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Development of differential pressure based flow sensor using pulsating sensor based instrument for low flow applications with in-house built calibrator

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ABSTRACT

Accurate measurement of flow rate of liquids and gases is very much essential in power plants, chemical industries and petrochemical industries in order to maintain the quality of industrial processes. In most of the industrial loops which handles flow of liquids and gases, the monitoring as well as control of flow rates of incoming liquids or gases is essential in order to achieve the objective whichever is necessary for that particular industry. In order to satisfy the diverse requirements of flow measurement like volumetric flow rate measurement, mass flow rate measurement, flow measurement for different nature of fluid, flow measurement either intrusive or nonintrusive, various types flow measuring techniques are being used in such industries.

A high resolution differential pressure sensing device[2] has been developed in Innovative Sensors Section (ISS) for online measurement of small shift in differential pressure down to 0.1 mbar. With successful performance in many laboratory applications differential pressure (DP) sensing devices of industrial grade have been made in-house for the measurement of small shift in differential pressure which has been used in nitrogen circuit of Prototype Fast Breeder Reactor (PFBR). The excellent performance achieved through in-house made DP sensors prompted for the development of an orifice type differential pressure based sensor for low flow (0-5LPM) applications.

In the present work the orifice type flow sensor was designed based on IS 15675 :2005 standard. The pressure drop across the orifice was measured by a high sensitive pulsating type differential pressure sensor. The output frequency from the sensor is calibrated against the measured flow using an in-house developed calibrator which is an expandable tank with a floating lid. Pressure correction for calibration was done for the measured volume flow rate which may occur due to the weight of the floating lid. The calibrated sensor was compared against two different rotameter fixed at the inlet and outlet of the flow section.

Initial results obtained from this study seem to be encouraging and the sensor was able to detect flow in the range

0-5LPM. Very stable value in pressure difference measurement and excellent stability in frequency measurement and suitable calibration technique had lead to the development of such a high resolution flow measurement system.

KEY WORDS
Gaseous flow meter, pulsating sensor, low flow, orifice

1. INTRODUCTION

Low flow measurement of gaseous fluids is of great significance in the power plants, chemical industries and petrochemical industries. Efforts have been made to develop such instrument which will give precise flow output directly in digital domain.

In order to satisfy the diverse requirements of flow measurement, depending upon the situation like volumetric or mass flow rate, the nature of fluid, the pattern of measurement either intrusive or nonintrusive, a variety of flow measuring techniques are being used in industries. The common types of flow meters that find industrial applications are listed below:
Obstruction type differential pressure or variable area flow meters (ii) Inferential or turbine flow meters, (iii) Electromagnetic flow meters (iv) Optical flow meters, (v) fluid dynamic or vortex shedding flow meters, (vi) Positive displacement flow meters (vii) ultrasonic flow meters (viii) Anemometer type flow meters (ix) Coriolis mass flow meter. (cite references against each type) Each type of instrument is having its specific merits and limitations. In the present work a differential pressure based flow sensing device with pulsating sensor based instrumentation which can measure gaseous flow between the ranges 0-5LPM has been presented.

2. PRINCIPLE OF FLOW MEASURING APPROACH

An orifice meter is a conduit with a restriction to create a pressure drop. The pressure drop is measured and will be displayed in the orifice meter. The principle of the method of measurement is based on the installation of an orifice plate into a pipe line in which a fluid is running full. It is simply a piece of flat metal with a flow-restricting bore that is inserted into the pipe between flanges. The orifice meter is well understood, rugged and inexpensive. Its accuracy under ideal conditions is in the range of 0.75-1.5%. An orifice in a pipeline is shown in figure 1 with a manometer for measuring the drop in pressure (differential) as the fluid passes through the orifice. The minimum cross sectional area of the jet is known as the “vena-contracta.” As the fluid approaches the orifice the pressure increases slightly and then drops suddenly as the orifice is passed. It continues to drop until the “vena contracta” is reached and then gradually increases until at approximately 5 to 8 diameters downstream a maximum pressure point is reached that will be lower than the pressure upstream of the orifice. The decrease in pressure as the fluid passes through the orifice is a result of the increased velocity of the gas passing through the reduced area of the orifice. When the velocity decreases as the fluid leaves the orifice the pressure increases and tends to return to its original level. All of the pressure loss is not recovered because of friction and turbulence losses in the stream. The pressure drop across the orifice (Fig.1) increases when the rate of flow increases.

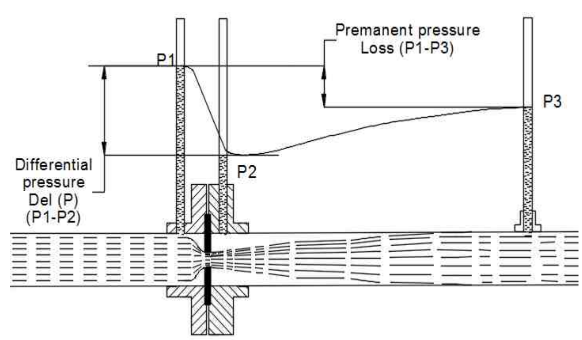

Figure 1- Pressure drop across an orifice

When there is no flow there is no differential pressure. The differential pressure is proportional to the square of the velocity, it therefore follows that if all other factors remain constant, then the differential is proportional to the square of the rate of flow. Hence in order to design a flow meter based on orifice principle a high resolution differential pressure sensor can be used in order to correlate flow rate with pressure difference. With this approach we developed a flow sensing instrument using a high resolution pulsating type differential pressure sensor in order to measure gaseous flow rate accurately.

3. DESIGN OF ORIFICE TYPE PULSATING FLOW METER

There are uncertainties in measurement of fluid flow using pressure differential devices some of which are listed below via. (1) tolerances in prediction of discharge coefficient, (2)physical properties of flowing fluid like compressibility, density etc., (3) fluid flow condition, (4) machining tolerances in components of the meter, (5) assembly of the flow measurement test section. The uncertainty in prediction of discharge coefficient is eliminated in the present work by introducing an indigenously designed calibrator. The compressibility is taken care in the present design. Other influencing factors as listed in (4) and (5) have been taken care in our design. For obstruction type flow meters an additional correction factor needs to be introduced to take into account the compressibility of the gas used. Since the calibration and the experiments are done in lab at controlled atmospheric pressure and temperature and also the flow is very small, the effect of compression due to flow is considered negligible. The fluid flow condition and the tolerance of machined components are taken care by following the IS standards.

3.1 Mechanical assembly of the experimental setup

The mechanical assembly can be classified into two parts via (1) orifice flow meter and (2) calibration setup.

The orifice flow meter consists of an argon cylinder from which the regulated flow is maintained, a variable area flow meter of flow rate 0-5LPM (rotameter) which will be used as a reference for calibration and operation, pipe test section, which is a Perspex tube of 20mm diameter and 2m length, where the orifice plate is mounted in-between two flanges via upstream flange and downstream flange. A quarter inch tubing is used to connect the argon cylinder and rotameter to the test section in order to match the connectors in the rotameter and the argon cylinder. Proper enlarger is used to connect the quarter inch tube and the Perspex pipe. A rotameter is provided to regulate the Argon from the cylinder which passes through all the components via enlarger, orifice plate, reducer, rotameter, as shown in figure1 then finally the Argon is let open to atmosphere through a normally open electrically operated solenoid valve. The calibrator is connected to the normally closed port of the solenoid valve. The orifice plate, the flange connectors for orifice plate and the flange pressure tapings are machined as per the IS standards.

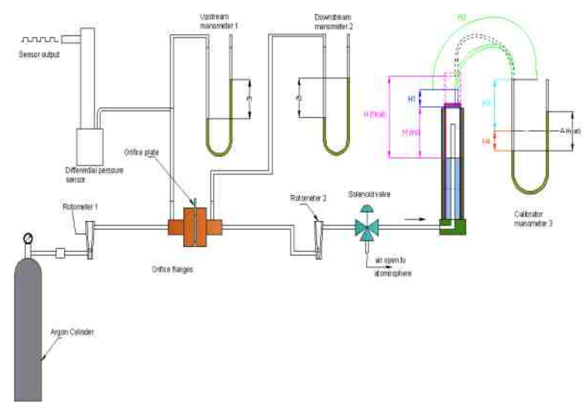

Figure 2- Experimental setup for demonstration of orifice meter with Argon cylinder.

All other conditions like flow straightening, circularity and cylindricity of the pipe, installation of fittings, required straight length between upstream and downstream of orifice plates and distance between orifice plate and fittings without flow conditioners also follows the IS 15675 :2003.

3.2 Calibration setup

The calibration setup consist of an air trap, electrically operated 3 way solenoid valve and a U tube for sensing pressure inside the vacuum trap. The air trap is an expandable type air collection tank. It consists of two cylindrical vessels with one end open in both. The bottom vessel contains a low volatile oil filled to its half. The top vessel is then inverted and inserted inside the bottom vessel so that some atmospheric air is trapped in-between the inverted vessel and the oil. A stainless steel (SS) tube runs through the centre of the vessels with one end of the tube open to the chamber of the air trap. The Argon coming out from the orifice plate is connected to the other end of the SS tube with a flexible tube via the three way solenoid valve. The schematic diagram of the calibration setup is shown in fig.3.

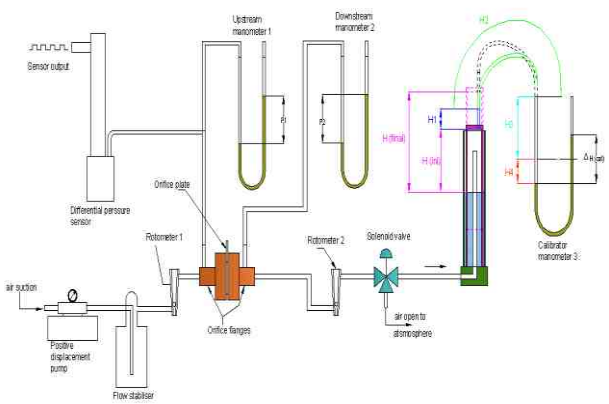

Figure 3 - Experimental setup for demonstration of orifice meter with positive displacement pump.

3.2.1. Orifice plate selection considerations and tap locations

The flanges and the orifice plates were designed as per IS standard. There are various criteria by which the selection of orifice plate sizes, tap locations and assembling procedure has to be followed. Differential pressure is measured through pressure taps located on each side of the orifice plate. Pressure taps can be positioned at a variety of different locations like flange Taps, corner Taps, radius Taps, vena-Contracta Taps, pipe Taps. We have taken up the radius taps otherwise known as D and D/2 tapings where D is the internal diameter of the pipe section where the orifice is fitted.

The flanges were designed such that the D and D/2 tapings are a part of the flanges. The spacing D and D/2 of a pressure tapping is the distance between the centerline of the pressure tapping and the plane of a specified face of the orifice plate. The spacing D and D/2 are measured from the upstream face of the orifice plate. The upstream flange (inlet flange) pressure taping was taken at a distance of one diameter (i.e.) 20mm from the centre of orifice plate and the downstream pressure tapping was taken at a distance of 0.5 times the diameter of test pipe section. The diameter of pressure tapings should be less than 0.13D and was kept 2mm which meets the standards. The thickness of the plate was fixed as 0.7mm. Since the ratio of orifice plate bore to the tube internal diameter (d/D) was decided to be 0.1 and the orifice size was taken as 2mm. The centre line of the pressure tappings and the centre line of the flow are made at 90° angles to each other. A groove of 0.25mm depth was machined in the flanges in order to keep the orifice plate intact and to maintain concentricity between the pipe and the orifice. Since we are intending to measure very low flow of gas, the problem of plastic buckling and elastic deformation of the plate, due to the magnitude of the differential pressure or of any other stress will not exist. To ensure the flatness and to avoid distortion due to the cutting force during machining of the upstream side of the plate special purpose machining like EDM wire cutting was adopted. During assembly also due care was taken to avoid distortion of plate due to assembling procedure. Orifice plate was machined using a mirror polished SS plate to take care of the roughness criteria specified in the standards.

3.3 Calibration methodology

A simple basic technique was used for calibration of the orifice meter. An indigenous calibration setup was designed and integrated with the flow measurement device. The calibration setup is shown in the figure 4. In order to use the developed flow meter for flow measurement it is necessary to empirically calibrate them. In order to calibrate the flow measurement device we decided to adopt quick closing valve technique to collect the flowing fluid which gives the information regarding the flow. An air trap which is the integral part of the calibration setup was exclusively designed for this purpose. The fluid inlet to the air trap is controlled by PC by means of which the fluid is allowed inside the trap for a preprogrammed time. The air coming out of the orifice plate is collected in the air trap for 3 seconds which is the programmed time for our experiments. The time of fluid collection in the air trap was decided by the maximum volume of fluid that can be collected in the air trap.

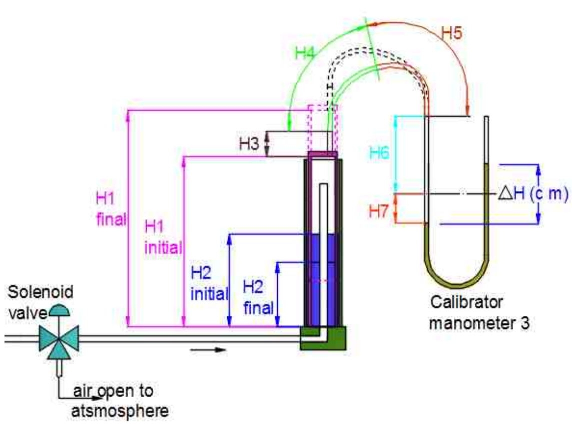

Figure 4 - Experimental setup of calibration.

The sensor and the air trap are connected using a normally closed electrically operated three way solenoid valve whose electrical actuation is controlled through a personal computer. One way of the valve is connected to the air trap and the other way is let open to atmosphere. The calibration setup is fitted in the pipe line to the far downstream, at a distance of 1m from the orifice plate. There is a pressure monitoring device connected to the top of the air trap which will give the information of the pressure inside the air trap after the fluid collection. During calibration, the pressure head information across the orifice is noted after which the valve is switched on for the preset time as discussed earlier and the fluid flowing through the pipe is collected in the air trap. The volume of fluid at atmospheric pressure trapped in the air trap is calculated using Boyle's law. By knowing the volume of fluid collected and the time of collection we can arrive at the actual volumetric flow rate. The volumetric flow rate is equated with the pressure difference and/or frequency to arrive at the calibration coefficients for the sensor.

4. INSTRUMENTATION

The differential pressure based flow meter is designed for a low order flow rate of 0-5 LPM. Hence it is obvious that to measure such a low range of flow, a high precision differential pressure sensor cum monitoring device is essential. For this purpose an indigenously developed differential pressure (DP) sensor of the range 0-65mbar was used. The differential pressure sensor is a capacitive type sensor consisting of a set of rectangular SS plates positioned vertically inside a well type manometer with uniform gap. The assembled capacitive component is placed in the timing circuit of a specially designed LGO. The LGO circuit is embedded on the probe head and is driven by 5 V DC supply from the monitoring device. The train of rectangular pulses generated at the output of the pressure sensor from the probe is processed by a stand-alone embedded processor with LCD display named as DP monitoring Device (DPMD) [3].

The sensor electronics and the DPMD are powered by ground isolated dual 5 V DC Power Supply. The signal from the sensor is isolated using opto-coupler in order to avoid the noise interference through common ground potentials. The function of DPMD is to (i) count the number of input pulses for a fixed duration of time for determining pulse frequency generated at the output of the pressure sensor (ii) convert the pulse frequency to pressure using pre-determined mathematical relation between frequency and differential pressure in mbar generated during calibration of the sensor iii) display the parameter on LCD iv) stores the configuration values (coefficients of polynomial equation which represents mathematical relation between frequency and DP) in a non volatile memory and retrieve them during power reset.

The output from opto-coupler is counted by a Programmable Interval Timer/Counter (PIT) for a fixed duration set by the user during configuration. A reference clock is used by the PIT to generate the fixed time interval. An 8-bit microcontroller calculates the frequency of the sensor signal and converts it into pressure in mbar. A polynomial equation relates the frequency to the pressure, whose coefficients are provided by the user during configuration.

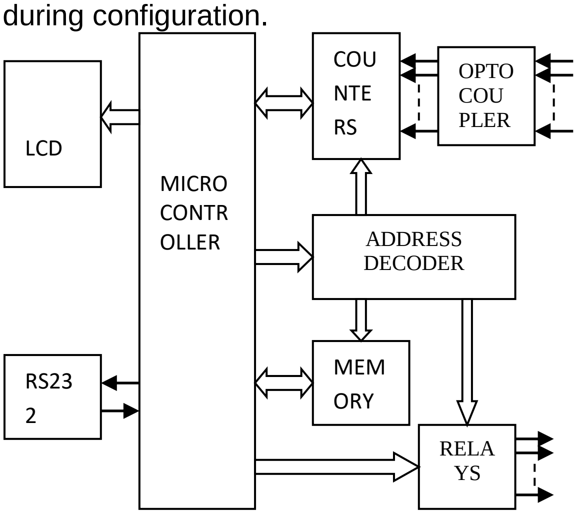

Figure 5 - Block diagram of instrumentation

The controller displays the frequency as well as the pressure value in LCD. Once the flow sensor is calibrated, a relation shall be obtained between the frequency output of the pressure sensor to the rate of flow so that the firmware of the microcontroller may be modified to give a direct display of the flow rate. A block diagram of instrumentation is shown in Fig. 5.

5. EXPERIMENTAL

The main aim of the experiment is to estimate flow using an indigenous calibrator which works on primary principle and also to validate the calibration approach with a well known proven measurement system. A rotameter of 0-5 LPM was identified and used for the purpose of validation. Various experiments were conducted with two different experimental setups as shown in figure 1 and figure 2 in order to bring out a relation between flow rate and the instrument output which is frequency. The first experimental setup uses a pressurized argon cylinder for creating the required flow. After assembling the setup, the flow was allowed in the pipe line by adjusting the inlet rotameter and the pressure difference readings in upstream and downstream side of the orifice, for the same flow was noted from the U- tubes. The frequency which in turn is a function of pressure difference was also noted from the differential pressure sensor connected in parallel with the U-tubes. Then a command was given to a computer controlled unit which actuates the solenoid for a preset time and the fluid was collected in the calibrator air trap. The height of the calibrator H1 and H2 was measured for the set flow. For the same flow two sets of calibrator readings were taken by resetting the inlet to the air trap. The air trap pressure readings were also measured using a separate U- tube fitted to the calibrator air trap. Similarly for different constant flow rates of air the frequencies and pressure difference and height of calibrator were measured. The flow rate of fluid passed through the calibrator was computed by using simple volume formulas. A model calculation is shown in Appendix-1.

In the second experimental setup we used a positive displacement piston pump to create the required flow. We introduced another passive component (gas washing bottle) before the inlet rotameter in order to reduce the turbulence effect created due to the piston pump. By using this flow stabliser we were able to get a stable value of flow in both the rotameters. The same experimental and calculation procedure as discussed above was repeated using this configuration. Each and every time care was taken to set the rotameter flow to an exact value.

6. Calculation of measured flow rate using in house built calibrator (Appendix-1)

Preliminary calculations are required to arrive at the measured value of flow which is done by measuring the volume of flowing medium collected for a certain interval of time.

The calculation shown below is for a flow of 5LPM.

The differential pressure between upstream and downstream side = $\rho g h$

= 830*9.81*66E-3

= 537.3918Pa

Initial volume of argon trapped in vacuum trap

$$(V_1) = \pi r_1^2 H_1 + \pi r_2^2 H_2 + \pi r_3^2 H_3 + \pi r_4^2 H_4$$

$$= (3.14 * 0.018^2 * 226) + (3.14 * 0.004^2 * 0.065) + (3.14 * 0.004^2 * 0.53) + (3.14 * 0.005^2 * 0.242)$$

$$= 0.000278813 m^3$$

Final volume of argon trapped in vacuum trap

$$(V_2) = \pi r_1^2 H_1 + \pi r_2^2 h H_2 + \pi r_3^2 H_3 + \pi r_4^2 H_4 + \pi r_4^2 (\Delta H_C)/2$$

$$= (3.14 * 0.018^2 * 226) + (3.14 * 0.004^2 * 0.065) + (3.14 * 0.004^2 * 0.53) + (3.14 * 0.005^2 * 0.242) + (3.14 * 0.005^2 * (196/2))$$

$$= 0.000407572 m^3$$

$H_1, H_2, H_3, H_4,$ are the heights of various section of tubes which is used in the calibration setup is shown in figure 3. The variables r1, r2, r3, r4 are the radius corresponding to heights H1, H2, H3, H4 respectively

Since the air trap is expandable in nature we can measure the volume of fluid collected in the trap and the pressure in it. With the measured values we can calculate the actual volume of fluid collected in the air trap at atmospheric pressure using the following P-V relation.

Assuming that the temperature is constant during calibration

We know that

$$p_a v_{t3} = \Delta P_C v_{t2}$$

Where

p_a = atmospheric air pressure;

v_{t3} = volume of air trapped in air trap at atmospheric pressure (to be calculated);

p_{t3} = trapped air pressure;

v_{t3} = volume of air trapped.

From the above equation

$$v_{t3} = \frac{\Delta P_C v_{t2}}{p_a}$$

$$= \frac{(1595.8908 + 101325)(0.000407572)}{101325}$$

$$v_{ta} = 0.000413991 m^3$$

Actual volume of air collected for 3 seconds in trap for 0.5LPM = $v_{t3} - V_{t1}$

$$= 0.000135178 m^3$$

The actual measured flow rate is the volume of air collected divided by 3 seconds.

Therefore the measured flow rate

$$= \frac{0.000135178)}{3} m^3/s$$

$$= (4.5059449 X 10^{-5}) m^3/s$$

= 2.7 lpm

7. RESULTS AND DISCUSSION

In the present work we developed an in-house made calibration facility to know the flow of fluid passed through the instrument. For a constant flow rate we computed the flow rate of the fluid using volume of fluid collected in the air trap and the collection time. From this the flow rate which is defined as volume of fluid passed per unit time (s) was computed. The relation between pulse frequency, and flow rate obtained using the first setup which uses compressed argon cylinder to create flow is shown in figure 6.

The relation between pulse frequency, and flow rate obtained using the second experimental setup which uses positive displacement pump to create flow is shown in figure 7. A better relation is observed in the later case which may be due to the effect of the positive displacement which reduces the effect of back pressure on the flow. In the former case the back pressure created in the calibrator setup is affecting the flow.

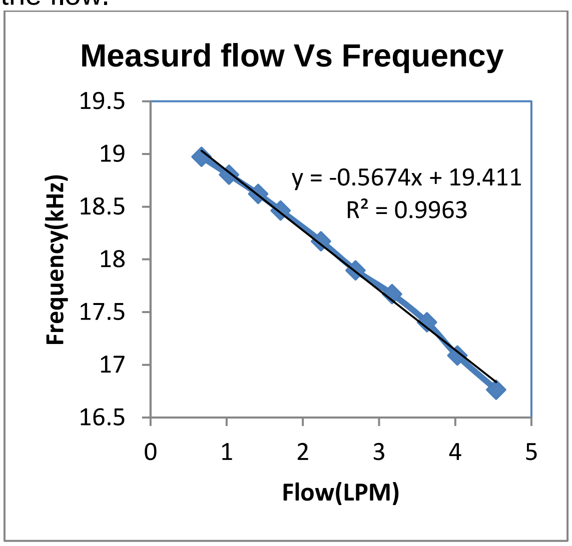

Figure 6 - Sensor output freq. against flow using calibrator (Argon cylinder).

The results obtained were reproducible and accurate. We observed good relation between flow rate and frequency which shows the correctness of the measurement system. Since we have adopted primary principle for computation of flow rate this approach seems to be more reliable. From the results it was also observed that average shift in frequency for 0.5LPM is 160Hz. The instrument has the capability to find a difference of 5Hz in frequency reading confidently. Form this it shows that this instrument can be used for high resolution flow measurement. The flow resolution and accuracy can be increased further by using smaller range differential pressure sensor available at our section.

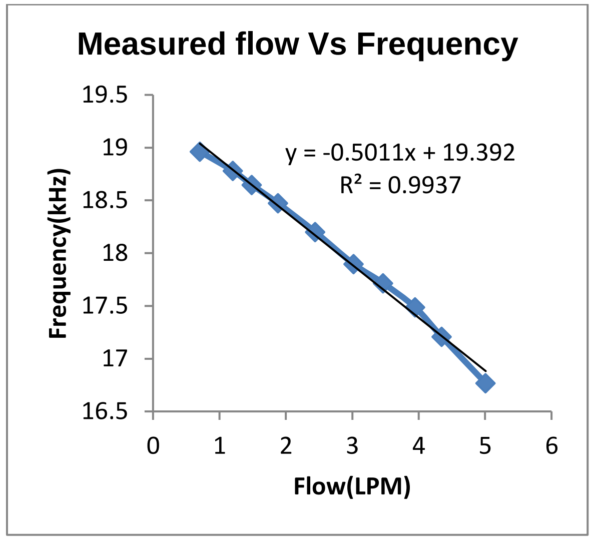

Figure 7 - Sensor output freq. against flow using calibrator (positive displacement pump)

A comparison of typical flow measurement using the positive displacement pump against the calculated flow is shown in the Table 1.

Table 1 – Comparison of a typical flow measurement vs. theoretical flow

Theoretical flow (LPM)	Experimental flow (LPM)	Percent error (%)
0.361	0.114	2.168
0.680	0.370	0.836
0.995	0.625	0.593
1.309	1.138	0.150
1.621	1.305	0.242
1.932	1.984	-0.026
2.243	2.159	0.039
2.554	2.615	-0.024
2.864	3.001	-0.046
3.174	3.095	0.026

The theoretical flow was calculated as per the procedure given in IS 15675:2005 standard. The error percentage (2.1% max) is higher at the lower flows because there was a back pressure during collection of fluid in the air trap. The air trap shall be designed to minimize the back pressure during measurement.

8. CONCLUSION

Initial studies towards design and development of a flow meter based on pressure difference principle were carried out. A high resolution pulsating type differential pressure sensor was deployed for measurement of flow. A calibrator was designed and used in the present work for flow rate calibration of the instrument. Initial results obtained from this study seem to be encouraging. Very stable value in pressure difference measurement and excellent stability in frequency measurement encourage us to go for high resolution flow rate measurement. The calibrator design has to be further refined in order to reduce the back pressure created during collection of air in the calibrator air trap. Electronics have to be further modified so that the sensor calculates all the values and displays the flow in the display unit.

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