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A THERMAL MASS FLOW SENSOR USING A CONSTANT DIFFERENTIAL TEMPERATURE ABOVE THE AMBIENT GAS TEMPERATURE

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ABSTRACT

A new sensor is presented for measuring the mass flow of gases. The sensor has an inherently linear response and minimal pressure drop, and responds to changes in flow rate in less than 300 milli-seconds. The sensitivity of the sensor to changes in the ambient temperature and other sources of error has been minimized. It provides a linear output from zero to 25 standard cm^3/min (SCCM)¹ of nitrogen, which is 200% to 500% greater than the operating range of previous thermal mass flow sensors. Detailed description of the sensor design, theoretical discussion of the measurement method, and performance data are presented.

NOMENCLATURE

C_p	= specific heat at constant pressure
C_v	= specific heat at constant volume
P	= electrical power supplied to either heater
P_d	= electrical power supplied to downstream heater
P_u	= electrical power supplied to upstream heater
R_l	= value of fixed resistor in series with either heater
$T_{ambient}$	= ambient gas temperature
T_{heater}	= heater temperature
T_m	= mean gas temperature
$T_{m,mid}$	= mean gas temperature at axial midpoint of tube
$T_{m,1}$	= mean gas temperature at tube inlet
$T_{m,2}$	= mean gas temperature at tube outlet
SCCM	= standard cubic centimeters per minute

¹ Note that the mass flow rate is expressed in SCCM by industry convention. This value expresses the mass flow rate as its equivalent volumetric flow rate at standard conditions of 0 °C and 101.325 kPa. The actual mass flow rate in SI units is obtained by multiplying the SCCM value by the gas density at standard conditions.

V_1	= voltage at top of either bridge
V_2	= voltage across either resistive heater coil
m	= mass flow rate of the gas
p	= pressure of the gas
q_{conv}	= rate of convective heat transfer
$q_{i,d}$	= rate of conduction by downstream insulation
$q_{i,u}$	= rate of conduction by upstream insulation
$q_{t,d}$	= rate of conduction by tubing at downstream
$q_{t,u}$	= rate of conduction by tubing at upstream
v	= volume of the gas
x	= distance along the tube

INTRODUCTION

Many methods for measuring gas flow are reviewed by Goldstein (1983). These measurement techniques can be classified either as volumetric flow measurements or mass flow measurements.

Volumetric flow measurements are often undesirable and inaccurate because the volume of a gas is directly proportional to the absolute gas temperature, and inversely proportional to the absolute pressure applied to the gas volume. Consequently, when a given number of molecules of a particular gas is passed through a volumetric flow meter at different operating conditions, the meter will indicate different flow rates. The output of a volumetric flow meter can be corrected by taking into account the temperature and pressure of the metered gas, but these additional measurements increase the complexity and cost of the volumetric flow meter.

Mass flow measurements, however, are substantially independent of variations in the temperature and pressure of the gas stream. Of the available methods for measuring the mass flow rate of a gas, thermal transfer sensors are the most common. These sensors all have some means of heating th

gas flow, since heat transferred to a flowing fluid is known to be proportional to the mass flow rate of that fluid. Conventional sensors will then obtain some temperature measurement which is indicative of the heat transfer rate, and is thus characteristic of the mass flow rate.

One common measurement approach is to maintain one aspect of the heater, such as the heater power, voltage, or current constant. The output from this approach is based on the temperature change of the gas at points upstream and downstream from the heater. Other conventional approaches utilize coils of temperature sensitive resistance wire which serve as combination heating elements and temperature monitors. The resistance of the wire will increase with an increase in temperature, which again is used to indicate the heat transfer rate, which is directly proportional to the mass flow rate.

Since these traditional sensing methods all rely on temperature measurements to indicate the mass flow rate, they introduce new temperature dependent errors in the mass flow signal. Changes in the temperature of the operating environment or in the ambient temperature of the sensed gas typically alter the conventional flow meter output by 0.05% to 0.1% per degree Celsius. This is a significant error considering the thermal mass flow meter commonly achieves 1% to 2% full scale error when run at stable temperature conditions.

It is easy to see that the conventional thermal mass flow sensor, while more desirable than volumetric flow sensors, does have limitations. The driving motivation for the work presented in this paper is thus to provide a new type of thermal mass flow sensor which can overcome the limitations of previous sensors.

SENSOR DESCRIPTION

A cross section of the sensor is shown in Fig. (1). The sensor consists of two coils of resistance wire with a high temperature coefficient of resistance (3500 ppm/ °C) wound around a stainless steel tube with internal diameter of 0.6604 mm and 7.62 cm length. Each coil is 1.372 cm in length, and they are separated by 1.27 mm distance. These two identical resistance wire coils are used to heat the gas stream, and are symmetrically located upstream and downstream on the sensor tube. Insulation surrounds the sensor tube and heater coils with no voids around the tube to prevent any convection losses. The ends of this sensor tube pass through an aluminum block and into the stainless steel sensor base. This aluminum block thermally shorts the ends of the sensor tube and maintains them at ambient temperature.

There are two coils of resistance wire that are wound around the aluminum block. The coils are identical to each other, and are symmetrically spaced on the aluminum ambient block. These coils are wound from the same spool of wire that is used for the sensor heater coils so they have the same resistivity and the same temperature coefficient of resistance as the sensor heater coils. The number of turns is controlled to have a resistance that is 10 times larger than the resistance of the heater coils. Thermal grease fills any voids between the

ambient temperature block and the sensor tube to ensure that the ends of the sensor tube are thermally tied to the temperature of this aluminum block.

Aluminum has a very high thermal conductivity which ensures that both ends of the sensor tube and the two coils wound around the ambient block will all be at the same temperature. This block is in good thermal communication with the stainless steel sensor base to ensure that the ambient block is at the same temperature as the main instrument block, and therefore the same temperature as the incoming gas stream. This allows the coils wound on the aluminum block to sense the ambient gas temperature.

Two identical Wheatstone bridges are employed, as shown in Fig. (2). Each bridge utilizes an ambient temperature sensing coil and a heater coil. The heater coil and a constant value series resistor comprise the first leg of the bridges. The second leg of each bridge contains the ambient sensing coil and two constant value series resistors. These Wheatstone bridges keep each heater temperature at a fixed value of 48 °C above the ambient sensor temperature through the application of closed loop control, and the proper selection of the constant value bridge resistors.

THEORY OF OPERATION

The heat convected to or from a fluid is proportional to the mass flow of that fluid. From Incropera and De Witt (1990) we know that the rate at which the heat is transferred is governed by Eq. (1):

$$\frac{dq_{conv}}{dx} = \dot{m} \frac{d(C_p T_m + p v)}{dx} \quad (1)$$

As in conventional thermal mass flow meters, an assumption is made that the fluid is a perfect gas. By making the perfect gas assumption and integrating over the total length of the sensor tube, Incropera and De Witt develop an expression for the total tube heat transfer rate which is:

$$q_{conv} = \dot{m} C_p (T_{m,2} - T_{m,1}) \quad (2)$$

Since the constant differential temperature sensor has 2 heater coils symmetrically spaced on the sensor tube, it is convenient to consider the upstream and downstream heat transfer modes separately. The electrical power supplied to

either of the heater coils will be converted to heat, which can be dissipated by radiation, conduction, or convection. The radiation term is negligible due to the low temperatures used by the sensor, and because the sensor construction preferentially favors the conductive and convective heat transfer modes. The thermal energy of each heater will then be dissipated by conduction down the stainless steel sensor tube, conduction to the insulating foam, plus the convection due to the mass flow of the sensed gas. This relationship between the power input to the heater and the heat dissipation mechanisms is thus shown in Eq. (3) for the upstream heater, and Eq. (4) for the downstream heater.

$$P_u = q_{i,u} + q_{i,u} + \dot{m} C_p (T_{m,mid} - T_{m,1}) \quad (3)$$

$$P_d = q_{i,d} + q_{i,d} + \dot{m} C_p (T_{m,2} - T_{m,mid}) \quad (4)$$

Because great care is taken to wind the resistive heater coils symmetrically about the midpoint of the tube, it is assumed that the heat conducted along the sensor tube from the upstream heater will be equal to the heat conducted through the tube from the downstream heater. Similarly, the heat conducted from the upstream and downstream coils to the foam insulation surrounding them is assumed to be equal, based on the symmetry of the sensor construction. By equating these conduction terms, Eq. (3) and Eq. (4) can be combined to give:

$$P_u - \dot{m} C_p (T_{m,mid} - T_{m,1}) = P_d - \dot{m} C_p (T_{m,2} - T_{m,mid}) \quad (5)$$

Since the sensor tube inlet and outlet are linked by an aluminum ambient bar, the high thermal conductivity of the bar provides a 'thermal short', constraining the ends of the sensor tube to be at equal surface temperature. Moreover, the tube ends and the aluminum ambient bar have intimate thermal communication with the main flow passageway prescribed by the main stainless steel flow meter body. This further constrains each end of the sensor tube to be equal to the ambient gas temperature. Incorporating these restrictions into Eq. (5), and combining like terms, Eq. (6) can be written.

$$P_u - P_d = \dot{m} C_p (2T_{m,mid} - 2T_{ambient}) \quad (6)$$

Since the length of each heater section is nearly 21 times greater than the inside tube diameter, the mean gas temperature at the tubes axial midpoint is approximately equal to the tube surface temperature at that point. Recall that the outside of the sensor tube is well insulated from the surroundings, therefore

the tube surface temperature at the axial midpoint is very close to the operating temperature of the heater coils. The mean temperature of the gas stream is then approximately the same as the heater temperature. By approximating the mean gas temperature as the heater temperature, we can write Eq. (7):

$$P_u - P_d = 2\dot{m} C_p (T_{heater} - T_{ambient}) \quad (7)$$

The value of the constant pressure specific heat of a gas is virtually constant over small changes in temperature. By maintaining both heaters at the same, constant temperature difference above the ambient gas stream temperature, the difference in heater power is a function only of the mass flow rate. Fluctuations in ambient gas temperature which cause errors in conventional mass flow sensors are avoided; The resistance of the ambient sensing coil changes proportionally with the ambient temperature fluctuations, causing the closed loop control to vary the bridge voltage such that the heater resistance changes proportionally to the ambient temperature fluctuation.

The power supplied to each of the 2 heater coils is easily obtained by measuring the voltage across the heater, shown as V_2 on Fig.(2), and the voltage across the fixed resistor R_1 . Since R_1 is in series with the heater R_H they have the same current flowing through them. The electrical power supplied to a given heater is then calculated:

$$P = \frac{(V_1 - V_2)V_2}{R_1} \quad (8)$$

With a constant differential temperature applied to each heater coil and no mass flow through the sensor the difference in heater power will be zero. As the mass flow rate through the sensor tube is increased, heat is transferred from the upstream heater to the gas stream. This heat loss from the heater to the gas stream will force the upstream bridge control loop to apply more power to the upstream heater so that the 48 °C constant differential temperature is maintained.

The gas stream will increase in temperature due to the heat it gains from the upstream heater. This elevated gas stream temperature causes the heat transfer at the downstream heater to gain heat from the gas stream. The heat gained from the gas stream forces the downstream bridge control loop to

apply less power to the downstream heater coil in order to maintain a constant differential temperature of 48 °C.

DESCRIPTION OF EXPERIMENTAL METHOD

Data is presented for the accuracy, temperature coefficients, response time to a step change in flow, and pressure drop of the sensor. In all of the experiments the sensors under test were mounted on identical flow meter bodies, through which the main gas flow was passed.

The accuracy test were conducted by passing dry nitrogen through a pressure regulator, and into a flow control valve, which was used to vary the mass flow rate of the gas. From the valve, the nitrogen passed through a flow reference, and then into the units under test. The reference used was a commercially available calibration instrument which indicates the mass flow rate with $\pm 0.2\%$ accuracy. All of the instruments under test were configured such that all of the gas flow passed through the sensor tube.

Tests of the sensor temperature coefficient were conducted using a computer controlled environmental chamber. The sensors under test were placed inside the environmental chamber, while the flow reference was located outside the chamber where it was unexposed to thermal changes. Leak free gas lines passed through an access port in the chamber wall, connecting the flow reference to the test sensors. These gas lines were made of copper with sufficient length such that the test gas achieved the temperature of the environmental chamber before entering the test sensors. The chamber was cycled from 56 to -10 degrees Celsius while maintaining the humidity level as low as possible. The sensors were operated at 20% of their calibrated full scale for 1.5 hours after each step change in chamber temperature. After this temperature stabilization time the mass flow rate through the sensors was cycled from zero to full scale. Sensor output, temperature, and output of the mass flow reference were recorded after 4 minutes of stabilization time at each flow set point.

Response time tests were conducted using dry nitrogen. The nitrogen was passed through a pressure regulator and into a bleed valve, which was used to adjust the gas flow rate. After the bleed valve, the gas was routed into a two position solenoid valve. The solenoid valve had minimal internal volume and was used to trigger a step change in flow by diverting the nitrogen between its 2 outlets. A sensor was connected to each outlet of the solenoid valve so that both paths had equal flow resistance. A mechanical rough pump was connected to the downstream end of the sensors to prevent the gas from compressing during the step change from the no flow to full flow condition. A calibrated oscilloscope collected the sensor outputs.

Sensor pressure drop versus flow rate was measured for dry nitrogen at 22 °C. The sensors were mounted on a flow meter base which was configured so that all of the gas flow passed through the sensor. A calibration instrument which indicates the mass flow rate with $\pm 0.2\%$ accuracy was placed upstream of the test sensor. One side of a calibrated

differential pressure gauge was connected between the flow reference and the inlet to the test sensor. The other side of the differential pressure gauge was connected to the outlet of the device under test, which was vented to atmosphere. Another calibrated pressure gauge was used to measure the atmospheric pressure.

TEST RESULTS

A graph of the sensor output versus mass flow rate is shown in Fig. (3). Both heaters require a power of 110 mW at zero flow, which is an output of 0 mW. With gas flow through the sensor the heater power diverges producing an output with typical sensitivity of 2.35 mW / SCCM. The output is inherently linear for flow rates up to 25 SCCM, having less than 0.75% deviation from a terminal based line, as shown in Fig. (4). In contrast, existing mass flow sensors must remain below 5 SCCM to 10 SCCM, depending on the design, in order to achieve a similar degree of linearity.

Information on the thermal stability of the constant differential temperature sensor is shown in Fig. (5) and Fig. (6). Figure (5) gives the percentage change in full scale output versus ambient temperature. The maximum deviation of the full scale output from the original full scale value is equivalent to a full scale thermal coefficient of 0.03% per degree Celsius. The percentage change in the zero flow output versus the ambient temperature is shown in Fig. (6). At the zero flow condition maximum thermal coefficient of the sensor is 0.052% per degree Celsius.

A graph of the typical sensor response to a step change in flow rate is shown in Fig. (7). Rise time for the sensor is less than 300 milli-seconds. Settling time occurs in under 450 milli-seconds, with less than 2% overshoot.

The sensor has an inherently linear pressure drop over its 25 cm³ / min measurement range, as shown in Fig. (8). The typical differential pressure required per cm³ / min of mass flow is 5.6 Pa. Existing sensors typically require a 50 Pa pressure difference in order to drive 1 cm³ / min through the sensor.

CONCLUSION

The constant differential temperature sensor described in this paper provides superior performance in accuracy, measurement range, response time, and thermal stability. It is also less obtrusive to the measured gas flow than are conventional sensors, due to its minimal pressure drop.

ACKNOWLEDGMENTS

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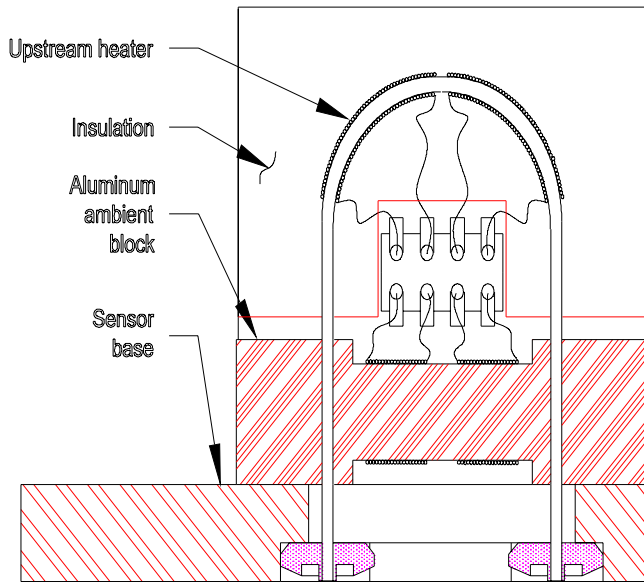


Fig. (1): Cross Sectional View of the Constant Differential Temperature Mass Flow Sensor

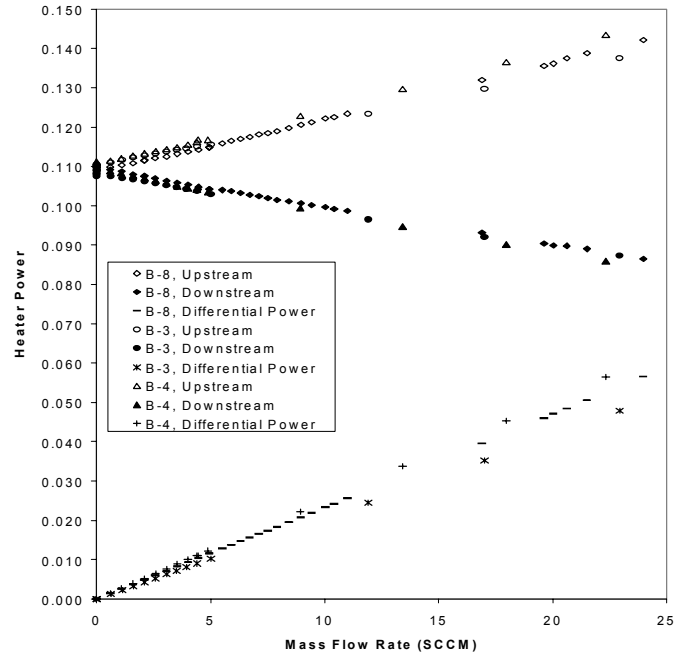


Fig. (3): Power Required To Maintain Constant Differential Heater Temperature Versus Mass Flow Rate

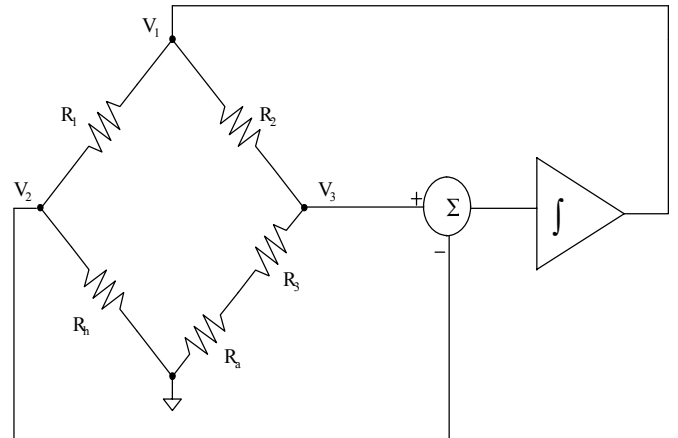


Fig. (2): Control Structure For Maintaining The Heated Resistor R_n At Constant Differential Temperature

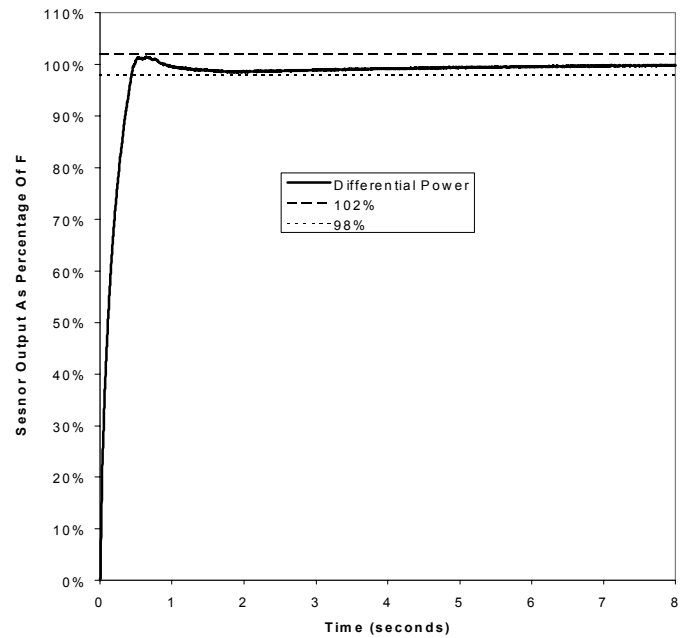
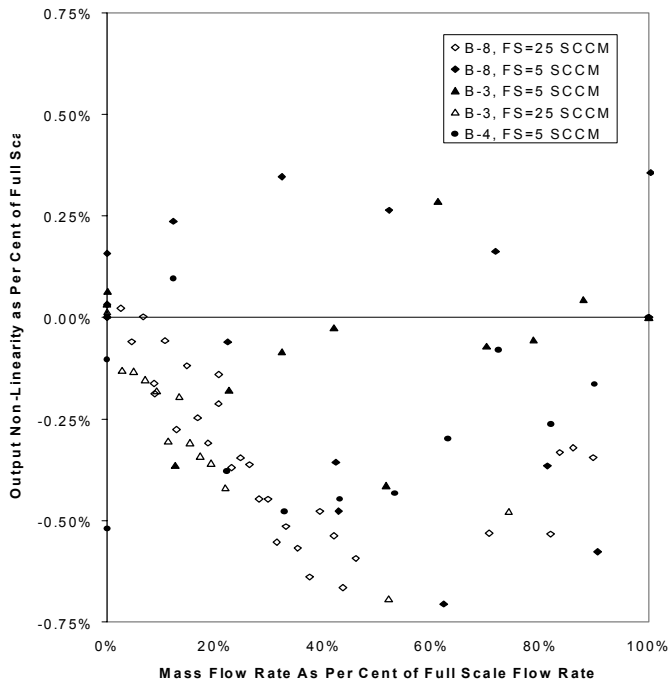


Fig. (4): Percentage Deviation In Sensor Output From A Terminal Based Line Versus Percent Of Full Scale Flow Rate

Fig. (7): Response Of The Sensor Output To A Step Change In Flow From 0 To 25 SCCM Of Nitrogen

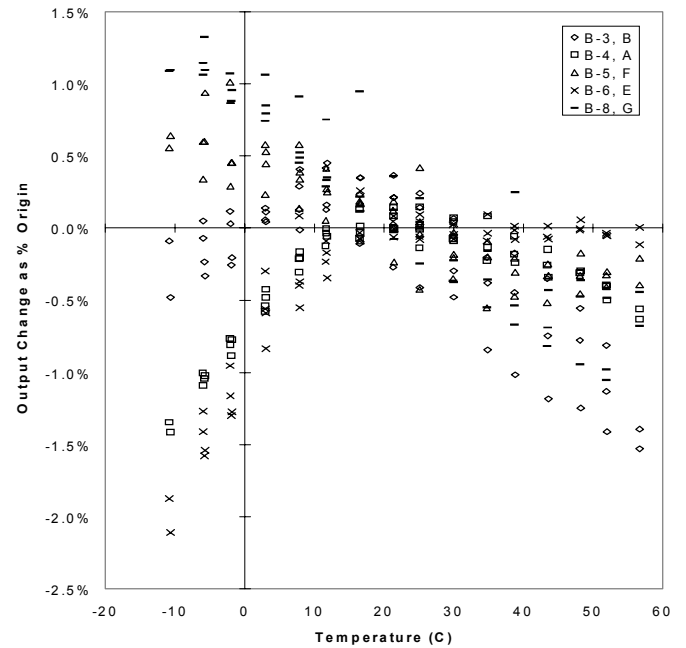
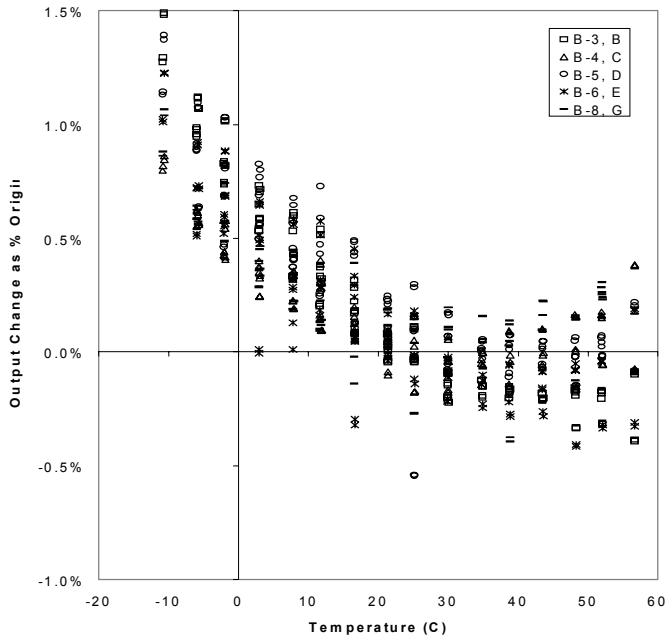


Fig. (5): Sensor Full Scale Output Variation Versus Ambient Gas Temperature

Fig. (6): Sensor Output Variation At Zero Flow Versus Ambient Gas Temperature

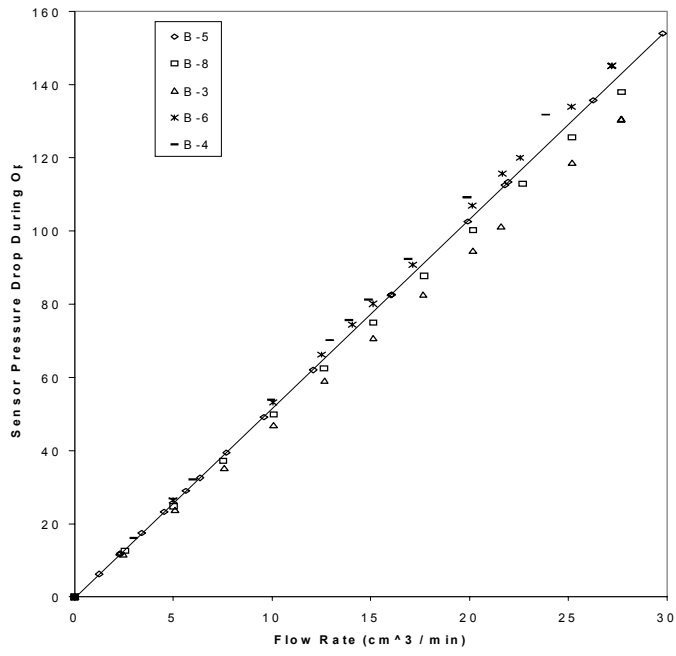


Fig. (8): Sensor Pressure Drop Versus Flow Rate Of