Publications from the Ph.D work

Publications in International Journal


3. M. Viswanathan, R. Rajesh, Dr. Nagaraj Sitaram and Dr. A. Kandaswamy - "Modeling and experimental investigations to locate the optimum positions for pressure sensing in a vortex shedding flowmeter and comparison of sensors" – under review for the international journal “Flow Measurement and Instrumentation” – U.K.

Papers presented in conferences


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CURRICULAM VITAE OF THE AUTHOR

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<table>
<thead>
<tr>
<th>Examination</th>
<th>Year</th>
<th>Institution</th>
</tr>
</thead>
<tbody>
<tr>
<td>B.E. (Electronics &amp; Communication Engineering)</td>
<td>1975</td>
<td>University of Madras (PSG College of Technology)</td>
</tr>
</tbody>
</table>

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      i) P.S.G. College of Technology, Coimbatore
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Development, modeling and certain investigations on thermal mass flow meters

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Abstract

This paper discusses a thermal mass bypass flow meter giving details of its design, principle of operation, calibration, and testing of effects of ambient temperature and orientation. Results of a computer model of the meter are also given. © 2002 Elsevier Science Ltd. All rights reserved.

Keywords: Modeling; Thermal mass flow meter; Computational fluid dynamics; Calibration; Accuracy; Gases

1. Introduction

The thermal mass flow meter [1–3] senses flow by measuring the rate of heat transfer from a heated tube to the gases flowing inside the tube. There are two measurement techniques that are commonly employed. The first technique is to provide a constant input power to a section of tubing and measure the temperature of the tube on both sides of the heated section. The flowing gas skews the temperature distribution of the tube such that the down stream temperature is larger than the upstream value. This measured difference is linearly dependent upon mass flow to the first order according to:

\[ \dot{m} = \frac{Q}{C_p(T)(T_{Cd} - T_{Cu})} \]

where \( C_p(T) \) is the temperature dependent molar heat capacity (J mol\(^{-1}\) k\(^{-1}\)), \( Q \) the rate of heat transfer (Js\(^{-1}\)) from the capillary wall to the gas, \( T_{Cd} \) the gas temperature (K) at the down stream of the heated capillary, \( T_{Cu} \) the gas temperature (K) at the upstream of the heated capillary, and \( \dot{m} \) is the molar flow (mol s\(^{-1}\)). The second technique heats the tube by maintaining a constant temperature independent of flow. The amount of power required to maintain the constant tube temperature is then proportional to the mass flow in the tube. The former technique is employed in our case.

2. Previous investigations on thermal mass flow measurement

The characteristics of a thermo tube type thermal gas flow meter were analyzed and experimental results were given by Komia et al. [3]. A thermal mass flow meter for the measurement of fuel consumption in automobiles and light aircraft, and of liquid flows in industrial processes was designed and evaluated by Hujsing et al. [4]. Wardle [5] has reported the design and construction of a simple and inexpensive mass flow meter based on a miniature bead thermistor, and suitable for direct interfacing with a microcomputer/microprocessor. A coriolis mass flow meter measures three process variables—direct mass flow, temperature and density with a single sensor [6]. Constant temperature anemometers and resistance temperature detectors have been adapted to measure the instantaneous mass flow rates and temperatures in the oscillating gas flows at frequencies up to 30 Hz and temperatures down to 70 K [7]. Bartos [8] has reported that accurate fluid flow measurement depends on undisturbed velocity profiles in the flow stream.

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3. Development of thermal mass flow meters

Two numbers of thermal mass flow meters 1 slpm (standard liters per minute, i.e. mass flow rate equivalent to liters of gas at standard temperature and pressure) and 5 slpm have been designed and developed by us. The schematic of electronic circuits for the above are shown in Fig. 1. The cable length between the flow sensor and the signal conditioner unit is 1.5 m which is fixed and that between signal conditioner unit and indicator unit is 200 m in the case of both 1 and 5 slpm meters. The indicator accepts 230 V, 50 Hz power supply and displays the flow rate in four digits with a resolution of 0.001 slpm and totalized mass in six digits and has low and high (variable at site) set points or alarms. It has a crystal oscillator for generating 24 V AC (variable), 16.38 kHz supply which is transmitted from the indicator to the sensor through the signal conditioner unit where this AC supply is used for generating ±15 V DC for the operation of electronic circuits in it.

The thermocouples are fixed in the bypass capillary tube. The oscillator in the indicator generates 24 V, 16.38 kHz which when reaches the heater coil in the sensor becomes 21 V, 16.38 kHz because of the voltage drop in the 200 m cable between indicator and signal conditioner unit. AC current of around 350 mA will flow through the coil for heating the capillary bypass tube and the corresponding temperature at the top of the bypass tube is approximately 200°C for the applied voltage (21 V AC, 16.38 kHz). The heat generated is held at a fixed value by keeping the supply voltage and frequency constant. The meter need not be recalibrated if the cable length between the indicator and signal conditioner is changed. For this purpose, a potentiometer is provided in the indicator which when adjusted will ensure a voltage of 21 V AC, 16.38 kHz to the heater coil. The oscillator circuit uses a variable DC power supply of 0–35 V DC. This DC voltage when increased using the potentiometer in the indicator will increase the AC voltage to the heater coil and vice versa. Thus whenever the cable length between the indicator and signal conditioner is changed, the 0–35 V DC voltage is varied using the potentiometer in the indicator so that a voltage of 21 V AC, 16.38 kHz is ensured to the heater coil always. So there is no need for recalibration if cable length is changed. The cable length between the flow sensor and the signal conditioner is always kept at 1.5 m and is never changed (if this cable length is changed the

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**Fig. 1. Schematic of transducer, signal conditioner unit and indicator unit of 1slpm & 5slpm thermal mass flow meters.**

The 0-10 or 0-50 kHz signal is used for 0-1 or 0-5 slpm count option and its output is given to a divide-by-60,000 equipment. Here 0-10 V DC is further converted into 4-20 mA. This 0-10 V DC is given as input to the set point indicator, the 4-20 mA signal is converted into 0-10 V DC by a voltage to current converter and is then transmitted to 0-10 V DC which is then converted into 4-20 mA and is also converted into (0-100) kHz using a voltage to frequency converter and is further divided to get (0-50), (0-10) and (0-5) KHz, respectively, to get count options of 100, 50, 10 and 5 counts/min, respectively. A 5-position switch is used for selecting the required count option and its output is given to a divide-by-60,000 counter and is counted by a 6-digit BCD counter.

Let the 5-position switch be connected to 0–50 kHz signal; this corresponds to 50 counts/min. When full flow is there, 50 kHz output will be obtained which is divided-by-60,000. Hence,

\[
\text{Output frequency} = \frac{50 \times 10^3 \times 60}{60000} \quad \text{cycles/min}
\]

\[
= 50 \text{ counts/min.}
\]

Similarly, 100, 10 and 5 counts/min can be obtained, when the 5-position selector switch is connected to 0–100, 0–10 and 0–5 kHz signals, respectively, at 100% flow. The output of divide-by-60,000 counter is counted by two 3-digit BCD counters. The output of the counters are latched and decoded into 7-segment output. Six common cathode 7-segment LEDs are used to display the totalized count. The 0–10 or 0–50 kHz signal is used for 0–1 or 0–5 slpm meter, respectively, and is counted by pulse counter and is then given to a 4-digit flow rate indicator. The thermal mass flow transducer assembly for 1 slpm meter is shown in Fig. 3. The tube bundle is provided for laminar flow and also for providing sufficient flow through the bypass capillary tube. The pressure drop due to this tube bundle must be as minimum as possible. No other reason is there for the particular choice of restriction in the main tube.

4. Calibration

One and 5 slpm meters were calibrated at 20°C and at ambient pressure with nitrogen as the calibration gas using the primary standard A-200F CALIFLOW system, a fully automatic flow rate calibrator purchased from M/S MKS Instruments Inc, USA. The Califlow system (reference instrument) has an accuracy of ±0.2% of flow rate in the flow range of 0.02–50 slpm. The schematic of the calibration setup is shown in Fig. 2.

4.1. Description of MKS Califlow A200 calibration system

The gas flow rates are measured by collecting volume of gas under a piston, which moves vertically inside a precision baro silicate glass cylinder. A smaller 1.5-in.-diameter cylinder is selected for flow rates less than 1 slpm and for flow rates up to 50 slpm, a 6-in.-diameter cylinder. The test nitrogen gas flows through the selected mass flow controller, the instrument under test and into the cylinder, which displaces the piston. A mercury seal between the piston and the cylinder serves to contain the test gas and minimize the frictional forces. A counter-weight balancing each piston further enhances the sensitivity of the system. Each cylinder is provided with optical encoder, generating a pulse representing an incremental change in the displaced volume, whenever the piston moves in vertical direction. The system’s electronics initiates/terminates the operation of a precise, crystal clock concurrent with leading edge of square wave pulse generated by the encoder. The encoder/timer provides for exceptional volume/time measurement accuracy. In order to accurately calculate the mass flow rate, the temperature and pressure of the entrapped gas in the cylinder during each test must be known. In A200, the temperature is measured with a precision platinum resistance thermometer (PRT) and the pressure is measured by the capacitance manometer system with an accuracy of ±0.05% of reading. The thermometer output along with that of the encoder, timer, and capacitance manometer is processed through interface electronics to the computer where the flow rate is calculated and displayed. Four mass flow controllers are provided with A200 with full-scale ranges of 0.05, 0.5, 5 and 50 slpm. These establish the flow rate of the test gas, which passes through the instrument under test and into califlow where the final volumetric measurement is made. A desktop computer has been configured to become an integral part of the califlow system. Analog to digital converter reads the outputs of mass flow controllers, pressure electronics unit and PRT. The digital to analog converter establishes flow set points for the flow
controllers. Logic circuits read/set switch positions and an
electronic counter counts both encoder and clock pulses.
The system provides continuous multiset point
calibrations automatically. It has provision for manual
operation also.

In order to improve the accuracy of the meter, two cali-
brations were done. After the first calibration, the data for
the look-up table for EPROM was obtained. After pro-
gramming the EPROM, the meter was tested again with
the califlow system and that data are only given in Tables
1 and 2. The quoted error of ±0.3% was obtained after
second calibration. By taking indicated reading B along
x-axis and the reference reading A along y-axis, a best-fit
line was obtained and its equation is as follows.

Actual flow rate \( M(\text{slpm}) = 1.0023 \, B + 0.0003 \) for 1
slpm meter and actual flow rate \( M(\text{slpm}) = 1.0011 \, B - 0.009 \) for 5 slpm meter.

5. Outline of numerical modeling

Numerical modeling of thermal mass flow meters is
performed using FLUENT 5.0 (a CFD package) which is
a finite volume based package and is capable of modeling
fluid flow and heat transfer problems. The basic governing
equations used are the conservation laws, which support
any transport problem; mass, momentum and energy.
Material properties viz. density, viscosity, thermal heat
capacity and thermal conductivity are defined as tempera-
ture dependent [9].

6. Numerical approach

In the present case flow is governed by 3-dimensional
steady Navier–Stokes equations.

At steady state, the continuity, momentum and energy
equations in vector form 10 are:

\[
\nabla \cdot (\rho \mathbf{V}) = 0
\]

\[
\rho (\mathbf{V} \cdot \nabla) \mathbf{V} = -\nabla p + \mu \nabla^2 \mathbf{V} + \rho g \mathbf{B} T
\]

\[
\rho C_p \mathbf{V} \cdot \nabla T = \nabla (K \nabla T)
\]

where \( \mathbf{V} \) is the flow velocity, \( \rho \) the density of the flow
medium, \( p \) the pressure, \( \mu \) the dynamic viscosity of the
flow medium, \( g \) the acceleration due to gravity. \( T \) the
Table 1
Calibration results of 1 slpm thermal mass flow meter

<table>
<thead>
<tr>
<th>Sl. No.</th>
<th>Reference reading A (slpm)</th>
<th>Indicated reading B (slpm)</th>
<th>From best-fit line Actual flow rate $M$ (slpm) = $1.0023B + 0.0003$</th>
<th>Error $(B-A)/1.0 \times 100$ (%) of span</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0.000</td>
<td>0.000</td>
<td>0.000</td>
<td>0.00</td>
</tr>
<tr>
<td>2</td>
<td>0.186</td>
<td>0.184</td>
<td>0.185</td>
<td>-0.20</td>
</tr>
<tr>
<td>3</td>
<td>0.284</td>
<td>0.284</td>
<td>0.285</td>
<td>0.00</td>
</tr>
<tr>
<td>4</td>
<td>0.386</td>
<td>0.385</td>
<td>0.386</td>
<td>-0.10</td>
</tr>
<tr>
<td>5</td>
<td>0.488</td>
<td>0.486</td>
<td>0.487</td>
<td>-0.20</td>
</tr>
<tr>
<td>6</td>
<td>0.587</td>
<td>0.586</td>
<td>0.588</td>
<td>-0.10</td>
</tr>
<tr>
<td>7</td>
<td>0.686</td>
<td>0.685</td>
<td>0.687</td>
<td>-0.10</td>
</tr>
<tr>
<td>8</td>
<td>0.793</td>
<td>0.790</td>
<td>0.792</td>
<td>-0.30</td>
</tr>
</tbody>
</table>

Table 2
Calibration results of 5 slpm thermal mass flow meter

<table>
<thead>
<tr>
<th>Sl. No.</th>
<th>Reference reading A (slpm)</th>
<th>Indicated reading B (slpm)</th>
<th>From best-fit line Actual flow rate $M$ (slpm) = $1.001IB - 0.009$</th>
<th>Error $(B-A)/5.0 \times 100$ (%) of span</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0.000</td>
<td>0.000</td>
<td>-0.009</td>
<td>0.00</td>
</tr>
<tr>
<td>2</td>
<td>0.299</td>
<td>0.304</td>
<td>0.295</td>
<td>0.16</td>
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<td>3</td>
<td>0.797</td>
<td>0.805</td>
<td>0.797</td>
<td>0.16</td>
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<td>4</td>
<td>1.291</td>
<td>1.302</td>
<td>1.294</td>
<td>0.22</td>
</tr>
<tr>
<td>5</td>
<td>1.787</td>
<td>1.801</td>
<td>1.794</td>
<td>0.28</td>
</tr>
<tr>
<td>6</td>
<td>2.290</td>
<td>2.301</td>
<td>2.295</td>
<td>0.22</td>
</tr>
<tr>
<td>7</td>
<td>2.788</td>
<td>2.801</td>
<td>2.795</td>
<td>0.26</td>
</tr>
<tr>
<td>8</td>
<td>3.285</td>
<td>3.291</td>
<td>3.286</td>
<td>0.12</td>
</tr>
<tr>
<td>9</td>
<td>3.775</td>
<td>3.777</td>
<td>3.772</td>
<td>0.04</td>
</tr>
<tr>
<td>10</td>
<td>4.267</td>
<td>4.272</td>
<td>4.268</td>
<td>0.10</td>
</tr>
<tr>
<td>11</td>
<td>4.765</td>
<td>4.760</td>
<td>4.756</td>
<td>-0.10</td>
</tr>
</tbody>
</table>

temperature, $C$ the specific heat capacity, $K_t$ the thermal conductivity and $\beta$ is the temperature coefficient. In addition, we have the equation of state of the gas, $p = pRT$ where $R$ is the gas constant. Variation of $K_t$ with temperature is taken from the data book [9].

7. Geometry

Computational domain includes straight lengths of 10D upstream and 5D downstream of the mass flow meter transducer shown in Fig. 3. Geometry is modeled using GAMBIT-preprocessor of FLUENT 5.

8. Assumptions

The following assumptions were made in the modeling.

(a) The flow is laminar as the Reynolds number in the main tube is 64 for the flow rate of 1 slpm.
(b) The straight lengths of 10D upstream and 5D downstream of the mass flow meter assembly are considered for the computation.
(c) Body forces other than gravity are not considered.
(d) The fluid is in single phase and is air.

9. Boundary conditions

At the inlet, mass flow rate range is 0–1 slpm, without any transverse velocity components. The inlet profile is not assumed to be parabolic but to be uniform. The center of the capillary tube is kept at the temperature range of 180–220°C by keeping it at constant heat flux. The boundary condition at the interface between materials is

$$T_{\text{fluid}} = T_{\text{solid}}$$

When the solid heat flux is known, as in the areas sur-
rounding the electrical inductive heater of the sensor, the corresponding boundary condition becomes:

\[(K_\varepsilon \partial T/\partial \eta)_{\text{fluid}} = q_{\text{solid}}\]

where \(\eta\) represents the generalized coordinate direction normal to the interfacial surface and \(q\) is the heat flux. At the outlet normal axial velocity gradients are vanished. No slip boundary conditions are applied at the walls with the proper temperature conditions.

10. Solution

Three-dimensional Laminar Solver is used. At no flow condition temperature distribution along the capillary sensor is found first. Then solution for flow rates of 0.25, 0.5, 0.75 and 1 slpm are found out at the temperature range of 180–220°C. Gravitational forces are also considered. Variation of fluid properties with respect to the temperature is taken into consideration by providing proper profiles as per the standard data. Flow medium is air.

11. Results of modeling

Fig. 4 shows the linear variation of \(\Delta T\), which is the difference in temperature between the downstream and upstream of the heater of the capillary tube with the flow rate ranging from 0.25 to 1.0 slpm and for different temperatures maintained at the center of the capillary tube. Fig. 5 shows the distribution of axial temperature along the capillary tube for the same variation of flow rates. From Fig. 5 it can be seen that the temperature profiles are skewing towards right because of transfer of heat to the fluid from the walls.

12. Experimental investigations on the performance of the meter due to the change in ambient temperature and orientation

The transducer and the signal conditioning units of 5 slpm meter were kept inside an environmental chamber and the indicator was kept outside. Inside the chamber the relative humidity was 55%, the temperatures were 20, 25, 32, and 40°C, and the results on the performance are given in Table 3.

Further 5 and 1 slpm meters were tested for their zero and span with the meters both in normal position i.e. perpendicular to gravity (orientation 1) and also in a position parallel to gravity i.e. the direction of the flow coincident with gravity (orientation 2). The results obtained are given in Table 4.

13. Results and discussions

The accuracy of most of the thermal mass flow meters available in the market today is ±1% full scale [11] and that of 1 and 5 slpm meters designed and developed by us is ±0.3% full scale. The gas correction factor (which is defined as the number used to indicate the ratio of flow rates of different gases which will produce the same flow rate reading from the flow meter) for nitrogen and air are same (1.00) and hence the effect of calibration using either nitrogen or air is the same. Nitrogen is used for calibration because it is an inert gas. The supplier of Califlow system recommends only nitrogen and not air for calibration. The gas correction factor (GCF) for typical gases have already been found out and reported by others. If we want to calculate the actual flow rate of another gas (say ammonia, NH₃) through the thermal mass flow meter, which has already been calibrated using nitrogen and if the meter reading is \(y\) slpm with
Table 3
Effect of ambient temperature on 5 slpm meter

<table>
<thead>
<tr>
<th>Sl. No.</th>
<th>Reference reading A (slpm)</th>
<th>Indicated flow rate B (slpm) at temperatures (°C)</th>
<th>Maximum error (B - A)/5.0 x 100 at</th>
<th>(B - A)</th>
<th>max (% of span)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>20</td>
<td>25</td>
<td>32</td>
<td>40</td>
</tr>
<tr>
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<td>0.001</td>
<td>0.002</td>
<td>0.003</td>
</tr>
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<td>2.324</td>
<td>2.326</td>
<td>2.327</td>
<td>2.326</td>
<td>2.326</td>
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<tr>
<td>3</td>
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<td>3.835</td>
<td>3.835</td>
<td>3.836</td>
<td>3.836</td>
</tr>
<tr>
<td>4</td>
<td>3.867</td>
<td>3.869</td>
<td>3.869</td>
<td>3.869</td>
<td>3.868</td>
</tr>
<tr>
<td>5</td>
<td>4.156</td>
<td>4.159</td>
<td>4.158</td>
<td>4.158</td>
<td>4.158</td>
</tr>
</tbody>
</table>

Table 4
Effect of orientation on 1 and 5 slpm thermal mass flow meters

<table>
<thead>
<tr>
<th></th>
<th>Full-scale flow rate of the meter (slpm)</th>
<th>Orientation 1 (perpendicular to gravity)</th>
<th>Orientation 2 (parallel to gravity)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Reference reading</td>
<td>Indicated reading</td>
<td>Error % of span</td>
</tr>
<tr>
<td>Zero</td>
<td>5</td>
<td>0.00</td>
<td>0.00</td>
</tr>
<tr>
<td></td>
<td>1</td>
<td>0.000</td>
<td>0.001</td>
</tr>
<tr>
<td>Span before zero adjustment</td>
<td>5</td>
<td>4.955</td>
<td>4.96</td>
</tr>
<tr>
<td></td>
<td>1</td>
<td>0.982</td>
<td>0.985</td>
</tr>
<tr>
<td>Span after zero adjustment</td>
<td>5</td>
<td>4.975</td>
<td></td>
</tr>
<tr>
<td></td>
<td>1</td>
<td>0.986</td>
<td></td>
</tr>
</tbody>
</table>

the other gas (say ammonia) then the actual flow of ammonia is calculated as follows:

Actual flow rate of ammonia through the meter
= meter reading \times GCF for ammonia
= \text{y} \times 0.73 \text{ slpm}

Numerical modeling predicts that the temperature difference (ΔT) between the downstream and upstream of the heater of the capillary tube increases linearly (Fig. 4) with increase in flow rate through the meter and its slope increases with the increase in heater temperature. The output of the instrumentation amplifier (in the signal conditioner unit) which is the amplified value of the difference between the outputs of the two thermocouples fixed in the capillary tube have been found out experimentally for various flow rates and the results are given in Fig. 6. The difference between the outputs of the two thermocouples is directly proportional to the temperature difference (ΔT) between the downstream and upstream of the heater of the capillary tube.

Numerical modeling was done for heater temperatures of 180, 200 and 220°C as in Fig. 4 but experimentally, it was possible to take readings only for heater temperatures of 180, 200 and 210°C. The value of the slopes calculated from modeling for heater temperatures of 180, 200 and 220°C are 6.17, 6.92 and 7.18, respectively, and those from experiment for heater temperatures of 180, 200 and 210°C are 9.72, 9.87 and 9.89, respectively. Though the y-axis quantities in Figs. 4 and 6 are different, they are related to each other. The y-axis quantity in Fig. 4 is ΔT (the difference in temperature between downstream and upstream of the heater of the capillary tube) and that in Fig. 6 is output voltage of the instru-
mentation amplifier (in the signal conditioner unit) which is nothing but a quantity directly proportional to $\Delta T$. (Since it is very difficult to measure the $\Delta T$ directly across two point locations, the authors have measured the output voltage of the instrumentation amplifier). The slopes obtained from numerical and experimental results should not be compared directly. Since the $y$-axis quantity in Fig. 6 is directly proportional to the $y$-axis quantity in Fig. 4, the slopes in Fig. 6 need not or cannot match with those in Fig. 4. (In Fig. 4, if $\Delta T$ is taken as $y_1$ and flow rate as $x$, then we can write $y_1 = m_1x$. In Fig. 6, if $y$-axis quantity is taken as $y_2$, then $y_2 = m_2\Delta T = m_2y_1 = m_2m_1x$). Thus, the slopes in Figs. 4 and 6 are different. The quoted slopes in Figs. 4 and 6 do not mean anything other than the fact that $\Delta T$ increases linearly with the increase in the flow rate through the thermal mass flow meter and this slope increases with the increase in heater temperature. Thus, the results of numerical modeling agree qualitatively with the experimental results. Though modeling was done for 1 slpm meter only, it is applicable for 5 slpm meter also with minor variations. Also tests were carried out with gas temperatures at 20 and 32°C. The mass flow rate reading was read correctly at both the above temperatures.

Effect of ambient temperature on the performance of 5 slpm meter, as shown in Table 3, is only 0.06% of span when the ambient temperature changes from 20 to 40°C. This experimental result is also applicable to 1 slpm meter to a great extent as the electronic components used in the signal conditioning unit and the mechanical parts used in the flow sensor of both the meters have similar temperature dependence.

Both the 5 and 1 slpm meters did not indicate any difference in reading for zero flow when the orientation was changed from 1 to 2. The display in both the meters is designed in such a way that it cannot indicate negative values i.e., for all values less than or equal to 0.0025 V DC for 0-1 slpm meter and was -0.0101 V DC for 0-1 slpm meter.

The 5 slpm meter gave an error of $+0.1\%$ of span in orientation 1 and $-2.9\%$ of span in orientation 2 without adjusting zero for 100% flow. The same meter did not show any difference in reading for zero flow when orientation was changed from 1 to 2. The 1 slpm meter gave an error of $+0.3\%$ of span in orientation 1 and $-1.6\%$ of span in orientation 2 without adjusting zero for 100% flow. The same meter gave an error of $0.1\%$ of span in orientation 1 and $0.0\%$ in orientation 2 for zero flow. Both the 5 and 1 slpm meters gave an error of $-1.0\%$ of span after readjustment of zero for 100% flow when the orientation was changed from 1 to 2.

Tison [11] has reported that the maximum change in orientation of the five Thermal Mass flow meters evaluated by him has resulted in a change of $0.4\%$ of full scale for zero flow and less than $\pm0.5\%$ of full scale for 100% flow after readjustment of zero. He has not reported the values of errors of the 5 meters before readjustment of zero.

14. Conclusions

1. It is possible to develop thermal mass flow meter with an error of $\pm0.3\%$ of full scale.
2. The result of numerical modeling of thermal mass flow meter agrees qualitatively with the experimental results.
3. The effect of change in ambient temperature on the performance of the thermal mass flow meters is negligible.
4. The effect of orientation on the performance is significant, and is different for different meters mean for different flow rate ranges.

References

Design and development of thermal mass flowmeters for high pressure applications

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Abstract

This paper discusses the design and development of two thermal mass by-pass flowmeters for the ranges of 90 grams per second (g/s) and 15 g/s operating at 18 bar and 19.5 bar pressures respectively for air flow measurement. © 2002 Elsevier Science Ltd. All rights reserved.

Keywords: Thermal mass flow meter; Design; Calibration; Accuracy; Air

1. Introduction

In industrial processes involving gases, at times, mass flow rate (rather than volume flow rate) is the critical variable and is more accurate for measuring material transfer. Orifice plate, venturimeter, vortex/turbine/ultrasonic meter etc., cannot measure mass flow without a pressure transmitter and a temperature transmitter to arrive at mass flow, whereas thermal mass flow meter measures mass flow directly without any additional hardware.

Thermal mass flowmeters [1,2] operate on the principle whereby a capillary tube is heated uniformly around its center as shown in Fig. 1(a). The ends of the capillary tube are held at ambient temperature by the base of the transducer, which acts as a heat sink. The thermocouples are attached upstream and downstream of the heater. When power is applied to the heater and no flow of gas is present, a symmetrical temperature gradient exists across the tube as shown in Fig. 1(b). When flow passes through the tube, heat is transferred from the tube to the gas stream on the inlet side, reducing the temperature at TC-1. As the gas continues through the tube, it begins to return the heat to the tube on the outlet side, increasing the temperature at TC-2. For a constant power input, the difference in temperature measured in millivolts by the thermocouples, is proportional to the mass flow rate (through the tube) and heat capacity of the gas. As the heat capacity of the gas is relatively constant over wide ranges of temperature and pressure, the flowmeter can be calibrated directly in mass units for any gas.

High ranges of flow are achieved by dividing the flow with a fixed ratio shunting arrangement, as shown in Fig. 2. By placing the measuring tube in parallel with one or more dimensionally similar channels (laminar flow elements), viscous restrictions are created. Thus the sensor needs to heat only a small portion of the total gas which results in low power requirements while retaining mass measuring characteristics.

The standard flow meter calibration is for air. Gas Correction Factor can be applied to use the same flow meter for other gases.

2. Previous investigations on thermal mass flow measurement

A thermal mass flow meter for the measurement of fuel consumption in automobiles and light aircraft, and of liquid flows in industrial processes was designed and evaluated by J. H. Huijsing et al. [3]. The characteristics
3. Design and development of thermal mass flow meters

The block diagrams of the electronic circuits for thermal mass flowmeters for the ranges of 0-90 g/s and 0-15 g/s operating at 18 bar and 19.5 bar pressure respectively are given in Figs. 3 and 4. Fig. 3 gives the schematic of transmitter of thermal mass flowmeter (both 90 g/s and 15 g/s). Similarly, Fig. 4 gives the schematic of indicator unit of both the above meters. The electronic flow rate indicator accepts 230 V, 50 Hz supply and displays flow rate in 4 digits using LEDs with a resolution of 0.01 g/s. It gives a 0-10 V analog output also proportional to the mass flow rate through the meter.

3.1. Flow transmitter

A constant current of magnitude around 123 mA is used for heating the bypass capillary tube. This constant current is obtained by using the stable 1.23 V reference voltage. The outputs of the two thermocouples are fed to the instrumentation Amplifier AD 625 which is made to give an output voltage of 2 V for full scale flow rate and a voltage of 0 V for zero flow rate.

The ADC is based on the 4 1/2 digit integrating AD chip ICL 7135. The “CLOCK” signal of 125 KHz, generated using 4 MHz crystal oscillator and divider circuit, is used to give an output voltage of 2 V for full scale flow rate and a voltage of 0 V for zero flow rate.

The ADC requires 40,000 clock pulses for one conversion. At 125 KHz clock frequency, the ADC performs 3.125 conversions per sec and the same is the display update rate.

The ADC integrates the input voltage for 10,000 clock pulses and de-integrates using the reference voltage to integral becomes zero or for a maximum of 20,000 clock pulses. Thus the clock counts during the de-integrating period is the measure of input voltage.

\[
\text{COUNTS}_{\text{de-integration}} = \frac{V_{in}}{2 \times V_{ref}} \times 20,000
\]

where

\[V_{in} = 2V_{ref}\]
The STATUS line (ie. BUSY) of ADC goes high when the integration—a process that takes 10,000 pulse counts in duration—starts and goes to low after one clock pulse after the de-integration. Thus if 'N' is the counts corresponding to the input voltage (i.e. counts during the de-integration period), the total clock pulses during the ADC Busy period (ie. when the STATUS line is high) is given by

\[ \text{COUNTS}_{\text{ADC Busy}} = 10,000 + N + 1 \]

Thus the counts corresponding to the input voltage can be extracted from the "CLOCK" pulses and the STATUS output by counting the pulses during ADC BUSY period and subtracting 10,001 from it.

The STATUS and CLOCK outputs are sufficient to transmit the information about the input to ADC. Before transmission, these signals are buffered.

3.3. Flow indicator

The ADC STATUS and 125 KHz CLOCK pulses are compared to 2.5 V in order to shape the pulses. LM 311 chips in simple comparator mode are used for this purpose. After shaping, the ADC STATUS pulse is given to the RESET pin of CD 4017 Ring counter which is used as CONTROLLER here. The shaped CLOCK pulses are given to the CLOCK input of CD 4017 and through a buffer (using 74 LS 573) to CLOCK input of first stage of 15 bit counter (using four numbers of 74 LS 93).

3.4. The control logic using CD 4017 ring counter

ADC STATUS pulse (ie. ADC BUSY Signal) is high when ADC is performing integration and de-integration, and it goes to Low after one clock pulse after the de-integration. This ADC STATUS pulse keeps the controller CD 4017 in the RESET mode as long as it is "High". When this ADC STATUS pulse goes to "LOW" (ie. after one clock pulse after the de-integration) the controller CD 4017 starts counting from zero.

The signals Q9 (pin No. 11) Q1 (pin No. 2) Q2 (pin No. 12) Q3 (pin No. 4) and Q4 (pin No. 6) of CD 4017 controller are used for control purpose.

When the ADC STATUS signal goes to "High" the 15 bit counter starts counting from zero continuously till the signal Q9 of CD 4017 goes "High" and "RESETS" the 15 bit counter. This signal Q9 of CD 4017 controller is given to the HOLD input of the same CD 4017. Thus the controller CD 4017 is kept in the 'HOLD' mode by the signal Q9, and the controller is 'RESET' when the ADC STATUS signal goes to 'High' again for the next conversion (ADC performs 3.125 conversions per sec).

The signal Q1 of controller after buffering forms the LATCH pulse for the 15 bit latch (using 2 Nos. of 74 LS 573) and it latches the contents of the 15 bit counter present at that instant.
The signals $Q_z$ and $Q_7$ of controller are never ‘High’ simultaneously at any instant of time. These two signals are given to a NOR gate and its output forms the LATCH pulses for the DAC 1210 Digital to Analog Converter. When the signal $Q_z$ goes to High the NOR gate output will go Low and it latches the 8 MSBs (from 27 C 64 UVE PROM) to the DAC 1210; when the signal $Q_7$ goes to High the NOR gate output will go LOW and it latches the 4 LSBs (from 27 C 64 UVEPROM) to the DAC and the 12 bit input to DAC is updated.

The signal $Q_c$ (±10 output) of the controller after buffering forms the Ao (LSB of address line) to the 27 C 64 UVE PROM (where the data input for DAC is stored). The signal $Q_c$ of the controller is High during the first 5 clock pulses counted by the controller and it is Low during 6th to 10th clock pulses counted by the controller. This signal $Q_c$ of the controller also forms the BYTE SELECT and XFER lines of DAC.

3.5. The 15 bit counter stage

The 15 bit counter is realized using 4 Nos. of 4 binary counters 74 LS 93. The RESET pins of all the counters are connected together and are driven by the signal $Q_9$ of controller through a buffer. The shape of the CLOCK pulse (125 KHz) is applied to the first count chip through one buffer in the 74 A LS 573 (wired a buffer).

3.6. The 15 bit data latch using the Octal—D latch 74ALS573

The 15 bit latch is used to latch the 15 bit count from the counter and to drive the EPROMs. The latch is realized using 2 numbers of Octal D-latches 74ALS 573. The OUTPUT ENABLE pins are held enabled (ie. kept LOW). The LATCH ENABLE pins are active High an
are driven by the signal Q1 of the controller CD 4017 through one buffer in the chip 74 ALS 573 (wired as buffer).

As the data is latched by the signal Q1 of the controller, the 15 bit counter counts two more pulse counts after the BUSY period of ADC and before the data gets latched.

If 'N' corresponds to the count during de-integration period for a particular input, the count latched in the Data latch is 10,000+N+1+2. That is the output of the latch will have a positive offset of 10,003 counts for any input. The maximum value of 'N' possible is 20,000 (when V1=2xVref). Thus the maximum count latched in the Data latch is 10,000+20,000+1+2=30,003. Therefore to count upto 30,003 minimum number of bits required is 15. \(2^{15}=32,768\). That is why 15 bit counter is used.

3.7. The 4 digit look-up table using 32 K Byte EPROM 27 C 256

The data to be displayed is stored in the two 27 C 256 EPROMs. One EPROM stores the two MSDs and the other one stores the two LSDs. All the pins, except the data outputs of the EPROMs are connected in parallel. The data output of the 15 bit latch forms the 15 bit address of the EPROMs. The CHIP enable and OUTPUT ENABLE pins are always enabled (ie. kept LOW). As the latched count in the 15 bit latch corresponds to the input voltage value of ADC, the data to be displayed is to be stored in the address location whose value is equal to the count latched.

3.8. Twelve bit look up table for DAC

The DAC 1210 used is a 12 bit DAC. Each memory location in the EPROM from where the data is output to DAC has a word length of 8 bits only. The minimum and maximum values of data that can be output to DAC are 000h [i.e. \(0100_{10}\)] and FFFh [i.e. \(4095_{10}\)] respectively. Thus to store 4096 data values, the number of memory locations required is 4K provided the word length of each memory location is 12 bits. As the word length of each memory location used is 8 bits 8 MSBs are stored in one memory location and the remaining 4 LSBs are stored in the adjacent memory location in the left justified format (B3 B2 B1 B0 0000). The 4 LSBs of input to DAC are connected in parallel with the most significant nibble of input to DAC. Thus to store 4096 data values of 12 bit length each, the memory size required is 4Kx2=8K byte. Thus the total number of address lines to 27C 64 UVEPROM is 13 [12 from the 15 bit counter and 1, the least significant address bit \(Q_{15}\) i.e. \(Q_{15}+10\) output) from CD 4017 controller.

The data to be output to DAC is stored in 27C64, 8K byte UVEPROM. Data input 000h corresponds to zero (say 0.0V at 0.00 gm/sec flow rate) output from DAC and data input FFFh corresponds to span (say 10.0V at 90.00 gm/sec flow rate) output from DAC.

The 90g/s meter has a pipe size of 4 inches and 15g/s meter has a pipe size of 2 inches. The photograph of the 90g/s meter designed and developed by us is shown in Fig. 5. The transmitter and the indicator for the above two meters are the same or similar, and the difference lies in the pipe size only and hence the photograph of the 15g/s meter is not shown. Another difference in the above two meters is in programming the EPROMs in the indicators.

3.9. Calibration setup

The above two flowmeters were calibrated against positive displacement meters of M/s. Schlumberger, France, which were used as reference meters. The 15g/s meter was calibrated using our High Pressure Blow down facility and the 90g/s meter was calibrated using our Closed Loop Air test facility and the above facilities are described below.

3.10. High pressure blow down facility

The reference meter and the test meter are connected in series in the test loop as given in Fig. 6(a). The facility consists of three inter connected pressure vessels of capacity 11m³ (water volume) each designed for 20 bar maximum operating pressure. The air reservoirs are charged from two multistage air compressors connected in series. The test meter and reference meter are connected to the outlet of one reservoir after pressure regulator and filter. Provision is made to measure the pressure and temperature at both reference and test meters.

Fig. 5. Photo of 90 g/s thermal mass flow meter.
3.1. Closed loop air test facility

The reference meter and test meter are connected in the test loop as given in Fig. 6 (b). A reciprocating compressor with a rating of 30 bar(g), supplies air to the reservoir, and the same is charged to the required static pressure of 20 bar(g).

The test line is charged with air at required pressure from the air reservoirs. An unobstructed upstream straight length of about 20 D is provided for both test and reference flow meters. The encapsulated blower (recirculator) maintains continuous circulation of flow at constant pressure at test circuit after providing for necessary losses in the circuit. The blower is driven by a variable speed drive with power rating of 35 kW to achieve different flow rates through the loop. Provision is made for pressure and temperature measurement for reference and test meters.

4. Calibration procedure

4.1. High pressure blow down facility

The 15 g/s meter under calibration is connected in series with the reference meter as shown in Fig. 6 (a). Required instruments for measurements of pressure and temperature are connected for the positive displacement meter and the meter under calibration. After closing the downstream valve, the line is charged to the maximum pressure and the leak tightness is ensured. Flow is allowed through the meter by opening the valve. Required flow at steady test pressure is maintained by means of the pressure regulator and valve. The calibration is done for specified flow rates covering the range of the meter under calibration.

4.2. Closed loop air test facility

The 90 g/s meter under calibration is connected in series with the reference meter as shown in Fig. 6 (b) in the closed loop air test facility. Required instruments for measurements of pressure and temperature are connected for the positive displacement meter and the meter under calibration. After checking the whole system, the charging line from the reservoir is opened slowly till the complete test loop attains the testing pressure (18 bar). The complete line is checked for leakage. After ensuring the leak tightness, the blower is started and the required flow rate is set, using the blower controller.

In both the cases, the calibration is done for specified
flow rates covering the range of the meter under calibration. For each flow rate, the following data are recorded. Some rough calibration is done first to estimate the constant k, in the equation \( m = kE \) where ‘m’ is the mass flow rate and ‘E’ is the difference between the two thermocouple e.m.fs.

4.2.1. Reference meter—Positive displacement meter
1. Pressure
2. Temperature
3. Initial volume
4. Final volume
5. Time

4.2.2. Mass flow meter (meter under calibration)
Indicated mass flow rate

4.2.3. Ambient pressure
The above procedure is repeated for different flow rates covering the entire range of the meter under calibration. The calibration conforms to the standard “ISO/WD 14511—Measurement of fluid flow in closed conduits—Thermal mass flow meters”.

From the readings taken during calibration, the volumetric flowrates indicated by the positive displacement meters are converted into mass flow rates. The calibration results of 90g/s and 15g/s meters are given in Tables 1 and 2 respectively and the calibration charts of the above meters are shown in Figs. 7 and 8.

5. Results and discussion
In order to improve the accuracy of the 0–15g/s meter, two calibrations were done. After the first calibration, the data for the look-up table for EPROM in the indicator was obtained. After programming the EPROM, the meter was tested again in the calibration set up and those data only are given in Table 2. As shown in the above table, the maximum error of the 0–15g/s meter is ±0.23% of full scale.

From Table 1, we find that the maximum error of 0-90g/s meter is ±0.88% of full scale. This value of error

![Fig. 7. Calibration of 90g/s thermal mass flowmeter.](image-url)
was obtained after first calibration and as this magnitude of error was acceptable to the customer, a second calibration was not done to reduce the error further.

Repeatability of the flowmeter readings is fairly good. Regarding the zero drift, the UVE PROMS are programmed in such a way that whenever the flow rate is less than about 1.5% of full scale, the digital display will be 00.00 g/s, and the analog output will be '0' volt.

The meters have been made for specific applications. In new situations (e.g. at different pressures), they need recalibration.

6. Conclusion

Thermal mass flowmeters with ranges up to 90g/s and 15g/s and operating at 18 bar and 19.5 bar respectively were designed, developed and successfully tested with errors of ±0.88% and ±0.23% of full scale, respectively.

References

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