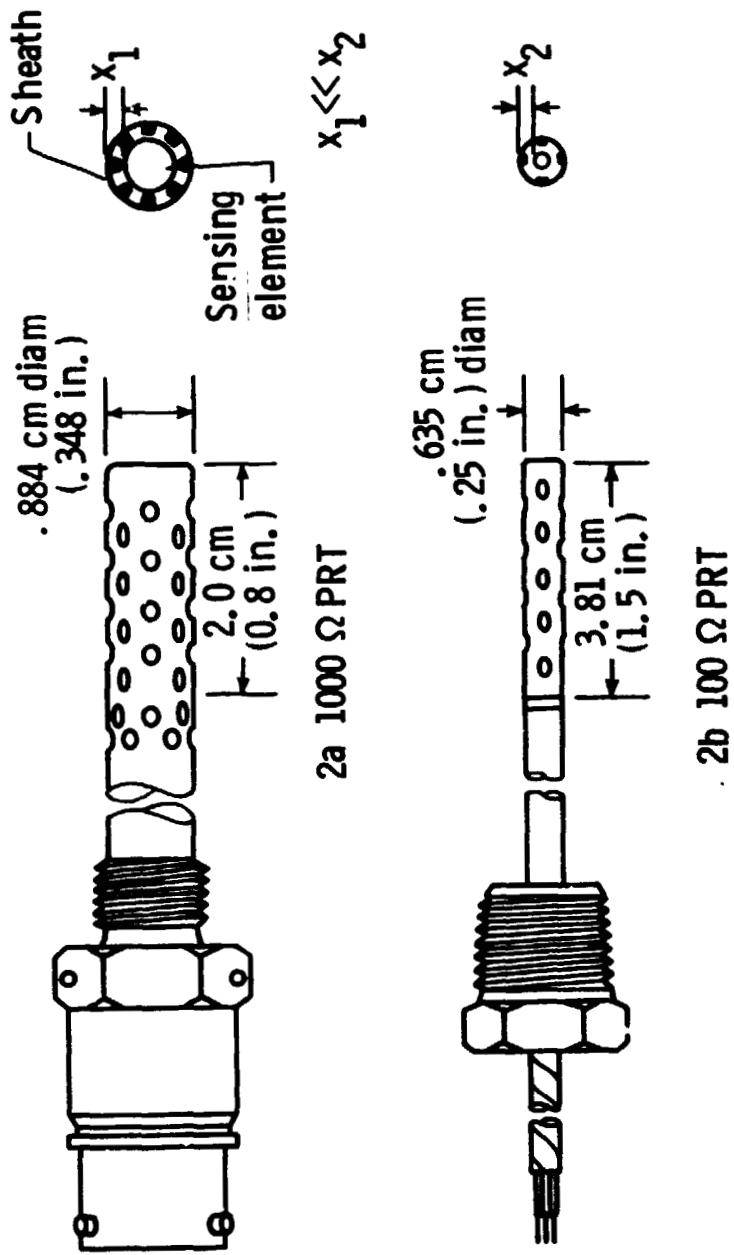


Figure 2 - Nominal differences in Rosemount and Hy-Cal PRT's.

Table 1

Specifications of the PRT's Tested

Specification	Rosemount	Hy-Cal
Model	134NA 48	RTS-54-B-100
Serial	19399	314
Sensor Type	Wet	Wet
$R_0$	1000 ohms	100 ohms
No. of Elements/RTU	1	1
No. of Lead Wires/Element	4	4
Sheath Diameter	.884 cm (.348")	.635 cm (.250")



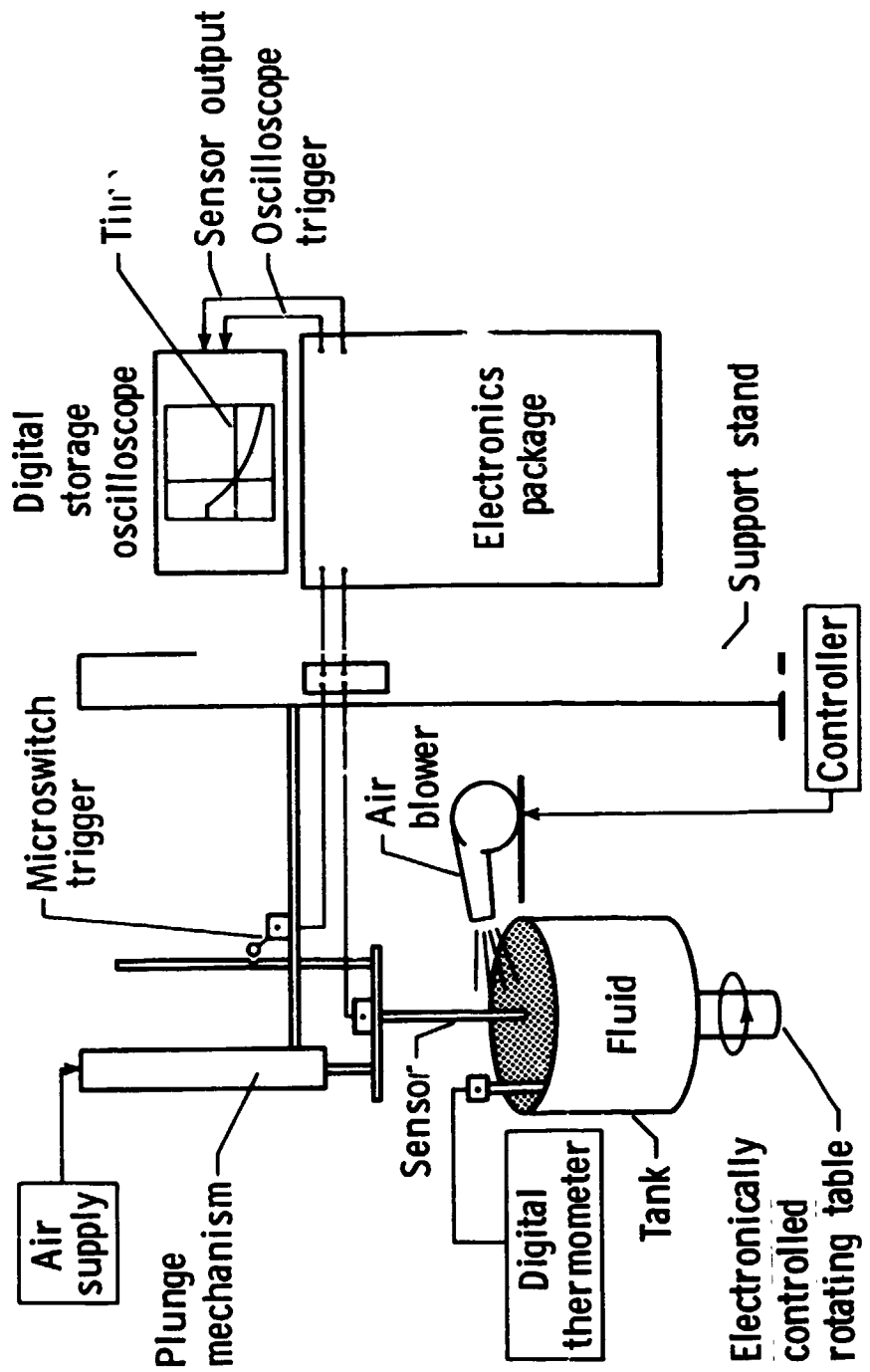


Figure 3. - Mechanical schematic of plunge apparatus.

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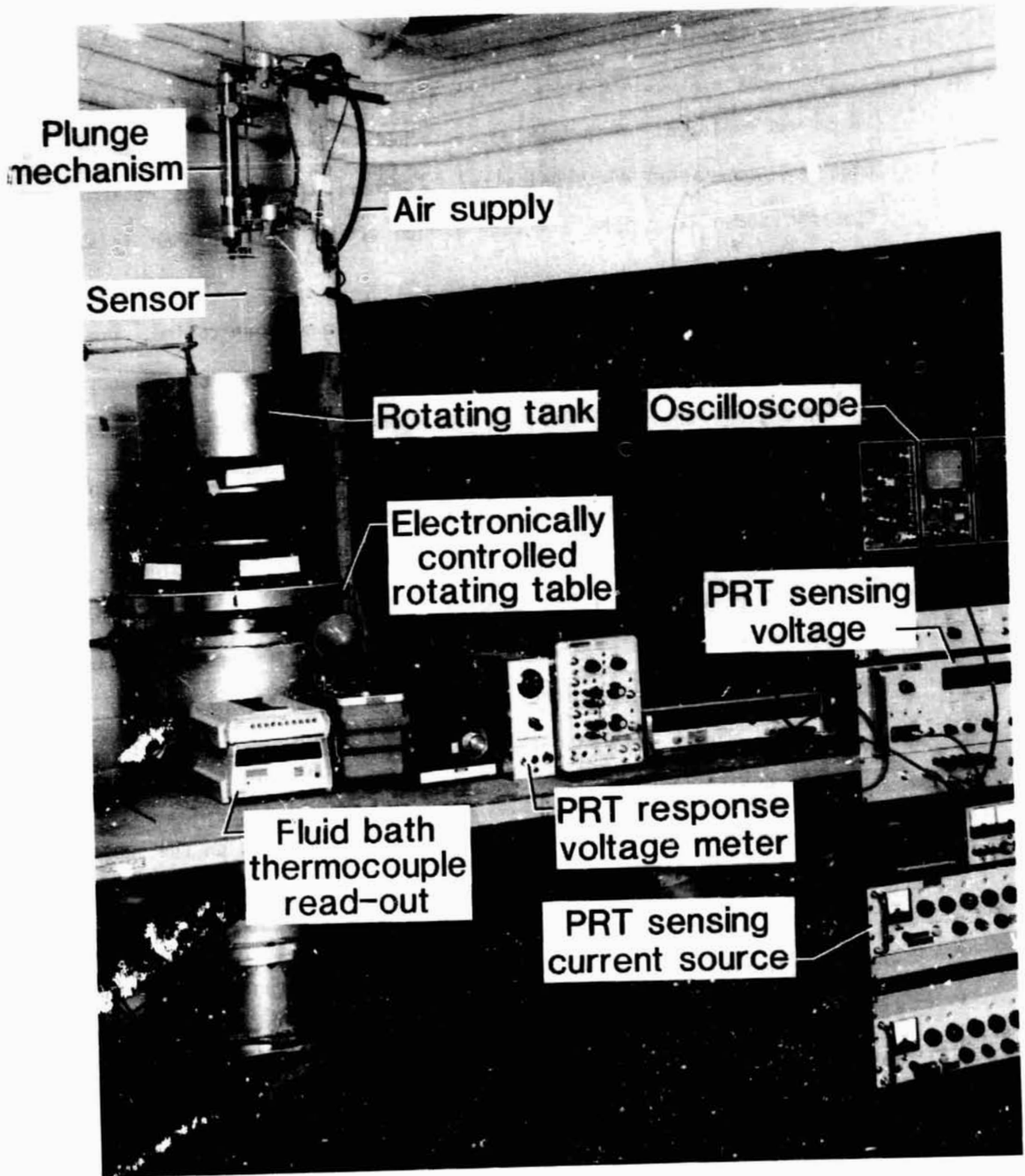


Figure 4. - Response time testing for PRT in flowing liquids.

## A. Mechanical System

The mechanical system had the following components:

I. Tank - A stainless steel tank with a diameter of 45 cm and height of 15 cm was employed. This tank was attached to a rotating table whose rotation was controlled electronically. Further, the tank was rotated at a specific speed to create a moving medium around the PRT when it was immersed.

II. Pneumatic Plunge Mechanism - A solenoid-controlled, pneumatic plunge mechanism held the PRT above the fluid medium and, on command, moved it from one thermal environment to the other creating the step temperature change. This mechanism also initiated a digital recording, via a micro-switch, of the PRT's output during the step change. The recording was started just before the PRT reached the fluid surface. An explanatory view of this mechanism is shown in Figure 5.

III. Microswitch - The microswitch was used to initiate the oscilloscope recordings just before the probe reached the fluid surface.

IV. Air Blower - The step temperature input was produced by heating the PRT, with controlled hot air from a blower, to a steady state temperature which was nominally 8°C above the fluid temperature in which the sensor was plunged.

## B. Electronics System

The electronics system is based on a constant current source (Figure 6) to activate the PRT as shown in Figure 7. This system had the following components:

V. Digital Storage Oscilloscope - This was used to store the PRT's output history when it was subjected to the temperature step change.

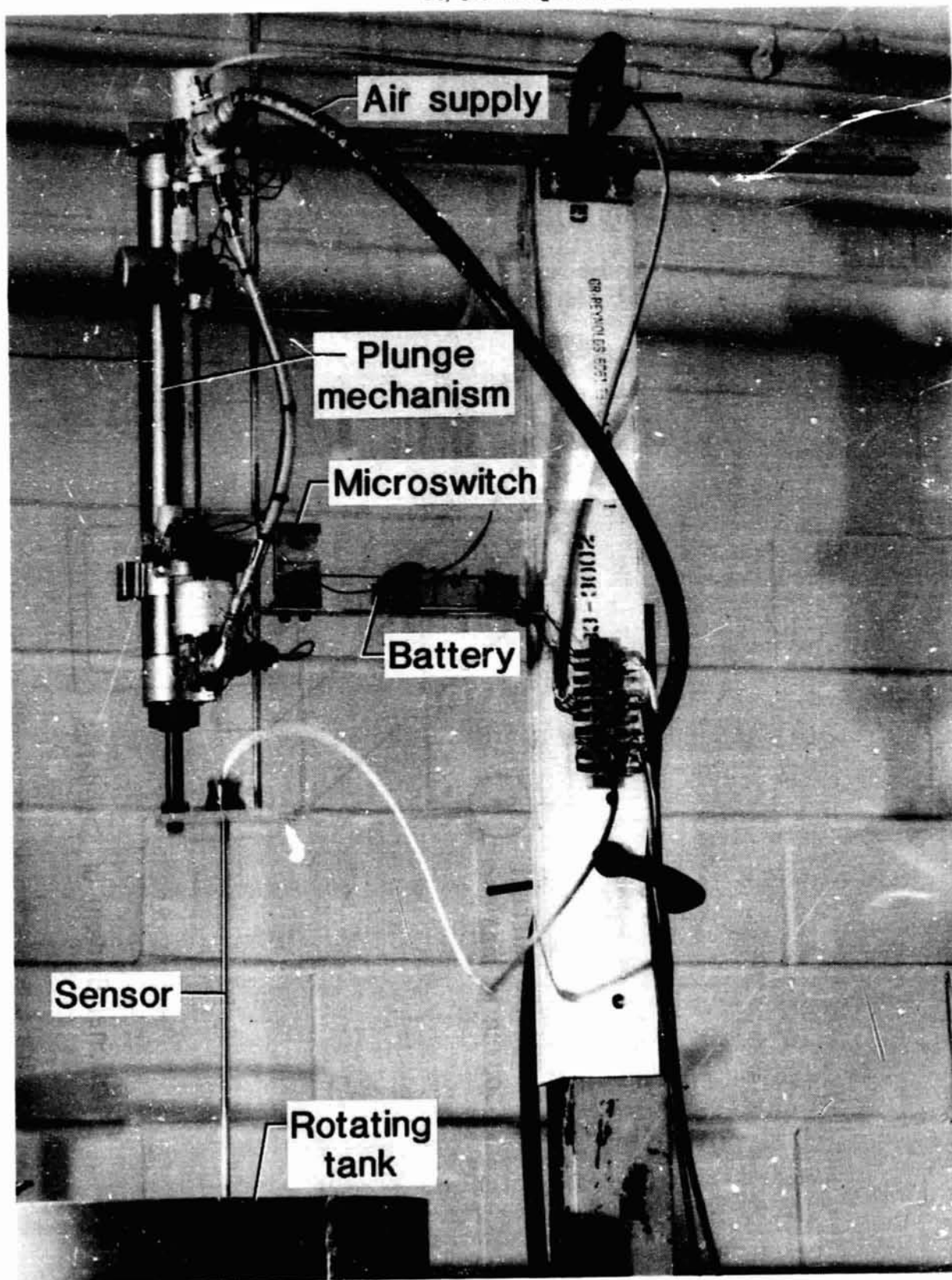
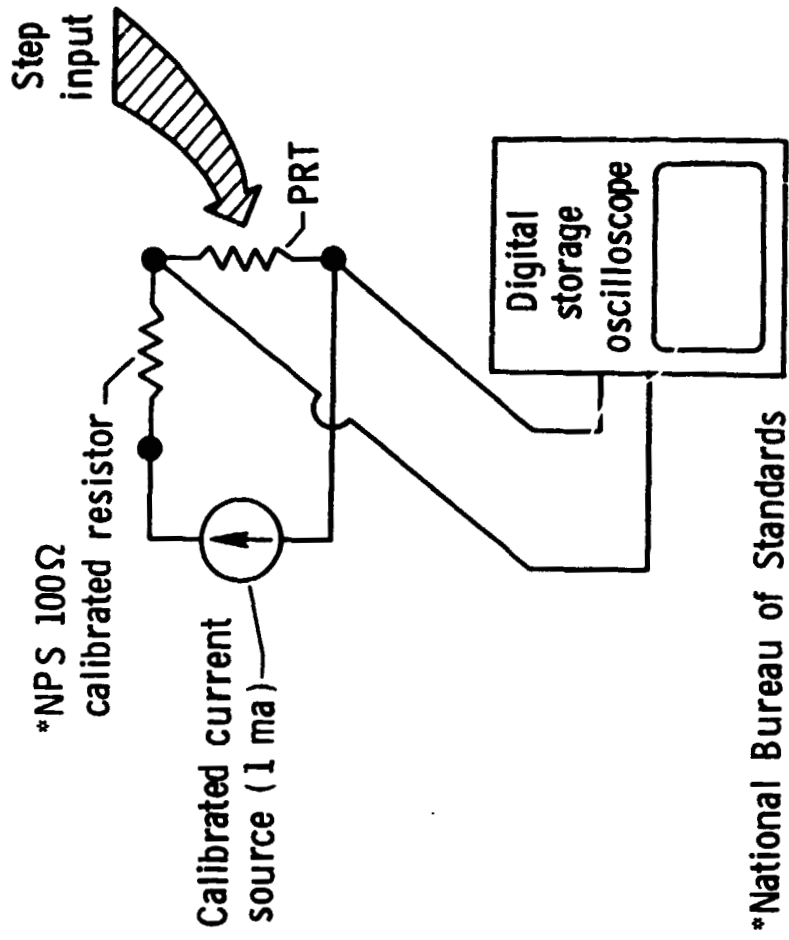


Figure 5. - Plunge mechanism.



\*National Bureau of Standards

Figure 6. - Electronic schematic of plunge apparatus.

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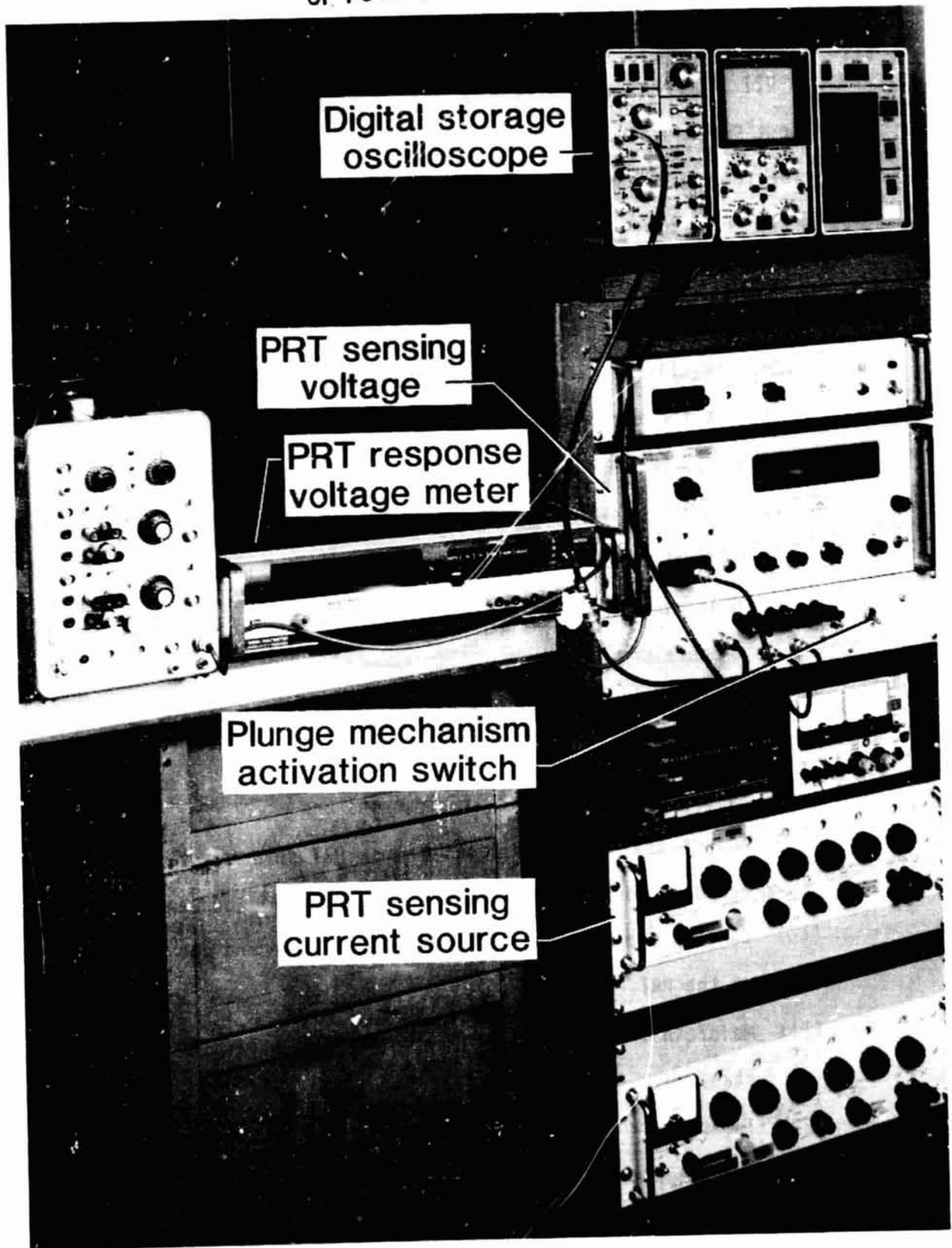


Figure 7. - Electronics package.

## VI. "Standard" Constant Current Source

## VII. Current and Voltage Meters

### C. Test Procedure

The test procedure consisted of the following steps:

- (1) Fill half of the rotating tank with fluid.
- (2) Put thermocouples into the moving fluid to measure the temperature.
- (3) Install the PRT in the plunge mechanism.
- (4) Set the air pressure at 20 psi needed for the plunge mechanism to drive the PRT smoothly into and out of the rotating tank.
- (5) Set the position of PRT radially into the rotating tank where the velocity of fluid within 1 m/second is assured.
- (6) Heat the sensor by an air blower up to 5 - 8°C above the fluid temperature.
- (7) Set speed of tank with electronic control in motion with agreement of Step 5.
- (8) Put all the electronics instruments on.
- (9) Adjust the immersion depth of the PRT into the flowing fluids to avoid conduction error along the length of the sensing element.
- (10) Connect the microswitch to the scope to record the response of the of the PRT.
- (11) Maintain 1 ma current across the PRT by adjusting 100 ohm working standard.
- (12) Immerse the PRT into the rotating fluid using the plunge mechanism actuation switch.
- (13) Wait for the voltage across the PRT to reach a steady state.
- (14) Move the sensor out of the rotating tank.

- (15) Observe the response behavior of the PRT on the scope and calculate the time constant  $\tau$  which is equal to the time required for a sensor output to register 63.2% of a temperature step change.
- (16) Take at least three readings for each experimental condition to minimize personal and instrumental errors.
- (17) Change the speed of rotating table to get the more experimental data at different conditions.

## 5.2 Response Time Testing for PRT in Flowing Air

In order to properly interpret the dynamic behavior of PRT's in a cryogenic gaseous medium, the next logical step was to observe their behavior in a gaseous medium (air) at room temperatures. Furthermore, it was desired to attempt to predict PRT gaseous response using the correlations developed from the liquid tests.

A low speed, open loop wind tunnel was used to determine transducer response over the speed range of 5 to 45 m/sec. That tunnel was described briefly by Daryabeigi et al. [20]. The present experimental setup used the same mechanical and electronics systems as detailed in Subsection 5.1. The wind tunnel configuration is shown in Figure 8.

### Test Procedure

- (1) Switch on the air wind tunnel.
- (2) Put the Pitot tube parallel to the air flow at the location where the PRT is supposed to be.
- (3) Read the pressure reading across the pitot tube using differential pressure transducer.
- (4) Read the temperature of the flowing air using a digital thermocouple.



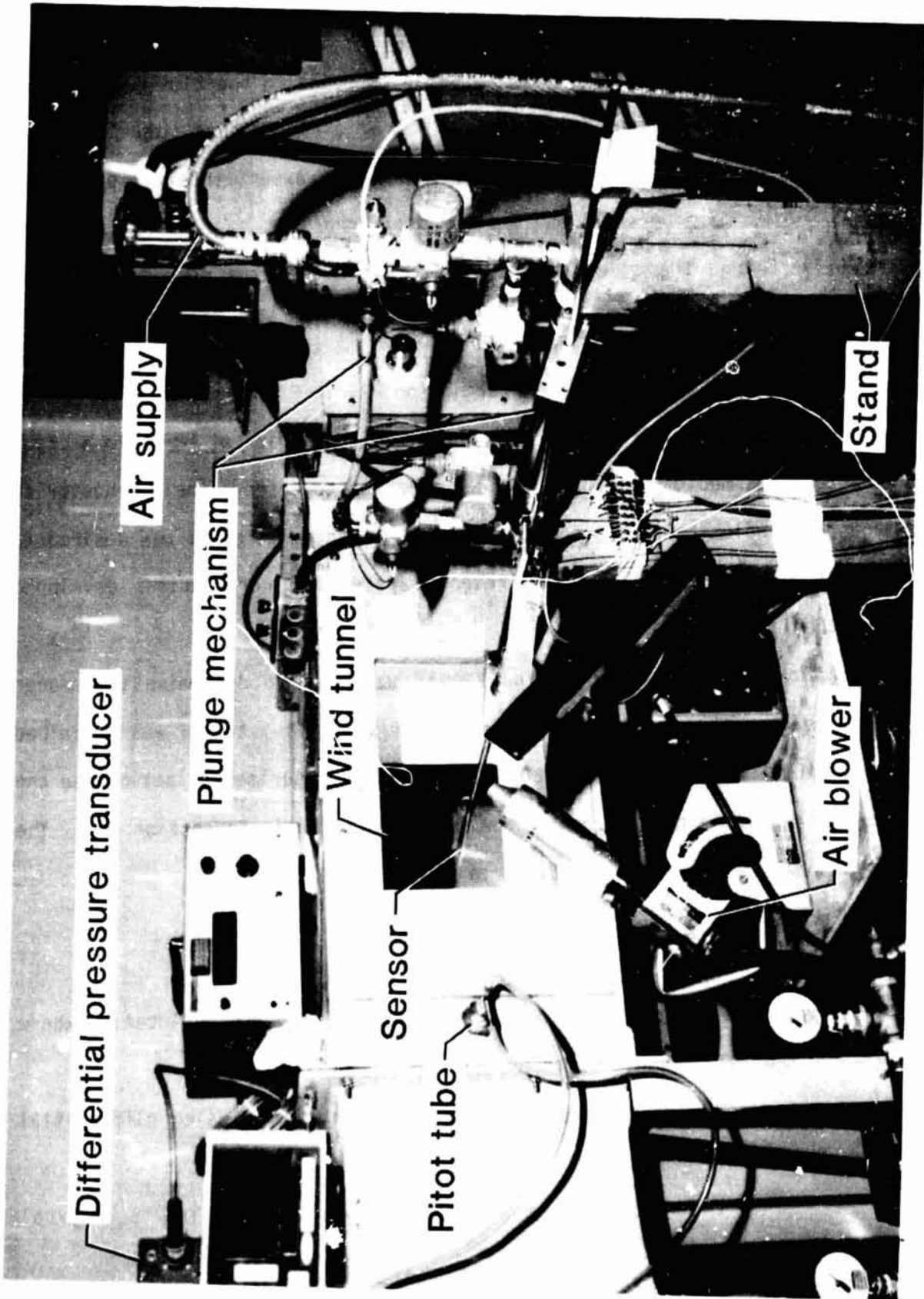


Figure 8. - Response time testing for PRT in flowing air.

- (5) Pull the Pitot tube close to the wall of the air wind tunnel.
- (6) Repeat the procedures of the plunging method as outlined in Sub-section 5.2 for flowing liquids.

## 6. RESULTS AND DISCUSSION

Distilled water, engine oil and air were used as the forced convection media, and their transport properties are summarized in Table 2.

To minimize the uncertainties involved in measuring the temperature dependent flow properties, the flowing fluid was kept at room temperature. Errors associated with maintaining the sensor at constant temperature, uncertainty in the fluid flow velocity, influence of temperature dependent sensor properties and fluctuations or drift in the electronics could not be avoided absolutely which is the basis for the estimated uncertainty of  $\pm 5\%$ . The present data are presented in two ways: one where the time constant is considered as a function of heat transfer coefficient ( $h$ ) only, which requires an additional heat transfer correlations, while the other way represents the time constant as a function of the Reynolds number ( $Re$ ) and Prandtl numbers. In the following sections, the results of response time for each PRT are discussed.

### 6.1 Response Time for the Hy-Cal Sensor in Flowing Liquids

The time constant,  $\tau$ , for the Hy-Cal Sensor determined experimentally in water and oil, is shown in Figure 9 as a function of the inverse of heat transfer coefficient. Numerical values used in this figure are displayed in Tables 3 and 4 for water and oil, respectively. Present data fit the correlation,  $\tau_{WO} = 1.597 + \frac{2083.3}{h}$  (which is also shown in Figure 9), to within a maximum error of 1.4 percent.

Table 2  
Thermophysical Properties of Reference Fluids [Ref. 18]

Property	Symbol	Water	Engine Oil	Air
Reference Temperature (K)	T	295.3	296.5	297
Density (Kg/m <sup>3</sup> )	$\rho$	997.06	896.1	1.191
Viscosity (Kg/m s)	$\mu$	$9.54 \times 10^{-4}$	0.696	$1.955 \times 10^{-5}$
Thermal Conductivity (w/m K)	k	0.606	0.1442	0.0260
Prandtl Number	Pr	6.58	9139	0.71

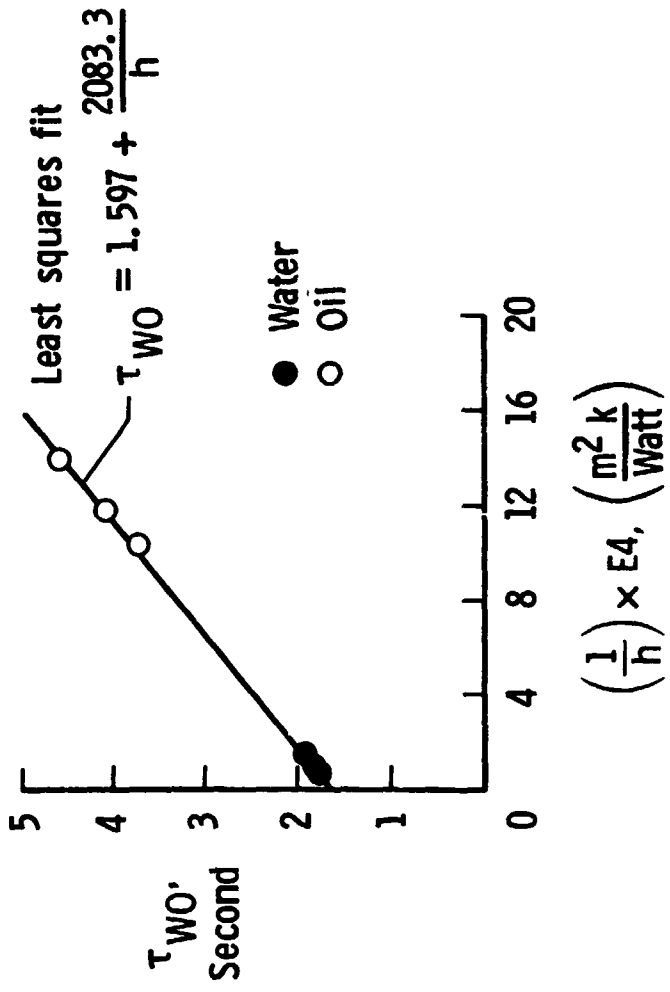


Figure 9. -  $\tau_{WO}$  vs  $1/h$ , for Hy-Cal in flowing water and oil.

Table 3

Time Constant ( $\tau$ ) for Hy-Cal in Flowing Water

U	Re	h	$\tau_E$	$\tau_{W0}$	$\tau_{HR}$ [13]
1.0	6,636	9,194	1.84	1.82	2.05
1.6	10,618	11,724	1.78	1.77	1.96
1.98	13,140	13,091	1.75	1.76	1.92

Table 4

Time Constant ( $\tau$ ) for Hy-Cal in Flowing Oil

U	Re	h	$\tau_E$	$\tau_{WO}$	$\tau_{HK}$ [13]
1.0	8.08	704.1	4.60	4.56	7.52
1.51	12.21	843.3	4.06	4.07	6.54
1.98	16.01	952.3	3.73	3.78	5.98

In addition, to avoid the need of heat transfer correlations, the present data (Tables 2 and 3) can be represented as

$$\tau_{WO} = 1.39 + 262.0 \text{ Re}^{-.632} \text{ Pr}^{-.333},$$

to within a maximum error of 4.8%.

## 6.2 Response Time for the Hy-Cal Sensor in Flowing Air

Table 5 displays the time constant data plotted in Figure 10 for the Hy-Cal Sensor (100 ohm PRT) in flowing air. Experimental data are compared with the time constant predicted by a correlation,  $\tau_{WO} = 1.597 + \frac{2083.3}{h}$  (based on water and oil data) and Hashemian and Kerlin's [13] correlation,  $\tau_{HK} = 1.6 + \frac{4168}{h}$ . The predicted time constant  $\tau_{WO}$  is 50% higher than the experimental data, while  $\tau_{HK}$  [13] predicts 185% higher than the experimental data. It is important to note that the present correlation  $\tau_{WO}$ , based on water and oil data, cannot be treated as universal. The error of 50% is consistent with the errors which occur in predicting heat transfer coefficient for air by using the heat transfer correlation based on water data (Equation 6). To establish a universal correlation, one has to use all the response time data observed in every fluid and should expect an appreciable error of 20-30%. Recently, Churchill and Bernstein [21] have reported a generalized correlation for heat transfer from solid cylinders placed vertically in the flow of liquids and gases within the uncertainties of 20-25%.

Therefore, the present data obtained in flowing water, oil and air, shown in Figure 11, are correlated by an equation,  $\tau_{WOA} = 2.0 + \frac{1264.9}{h}$

**Table 5**  
**Prediction of Time Constant ( $\tau$ ) for Hy-Cal in Flowing Air**

U	Re	h	$\tau_E$	$\tau_A$	$\tau_{WO}$	$\tau_{WOA}$	$\tau_{HK}$ [13]
9.10	3520	113.2	13.5	13.39	20.0	13.17	38.42
14.04	5431	144.8	10.49	10.75	15.98	10.74	30.38
18.45	7137	171.5	9.38	9.28	13.74	9.38	25.90
27.43	10,611	219.1	7.57	7.55	11.11	7.77	20.62
35.47	13,721	256.8	6.75	6.63	9.71	6.93	17.83
41.39	16,012	282.6	6.05	6.14	8.97	6.48	16.35



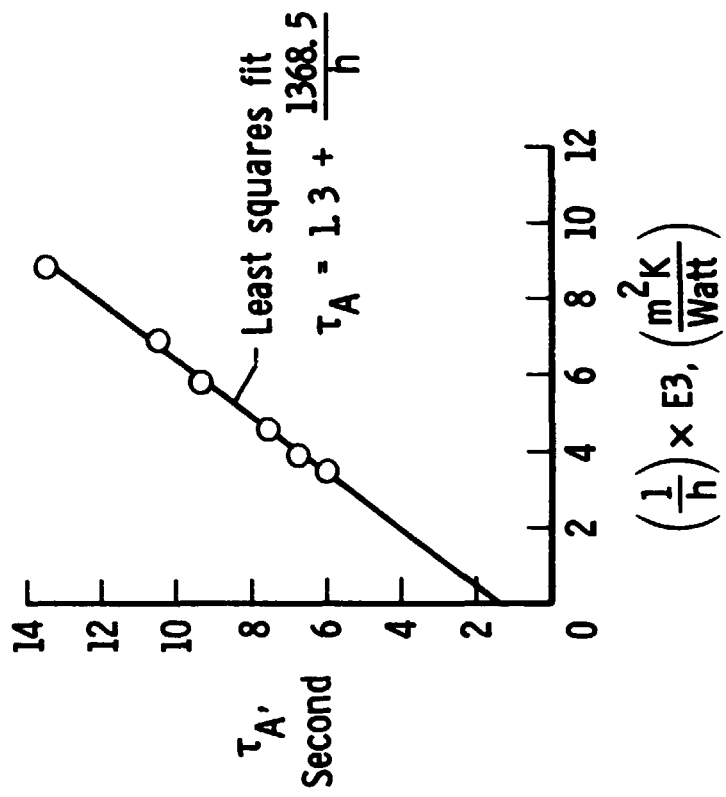


Figure 10. -  $\tau_A$  vs  $1/h$  for Hy-Cal in flowing air.

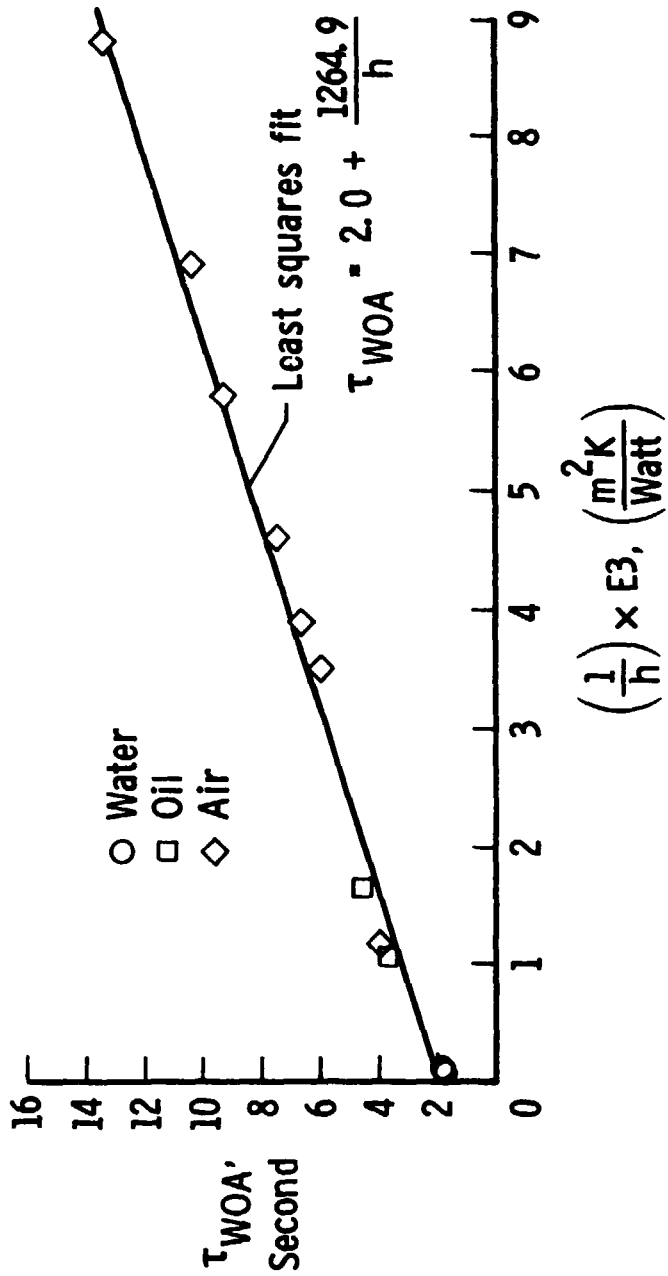


Figure 11. -  $\tau_{WOA}$  vs  $1/h$  for Hy-Cal in flowing water, oil and air.

within the maximum error of 20%. The values of heat transfer coefficients based on sheath diameter were obtained by using Equation (6) for water and oil and Equation (7) for air. Such correlation can be considered as a universal correlation for the Hy-Cal Sensor (100 ohm PRT) to predict the time constant in any flowing fluids. Also, the air data are fitted by the correlation  $\tau_A = 1.3 + \frac{1368.5}{h}$  within the maximum error of 2.5%. All three correlations,  $\tau_A$ ,  $\tau_{WO}$ , and  $\tau_{WOA}$ , are compared with the experimental data and Hashemian and Kerlin's [13] correlation in Table 5.  $\tau_{HK}$  [13] predicts larger errors overall because it was based on water data only. Therefore,  $\tau_{HK}$  [13] cannot be treated as a universal correlation. Response time correlations for Hy-Cal Sensor are summarized in Table 6.

### 6.3 Response Time for the Rosemount Sensor in Flowing Oil

Figure 12 shows the response characteristics for the Rosemount Sensor (1000 ohm PRT) in oil. A correlation was established using the oil data displayed in Table 7. This correlation,  $\tau_o = 0.132 + \frac{1288.5}{h}$  predicts the response time correctly to within an error of 1.4%. Present results are compared with Hashemian and Kerlin [13] in Table 7. It is important to note that the Hashemian and Kerlin [13] correlation predicts negative time constants in all cases. Note that the Hashemian and Kerlin [13] correlation was based on their air data only. Therefore, the applicability of their correlation in flowing oil is questionable.

### 6.4 Response Time for the Rosemount Sensor in Flowing Water

The information reported in references [13, 22] does not recommend the testing of the Rosemount Sensor in flowing water. The reason is associated with the dielectric properties of the Rosemount Sensor. Above all, it was

Table 6

Summary of Response Time Correlations for Hy-Cal (100 ohm PRT)

FLUIDS USED	CORRELATIONS	MPE
Water and Oil	$\tau_{WO} = 1.597 + \frac{2083.3}{h}$	1.4
Air	$\tau_A = 1.3 + \frac{1368.5}{h}$	2.5
Water, Oil and Air	$\tau_{WOA} = 2.0 + \frac{1264.9}{h}$	20
Water	$\tau_{HK} = 1.6 + \frac{4168}{h}$ [13]	—

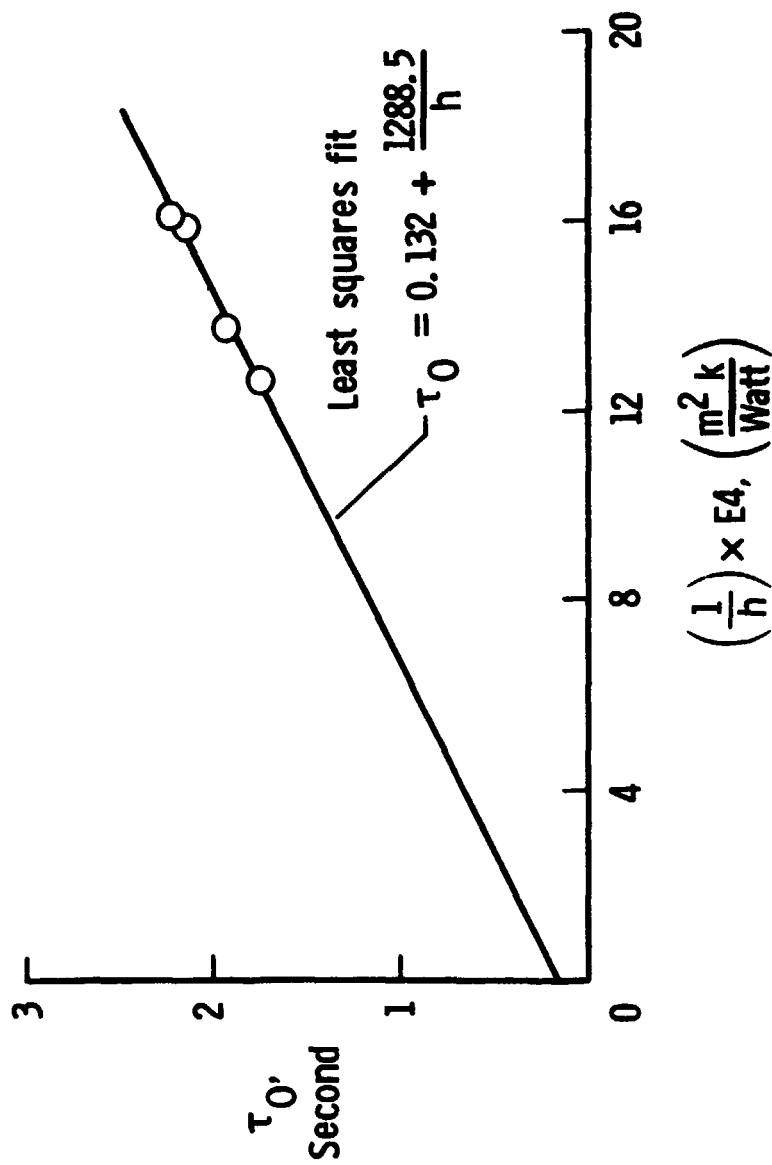


Figure 12 -  $\tau_0$  vs  $1/h$  for Rosemount in flowing oil.

Table 7

Time Constant ( $\tau$ ) for Rosemount in Flowing Oil

U	Re	h	$\tau_E$	$\tau_0$	$\tau_{HK}$ [13]
1.14	12.83	619.3	2.23	2.21	-7.84
1.19	13.39	631.2	2.14	2.17	-7.91
1.62	18.23	725.7	1.92	1.91	-8.39
1.96	22.06	792.2	1.75	1.76	-8.66

decided to test this sensor to determine its response behavior in flowing water. It was observed that it has a faster responsive nature in flowing water than in oil. Keeping these uncertainties in mind, the water data displayed in Table 8 is correlated separately. The data is plotted in Figure 13. Further, the water data is not used to establish a universal response time correlation for this sensor. Note that from Table 8, again Hashemian and Kerlin's [13] correlation predicts negative time constants in flowing water. The present correlation for the water data,  $\tau_w = 0.068 + \frac{413.0}{h}$ , is found to within an error of 0.9%.

#### 6.5 Response Time for the Rosemount Sensor in Flowing Air

The response time air data given in Table 9 are represented by an equation  $\tau_A = -1.983 + \frac{1309.5}{h}$  within an error of 2.5%. Experimental data plotted in Figure 14 are compared with the Hashemian and Kerlin [13] results. The existence of negative values for  $C_1$ , reported in the literature (reference 13) as well as found in the present correlation, are obviously inconsistent with the known fact that response time is positive even as heat transfer coefficient increases without bound. In addition, the present authors have tried other possible ways to correlate the experimental data in the following ways:

$$(A) \quad \tau_A = 5962 \text{ Re}^{-.754} \text{ Pr}^{-.333} \text{ within the maximum error of 5\%,}$$

and

$$(B) \quad \tau_A = -2.809 + 1393 \text{ Re}^{-.554} \text{ Pr}^{-.333} \text{ within the maximum error of 2.8\%.}$$

Note that Equations (A) and (B) will reduce to zero and -2.809, respectively, as  $\text{Re}$  approaches to infinity. Again, the predicted results become

Table 8

Time Constant ( $\tau$ ) for Rosemount in Flowing Water

U	Re	h	$\tau_E$	$\tau_W$	$\tau_{HK}$ (13)
1	9,239	7,837	0.121	0.121	-11.30
1.41	13,027	9,362	0.110	0.112	-11.35
1.77	16,353	10,532	0.108	0.107	-11.38



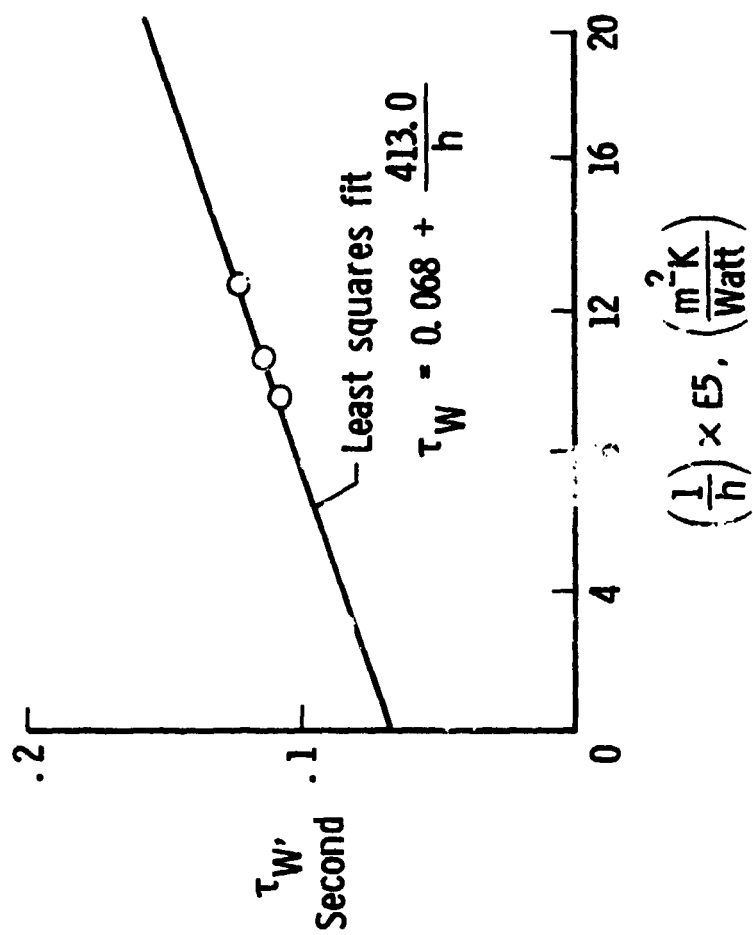


Figure 13. -  $\tau_w$  vs  $1/h$  for Rosemount in flowing water.

Table 9  
Prediction of Time Constant ( $\tau$ ) Rosemount in Flowing Air

U	Re	h	$\tau_E$	$\tau_A$	$\tau_O$	$\tau_{OA}$	$\tau_{HK}$ [13]
6.13	3301	78.9	14.61	14.61	16.46	14.12	17.88
9.10	4901	97.6	11.50	11.43	13.33	11.44	12:23
18.45	9936	151.1	6.57	6.68	8.66	7.43	3.79
27.41	1,4761	193.0	4.70	4.60	6.81	5.84	0.45
35.47	19,102	226.3	3.87	3.80	5.63	5.0	-1.32
41.39	22,290	249.0	3.40	3.28	5.31	4.55	-2.26

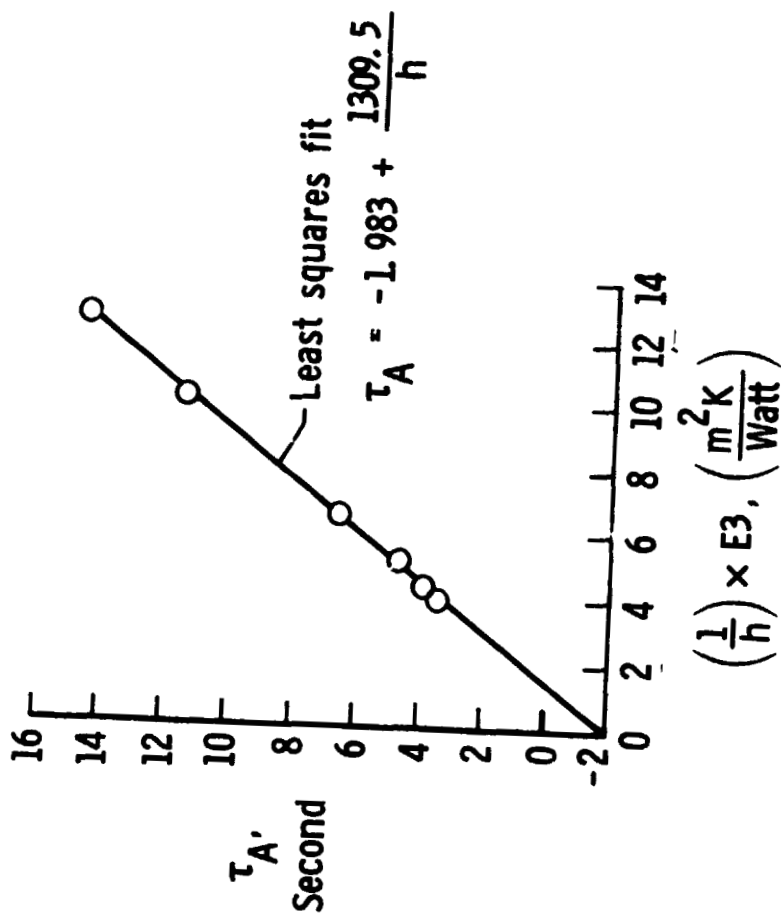


Figure 14. -  $\tau_A$  vs  $1/h$  for Rosemount in flowing air.

inconsistent with the true expected values of response time. Some other parameters, like Reynolds numbers based on sensor diameter, gap between the sheath and sensor, and the ratio of the hole diameter on sheath to the gap were tried, but the values of  $C_1$  remained negative.

It is necessary to note that the Rosemount Sensor's behavior does not become questionable in flowing liquids in which the values of  $C_1$  were never found to be negative. Therefore, it is possible that a universal correlation for the Rosemount Sensor exists for liquids other than water. In addition, the oil and air data were correlated by an equation  $\tau_{0A} = 0.112 + \frac{1105.6}{h}$  within the error of 30%. Note that  $C_1$  is not found to be negative. The air data are presented in Figure 15. The error of 30% is not large, once one is looking for a generalized correlation applicable to any situations. Note that this error is also associated with the values of  $h$  which were determined from the heat transfer correlations [14, 19] reported in literature. Heat transfer correlations are found within the error of 20-30%.

However, the authors believe that a universal correlation for this sensor can be found by having more data in flowing air and liquids. We also believe that a negative  $C_1$  in air correlation  $\tau_A$  (Table 10) is associated with the experimental data given in Table 9. There is a systematic error of 2 seconds between experimental data and predicted values by  $\tau_0 = 0.132 + 1288.5/t$  based on oil data (Table 7).

## 7. PREDICTION OF TIME CONSTANTS AT CRYOGENIC CONDITIONS

This section uses the response time correlations as established for the PRT's to predict time constants at a given cryogenic conditions. Note that

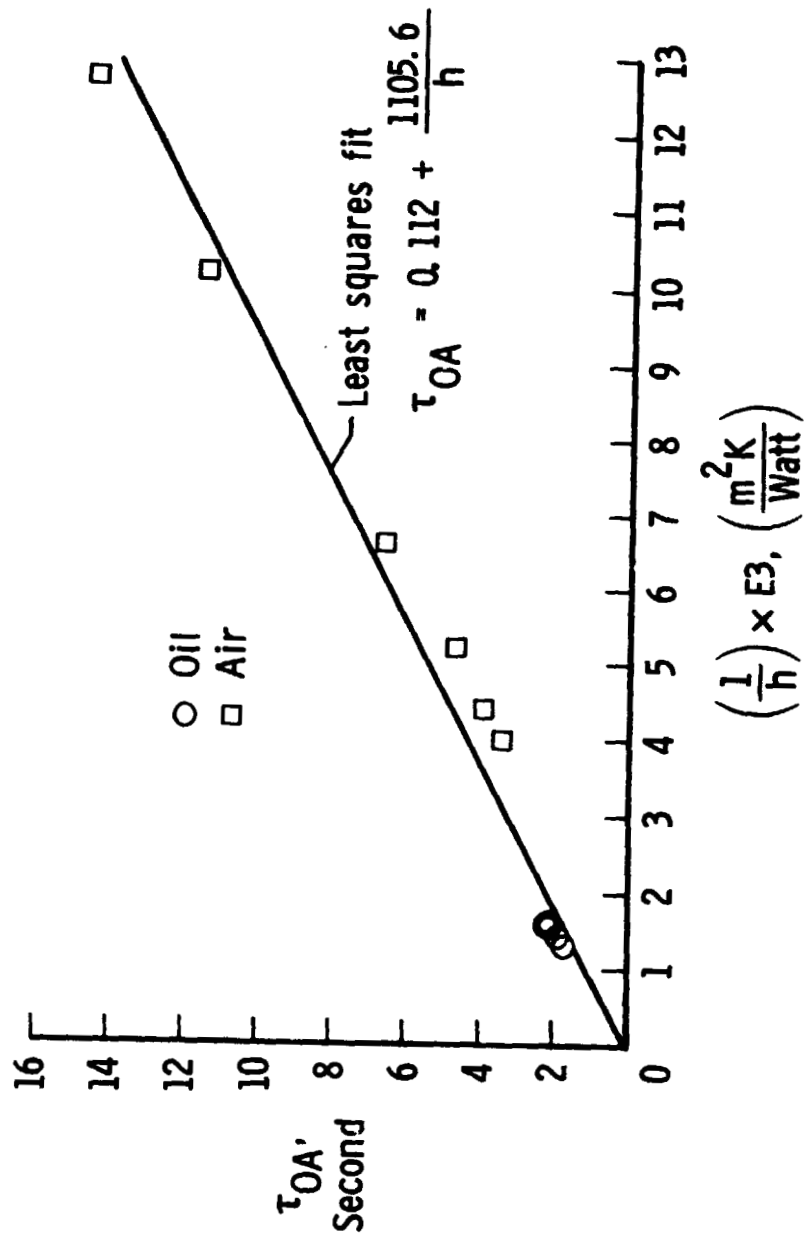


Figure 15. -  $\tau_{OA}$  vs  $1/h$  for Rosemount in flowing oil and air.

Table 10

Summary of Response Time Correlations For Rosemount (1000 ohm PRT)

FLUIDS USED	CORRELATIONS	MPE
Oil	$\tau_C = 0.132 + \frac{1288.5}{h}$	1.4
Air	$\tau_A = - 1.983 + \frac{1309.5}{h}$	2.5
Water	$\tau_W = 0.068 + \frac{413.0}{h}$	0.9
Oil and Air	$\tau_{OA} = 0.112 + \frac{1105.6}{h}$	30
Air	$\tau_{HK} = - 11.6 + \frac{2326}{h}$ [13]	—

the conditions used here, don't represent the real situation occurring in National Transonic Facility at NASA, Langley Research Center.

**EXAMPLE:** Estimate the time constants for the Hy-Cal and Rosemount Sensors exposed to Nitrogen gas flowing at 25 m/second in cryogenic wind tunnel. The gas is maintained at 1 atmospheric pressure and temperature of 200 K. Thermophysical properties of Nitrogen Gas [Ref. 18] are given below:

$$\begin{aligned}
 k &= 0.01824 \text{ w/m K} \\
 \rho &= 1.7108 \text{ kg/m}^3 \\
 \mu &= 12.947 \times 10^{-6} \text{ Kg/m.s} \\
 Pr &= 0.747 \text{ (closed to air)}
 \end{aligned}$$

Hy-Cal Sensor

$$\begin{aligned}
 D_{sh} &= 0.00635 \text{ m} \\
 Re &= \frac{D_{sh} \cdot \rho \cdot U}{\mu} = \frac{0.00635 \times 1.7108 \times 25}{12.947 \times 10^{-6}} \\
 &= 20,977
 \end{aligned}$$

Using Equation 7

$$\frac{h D_{sh}}{k} = 0.174 Re^{0.618}$$

or

$$\begin{aligned}
 h &= \frac{k}{D_{sh}} \times 0.174 \times Re^{0.618} \\
 &= \frac{0.01824}{0.00635} \times .174 \times (20,977)^{.618} \\
 &= 234.2 \text{ watt/m}^2 \text{ K}
 \end{aligned}$$

Present response time correlation estimates

$$\tau_{\text{WOA}} = 2.0 + \frac{1264.9}{234.2} = 7.40 \text{ seconds}$$

and

$$\tau_{\text{A}} = 1.3 + \frac{1368.5}{234.2} = 7.14 \text{ seconds}$$

while Hashemian and Kerlin's correlation [13] predicts

$$\tau_{\text{HK}} \text{ [13]} = 1.6 + \frac{4168}{234.2} = 19.40 \text{ seconds}$$

The universal correlation,  $\tau_{\text{WOA}}$  which is based on water, oil and air data, predicts a 3.6% larger error than a correlation  $\tau_{\text{A}}$  based on air data only. Such an error must be expected from a universal correlation. It is necessary to note that Hashemian and Kerlin's correlation,  $\tau_{\text{HK}}$  [13] overestimates the response time by 172%. Such a discrepancy is justifiable because their correlation was based on water data only. Therefore  $\tau_{\text{HK}}$  [13] cannot be used in flowing gases. Thus the universality of Hashemian and Kerlin's [13] correlation is questionable.

Rosemount Sensor:

$$D_{\text{sh}} = 0.00884 \text{ m}$$

$$\text{Re} = \frac{D_{\text{sh}} \cdot \rho \cdot U}{\mu} = \frac{0.00884 \times 1.7108 \times 25}{12.947 \times 10^{-6}}$$

$$= 29,203$$

Using Equation 7,



$$\frac{h D_{sh}}{k} = 0.174 \text{ Re}^{0.618}$$

or

$$h = \frac{k}{D_{sh}} \times 0.174 \times \text{Re}^{0.618}$$

$$= \frac{0.01824}{0.00884} \times 0.174 \times (29,203)^{0.618}$$

$$= 206.4 \text{ watt/m}^2 \text{ K}$$

Present response time correlation estimates

$$\tau_{OA} = 0.112 + \frac{1105.6}{206.4} = 5.47 \text{ seconds}$$

$$\text{and } \tau_A = -1.983 + \frac{1309.5}{206.4} = 4.36 \text{ seconds}$$

Using Hashemian and Kerlin's [13] correlation, the time constant is computed as

$$\tau_{HK} = -11.6 + \frac{2326}{h}$$

$$[13] = -11.6 + \frac{2326}{206.4} = -0.33 \text{ seconds}$$

The correlation  $\tau_{OA}$  which is based on oil and air data gives 5.47 seconds, while  $\tau_A$  based on air data only predicts 4.36 seconds at the same conditions. The relative error is found to be within 18%. Such error one

should expect from a universal correlation like  $\tau_{OA} = 0.112 + \frac{1105.6}{h}$ . It is important to note that Hashemian and Kerlin's correlation [13] does not survive in such an environment, although their correlation [13] was based on their air data. Furthermore,  $\tau_{HK}$  [13] also predicts negative time constants in flowing water and oil (Tables 8 and 9).

## 8. CONCLUSIONS AND RECOMMENDATIONS

Based upon the experimental measurements developed in this investigation, it is possible to conclude that the response time of ventilated, platinum resistance thermometers can be correlated with the reciprocal of the heat transfer coefficient in a given fluid. The experimental data correlated for the Hy-Cal and the Rosemount sensors are given in Tables 6 and 10, respectively.

Furthermore, a universal correlation  $\tau_{WOA} = 2.0 + \frac{1264.9}{h}$ , for the Hy-Cal Sensor within the uncertainties of 20% has been established. A universal correlation  $\tau_{OA} = 0.112 + \frac{1105.6}{h}$ , for the Rosemount Sensor based on oil and air data is found to be within the uncertainties of 30%. Such error one should expect from a universal correlation which can be applied to any flowing medium in which the Prandtl number varies from 0.7 to 10,000. It is necessary to mention that the important parameter,  $h$ , is computed from heat transfer correlations [14, 19] which are already reported uncertain to within 20-30%.

An example based on cryogenic conditions was also set up to test the present and previous response time correlations. It was found that the present response time correlations maintained its accuracies with the experimental data, while Hashemian and Kerlin's correlations,  $\tau_{HK}$  [13] were

determined inapplicable to every situation. The universalities of their correlations [13] were found highly questionable.

In conclusion, we recommend our universal response time correlations for each PRT to predict time constants in any flowing medium. We also recommend gathering more response time data so that the error as found in establishing a universal correlation could be reduced.

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