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THE DESIGN AND CONSTRUCTION OF THERMAL FLOWMETERS

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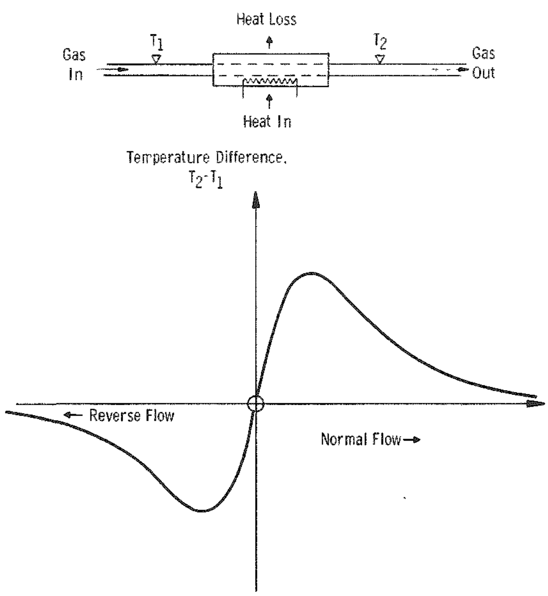
A thermal flowmeter has been designed and tested which will measure a wide range of flow rates for highly corrosive gases. Response to flow rate changes is fast. The parameters for changing the size and response of the flowmeter have been evaluated.

INTRODUCTION

Conventional flowmeters are usually adversely affected by the removal from or addition of material to the fluid channel. Even a small amount of corrosion will seriously alter the calibration of very small orifice meters and rotameters. This difficulty is overcome in the classical thermal flowmeter, in which flow is measured by a temperature difference produced in a flowing stream by adding heat at a known rate. A diagram of a classical thermal flowmeter is shown in Figure 1. However, this form of the thermal flowmeter has two important disadvantages:

Figure 1

CLASSICAL THERMAL FLOWMETER



1) the calibration curve is such that any particular reading can be given by either of 2 flow rates; and

2) the time of response to flow changes is slow at lower flow rates.

The two-valued calibration curve is a consequence of the following. For a given heat input rate, the temperature difference decreases from a higher value as the flow rate is increased. On the other hand, for a symmetrical construction the temperature difference is zero at zero flow. Thus the pattern of the classical flowmeter is such that the temperature difference rises from zero to a maximum after which it falls asymptotically to zero again. The maximum value is determined by heat losses and conduction in the pipe.

A modified thermal flowmeter design has been developed which does not have the above disadvantages. In principle, it consists of a short length of pipe with different constant temperatures maintained at the ends. With no flow, the temperature along the pipe is determined by heat conduction along the pipe wall due to the temperature difference. Midway between the fixed temperatures, the pipe temperature will be the average of the 2 temperatures. As the flow increases, the midpoint temperature will approach the inlet temperature.

A design using 2 pipe sections in a symmetrical U-configuration is shown in Figure 2.

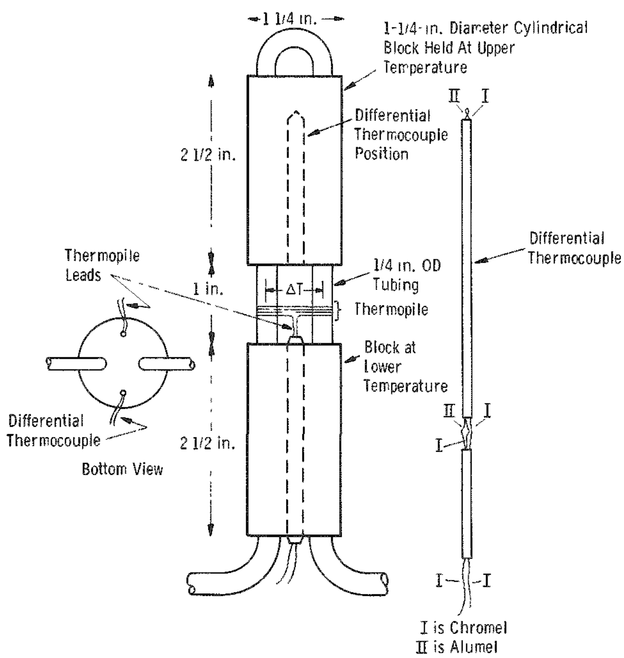


Figure 2

MARK II THERMAL FLOWMETER AND DIFFERENTIAL THERMOCOUPLE

The top block shown in Figure 2 is held at a fixed temperature above the lower block, which is not necessarily at a controlled temperature. This reduces the amount of control equipment and allows the bottom block to approach the inlet gas temperature. Use of 2 gas passes in opposite directions between the fixed temperatures and measurement of the output across the two midpoints reduces the effect of external temperature changes and temperature cycling of the top block. Associated instrumentation for the complete unit is shown in Figure 3.

This version of the thermal flowmeter has a very wide useful range. It is capable of measuring gas flow rates of 10 mℓ/min to 100 ℓ/min. Among the gases used have been hydrogen fluoride, uranium hexafluoride, bromine pentafluoride, and fluorine.

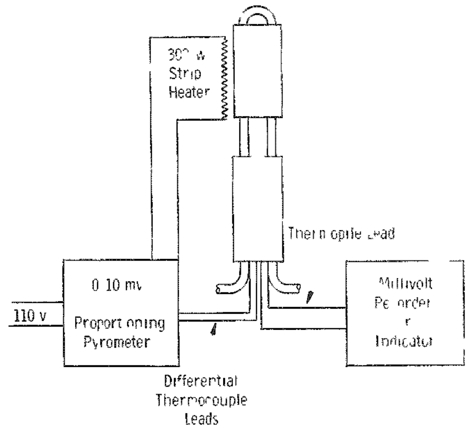


Figure 3

THERMAL FLOWMETER CIRCUIT SHOWING INSTRUMENTATION

DETAILS OF CONSTRUCTION

Two 2.5-in. lengths of 1.25-in.-OD brass bar stock were drilled with $\frac{7}{64}$-in. holes for $\frac{1}{4}$-in. tubing, and $\frac{3}{16}$-in. holes for the differential thermocouples and the thermopile leads. A 180° bend with $\frac{1}{2}$-in. ID was made in the center of a straight length of nickel tubing. This sharp bend can be made without collapsing the tube by filling the tube with sand or by using a specially constructed or modified tubing bender. The tubing and holes for the tubing were painted with silver solder flux before assembling. Good thermal contact between the block and the tube can be achieved by flowing silver solder between the block and the tube from the end of the block near the center of the unit until it appears at the other end of the block.

Chromel-alumel junctions have been used in the differential thermocouple and the thermopile because of the high strength and similarity of stiffness of the wires. These properties greatly facilitate the construction of the thermopile. The thermopile was constructed using number 30 wire and contains 4 junction pairs. It was wrapped around the 2 tubes midway between the 2 blocks. For electrical insulation of the thermopile, high-temperature insulating varnish was baked on the tubes before wrapping the thermopile. (It can also be insulated with very thin sheets of mica.) After the thermopile is in place, the junctions were fixed with insulating varnish or Sauereisen cement. This also aids thermal contact between the thermopile and the tubes. Thermopile lead wires were brought through a $\frac{3}{16}$-in. hole in the bottom block by means of porcelain thermocouple tubing and Sauereisen cement.

The differential thermocouple was constructed with number 20 Chromel and Alumel wire. The upper junction should be in contact with the brass block in order to reduce time lag. The lower junction was wrapped with a single layer of glass tape.

The space between the blocks was wrapped with some stiff insulating material such as mica. A strip about $\frac{1}{4}$ in. wider than the block spacing was held in place with glass adhesive tape. The cylinder so formed should be rigid enough to prevent any contact with the thermopile. Extensive and tight taping is necessary to prevent air leakage. Insufficient taping has produced noise signals in the output of the thermopile of several hundred microvolts. These noise signals dropped to less than 10 μv after re-taping.

Heating of the upper block with any type of contact heater should be satisfactory. Tube furnaces of the radiation type were found to have too large a time lag. When a high flow rate is stopped, the heat demand of the upper block may change from around 300 to 10 w. If the heating element is appreciably hotter than the upper block during the high heat demand with flow, the upper block temperature will rise above the control setting after the flow is stopped. Three-hundred-watt strap heaters were used on most of the flowmeters. Another heater used was made by winding a coil of Nichrome wire directly on the brass block by means of a thin sheet of mica between the wire and the block. The wire can be spaced very closely by winding a string with the wire as a spacer which is removed after the coil is wound. The coil is then coated with a Sauereisen cement to hold it in place. This type of heater has a smaller time lag than the strap heater. Thermal insulation around the upper block will increase the flow-measuring capacity of the meter. The bottom block should not be insulated, as this will cause the temperature to rise excessively under some conditions. If it is necessary to prevent condensation of the flowing gas, the lower block may be heated without insulation.

A NOTE ON TEMPERATURE MEASUREMENT

The use of a normal on-off type of pyrometer controller for the block heater will give a cycle time of the order of one minute. This oscillation will appear in the thermopile output with an amplitude of the order of 10 percent of the DC output voltage. For printing-type recorders this will give an unsatisfactory record, unless the printing frequency is much higher than the input oscillation frequency. In this case, or in the case of a continuous recording, the oscillation can be averaged to give a reading. Proportioning-type pyrometer controllers will give a cycle time of about 5 sec. In this case, the oscillations of the output are less than 10 μv under all flow conditions.

In one installation, a Brown strip-chart recorder gave sudden small changes in the recorded output when the heater switched opened or closed. A filter consisting of a 100-μf electrolytic capacitor and an inductor eliminated the effect. Apparently, a small amount of 60-cycle voltage is produced in the output by magnetic linkage between the heater and thermopile.

USE OF THERMISTORS

Thermistors (high-temperature-coefficient resistors) have been used instead of the thermopile to obtain higher output voltage at low flow rates. This method provides a more flexible unit because the zero-flow output voltage and output voltage change (with flow) are independently adjustable. A direct-current power supply is required with sufficient stability for the accuracy desired. A schematic of the circuit is shown in Figure 4. Output sensitivity varies with temperature of the bottom block and some degree of control of block temperature is required. The temperature-sensitivity relation is shown in Figure 5.

Figure 4

THERMISTOR CIRCUIT

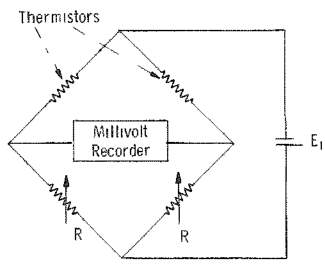
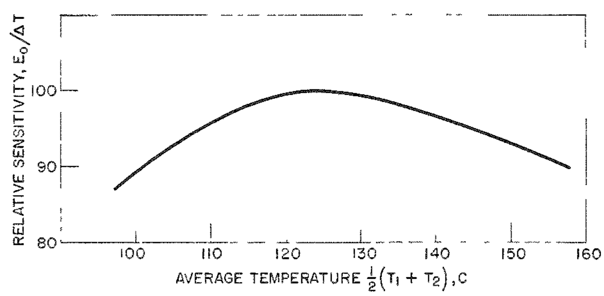


Figure 5

RELATIVE SENSITIVITY OF THERMISTOR CIRCUIT TO AVERAGE THERMISTOR TEMPERATURE (See Figure 2)



The thermistor resistance is accurately described by the equation:

$$R = R_0\, e^{B/T} \quad , \qquad (1)$$

where R_0 and B are constants and T is absolute temperature of the temperature of the thermistor. The thermistors used had specifications limits of ± 20 percent on R_0 and ± 5 percent on B. In order to reduce the change in zero-flow output voltage with temperature of the bottom block, the thermistors should be matched with respect to their temperature coefficients. The output of the circuit in Figure 4 is

$$E_0 = E_i \left(\frac{R}{R + R_0\, e^{B/T'}} - \frac{R}{R + R_0\, e^{B/T''}} \right) \quad , \qquad (2)$$

where T' and T" are thermistor temperatures. The condition for minimum change in sensitivity with temperature is

$$\frac{\partial^2 E_0}{(\partial T')^2} = 0 \qquad (3)$$

and gives

$$R = R_0 \, e^{B/T}\left[\frac{2B}{B + 2T} - 1\right] \quad . \tag{4}$$

The temperature in this relationship is the average temperature of the 2 thermistors, or approximately the temperature average of the upper and lower blocks, and is used to set the 2 fixed resistances in the bridge. Zero adjustment was then made by changing the 2 resistors while keeping the sum of the 2 constant. The thermistors used were Victory Engineering Corp. Type 32A12. They were mounted by cementing with insulating varnish in shallow notches filed in the inner side of the tubes midway between the blocks.

MATHEMATICAL ANALYSIS OF DESIGN

In order to simplify the mathematical analysis, the following assumptions are made:

1. The two blocks are at a uniform temperature.
2. The gas leaving a block is at the same temperature as the block.
3. The gas temperature in the tubes between the blocks is constant and at the same temperature of the block from which it left.

For the condition: temperature change = (heat conducted along tube) - (heat lost to fluid), the basic equation is

$$\frac{\partial T}{\partial t} = \frac{k}{\rho c}\frac{\partial^2 T}{\partial x^2} - \frac{hA_2}{\rho c A_1}(T - T_1) \quad . \tag{5}$$

The boundary conditions are

$$\begin{aligned} x &= 0 & T &= T_1 \\ x &= L & T &= T_2 \\ t &= 0 & T &= T_1 + x\frac{(T_2 - T_1)}{L} \quad . \end{aligned} \tag{6}$$

The general solution is

$$T = T_1 + \frac{2(T_2 - T_1)}{L}\sum_{n=1}^{\infty} -(-1)^n \sin\frac{n\pi x}{L}\left[\left(\frac{L}{n\pi} - \frac{n\pi k}{LZ}\right)e^{-tZ} + \frac{n\pi k}{LZ}\right] \quad , \tag{7}$$

where

$$Z = \frac{hA_2}{\rho c A_1} + \frac{k\pi^2 n^2}{\rho c L^2} \quad . \tag{8}$$

The time transient in the above solution decays exponentially with a time constant of $1/Z$ and has a maximum value when $n = 1$. The time constant would be less than this maximum value at the beginning of a transient and would approach this maximum.

The steady-state solution is

$$T = T_1 + (T_2 - T_1) \frac{\sinh (ax)}{\sinh (aL)} \quad , \tag{9}$$

where

$$a = \sqrt{hA_2/kA_1} \quad . \tag{10}$$

The temperature difference between the centers of the 2 tubes is

$$\Delta T = (T_2 - T_1) \left[1 - \frac{2 \sinh(aL/2)}{\sinh (aL)}\right] \tag{11}$$

when

$$aL \ll 1$$

and

$$\Delta T = (T_2 - T_1)\, a^2 L^2/8 \quad . \tag{12}$$

COMPARISON OF FLOWMETER DESIGNS

An early thermal flowmeter based on the classical design and referred to as Mark I[1] is shown in Figure 6. This design originated at Oak Ridge National Laboratory and is adequate for low flow rates. The straight part of the tubing loop was 0.006-in. wall, $\frac{1}{4}$-in. OD Inconel tubing, and the bend was copper tubing. The unit was assembled with solder and insulated by filling a surrounding box with expanded mica. The output was obtained from 6 iron-constantan pairs across the centers of the length of Inconel. The power input to the heater was about 14 w for the calibration shown in Figure 7. The time constant of the flowmeter was about 10 min at low flow rates to around 5 min at flow rates of 100 ml/min. The use of a length of 10 in. in the time-constant equation gave a maximum time constant of 8 min at low flow rates.

Figure 6

ORNL FLOWMETER
(Mark I)

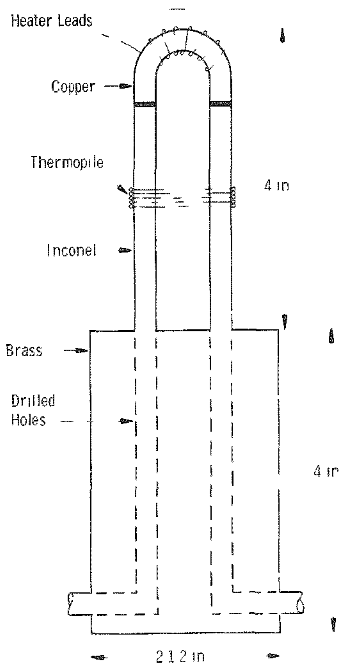
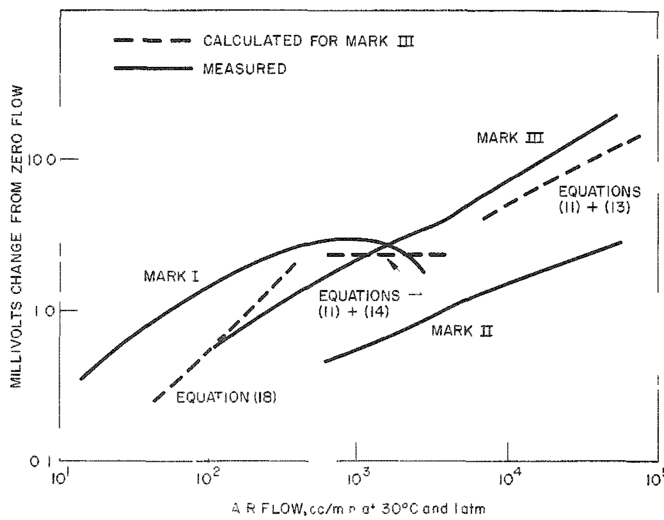


Figure 7

CALIBRATION OF THREE THERMAL FLOWMETERS WITH AIR



The modified wide-range flowmeter is designated Mark II and is shown in Figure 2. The calibration in Figure 7 was obtained with a temperature difference across the blocks of 150°C. The measured time constant was 3 sec and was independent of flow. The calculated maximum time constant is 5 sec.

The Mark III flowmeter is similar to the design given in Figure 2 except for an increase in block spacing to 1.5 in. and a coiling of the tubing in the top block. A 6-turn one-in. OD coil was formed and cast in an aluminum block 4 in. long by $1\frac{1}{4}$-in. OD.

THEORETICAL ANALYSIS OF MARK III CALIBRATION CURVE

The 3 calculated curves in Figure 7 were for the Mark III dimensions. The 2 curves at the higher flow rates were based on the assumptions previously stated, which includes that of a constant gas temperature in the tubes between the blocks.

For turbulent flow, the dimensional relationship for air is[2]

$$h = 16.6\ c_p\ G^{0.8}/D^{0.2} \quad . \qquad (13)$$

For $\frac{3}{16}$ -in.-ID tubing, turbulent flow starts at 7 l/min. For laminar flow, the literature gives average values of h for constant wall temperature and as a function of tube length to take care of entrance effects. The following theoretical relationship for fully developed laminar flow was used[3]:

$$h = 4.1\ k/D \quad . \tag{14}$$

It is apparent that the assumptions are not valid in this flow range, and the curve was included only to show the region of transition between the other two calculated curves.

At low flow rates the gas temperature will approach the wall temperature. Setting the two equal gives

$$\frac{d^2T}{dx^2} - a\frac{dT}{dx} = 0 \quad , \tag{15}$$

where

$$a = Mc_p/kA_1$$

$$T = T_1 + (T_2 - T_1)\ \frac{e^{ax}-1}{e^{aL}-1} \tag{16}$$

$$\Delta T = (T_2 - T_1)\left[\frac{2(e^{aL/2}-1)}{e^{aL}-1} - 1\right] \quad , \tag{17}$$

when

$$aL << 1$$

$$\Delta T = (T_2 - T_1)\ \frac{aL}{4} \quad . \tag{18}$$

Equation (18) is plotted on Figure 7 and is approached at low flow rates as was expected.

NOMENCLATURE AND UNITS

A_1	tubing wall cross sectional area, sq ft
A_2	tubing inside area per length, sq ft/ft
c	tubing heat capacity, Btu/(lb)(F)
c_p	gas heat capacity, Btu/(lb)(F)
D	inside tubing diameter, in.

E_i	bridge input voltage
E_0	bridge output voltage
G	mass velocity of gas, lb/(sq ft)(sec)
h	heat transfer coefficient of gas, Btu/(hr)(sq ft)(F)
k	thermal conductivity of tubing, Btu/(hr)(sq ft)(F)/ft
L	length of tubing between fixed temperature, ft
R	resistance, ohms
T	tubing temperature
T_1	lower block temperature
T_2	upper block temperature
T', T"	thermistor temperatures
ΔT	temperature difference between tubing midpoints
t	time
ρ	density, lb/cu ft
M	mass flow of gas, lb/hr
x	distance along tube

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