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Conducting Flow Measurement Laboratory Test Work

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***Abstract*—**Mass flow measurement is the basis of most techno-economic formulations in the chemical industry. This calls for reliable and accurate detection of mass flow. Flow measurement laboratory experiments were conducted using various instruments. These consisted of orifice plates, various sized rotameters, wet gas meter and soap bubble meter. This work was aimed at evaluating appropriate operating conditions and accuracy of the aforementioned devices. The experimental data collected were compared to theoretical predictions from Bernoulli's equation and calibration curves supplied by the instrument's manufacturers. The results obtained showed that rotameters were more reliable for measuring high and low flow rates; while soap-bubble meters and wet-gas meters were found to be suitable for measuring low flow rates. The laboratory procedures and findings of the actual work can assist engineering students and professionals in conducting their flow measurement laboratory test work.

***Keywords*—**Flow measurement, orifice plates, rotameters, wet gas meter, soap bubble meter.

I. Introduction

MEASUREMENT of mass flow is a milestone in running industrial operations as all balance determinations depend upon it. If to take the measure of a flow may seem trivial, the measurement accuracy and reliability may be a big challenge. These require good calibration of equipment and adequate installation of the piping-device setups. Flow measurement equipment ranges from simple to very complex. It should be noted that expensive and complex equipment is not needed where basic ones can be accurately calibrated and used. This work focuses on laboratory measurement of fluid flow rates using various rotameters, orifice plates, soap-bubble and wet gas meters.

II. Theoretical Background

A. Rotameters

A rotameter is a mechanical device that measures flow rate by allowing the cross sectional area inside the tube through which the fluid or gas travels, to vary. The rotameter consists of a uniformly tapered tube, float and measurement scale. The fluid flows into the tube which creates a force that moves the float up a certain height, which is reflected on the measuring scale. This observed height is used to calculate the flow rate, and subsequently different heights mean different flow rates. The float is always fluctuating in height so when it stabilizes then the flow rate is relatively constant. Additionally, factors such as pressure and temperature should be kept constant in order to promote greater accuracy of flow measurements [1]. Rotameters are to be calibrated from time to time by means of a calibration charts, mostly due to operational environment changes.

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B. Orifice Plate Meter

Orifice plates are used extensively in industry for flow measurements. They indicate flow rates by briefly reducing the area of the pipe, thus causing a pressure drop, which can be estimated using the Bernoulli equation.

The following approach enables the derivation of volumetric flow rate through both orifice plate and rotameters [2]. The mechanical energy balance through an orifice plate can be given by (1)

$$\frac{u_2^2}{2\alpha_2} - \frac{u_1^2}{2\alpha_1} + g(z_2 - z_1) - \int_{p_1}^{p_2} \frac{dp}{\rho} + W_s + F = 0 \tag{1}$$

Equation (1) can be simplified with the following assumptions:

- The fluid is incompressible
- There is no change in height
- The friction is negligible
- There is no shaft work

This leads to (2)

$$\frac{u_2^2}{2\alpha_2} - \frac{u_1^2}{2\alpha_1} + \frac{p_2 - p_1}{\rho} = 0 \tag{2}$$

Using the mass conservation principle for an incompressible fluid that states:

$$G_{in} = G_{out}$$
$$u_1 A_1 + u_2 A_2$$
$$u_1 = \frac{u_2 A_2}{A_1}$$

Equation (2) becomes then (3)

$$u_2 = \sqrt{\frac{2\alpha_2 (p_1 - p_2)}{\rho\left(1 - \frac{\alpha_2}{\alpha_1}\left(\frac{A_2}{A_1}\right)^2\right.}} \tag{3}$$

Equation (3) can also be written as (4)

$$u_2 = \rho C_c A_0 \sqrt{\frac{2\alpha_2 (p_1 - p_2)}{\rho\left(1 - \frac{\alpha_2}{\alpha_1}\left(\frac{C_c A_0}{A_1}\right)^2\right.}} \tag{4}$$

where Cc is the coefficient of contraction, with $C_c = \frac{A_2}{A_0}$

Mathematically the mass rate of flow through an orifice is given: $G = \rho Q = \rho u_2 A_2$

As a result, the coefficient of discharge for the orifice plate, which incorporates C_C as well as the frictional losses within the orifice plate, is given as by (5)

$$G = \rho C_D A_0 \sqrt{\frac{-2\Delta p}{\rho\left(1 - \left(\frac{A_0}{A_1}\right)^2\right)}} = \rho Q \tag{5}$$

Similarly, the coefficient of discharge for a rotameter (Cd), which incorporates friction losses along the tube, is given by (6)

$$G = C_D A_2 \sqrt{\frac{-2\rho\Delta p}{\rho\left(1 - \left(\frac{A_0}{A_1}\right)^2\right)}} = \rho Q \tag{6}$$

One can derive Q as follows (7)

$$Q = C_D A_2 \sqrt{\frac{-2\Delta p}{\rho\left(1 - \left(\frac{A_0}{A_1}\right)^2\right)}} \tag{7}$$

Changes in pressure and temperature affect the density of the gas in gas flow measurement. Since most gas measurements are made in mass units, variation in density can affect the accuracy of the measured flow rate if it is not compensated [3]. Equation (5) can be amended to reflect the variation of the density.

Substituting $\rho_{rot} = \frac{MP_{rot}}{RT_{rot}}$ and $\rho_{cal} = \frac{MP_{cal}}{RT_{cal}}$ in (5) and taking the ratios gives (8):

$$Q_{cal} = Q_{rot} \sqrt{\frac{P_{rot} T_{cal}}{P_{cal} T_{rot}}} \tag{8}$$

Equation (8) is known as a correction factor.

The Coefficient of discharge (C_D) can be found graphically using the chart in Fig. 1, if the Reynold's number of the fluid passing through the orifice and the ratio of the orifice diameter to the internal pipe diameter are given.

C. Soap Bubble Meter

The soap bubble meter is a device for air flow measurement consisting of a glass cylinder (where the soap solution is introduced), joined to a reservoir by a tube. It is used to calibrate other flow meters which have low to moderate flow rates.

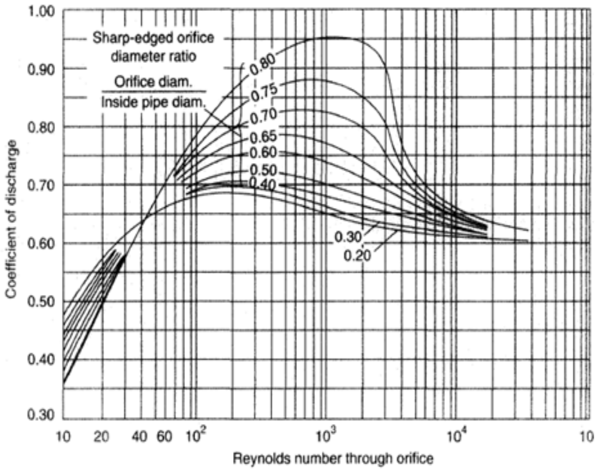

Fig. 1 Discharge coefficient (CD) abacus [2]

The volumetric flow rate (Q) using a soap bubble meter can be calculated by (9)

$$Q = \frac{V_{A,B}}{t} \tag{9}$$

where t is the time that takes a single bubble to travel from point A to point B with

$$V_{A,B} = \frac{d^2 h}{4} \tag{10}$$

where h, d are the height and the diameter of the soap bubble tube; A and B the referential marks on the tube.

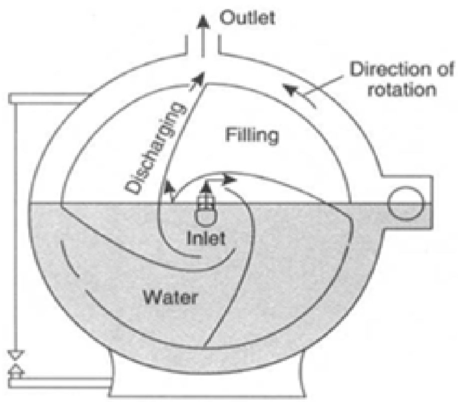

Fig. 2 Illustration of the positive displacement principle

D. Wet Gas Meter

This instrument uses the principle of positive displacement to measure the volumetric flow rate, as shown in Fig. 2. It consists of a cylindrical drum, separated into chambers, with a rotating axle. The drum is half-filled with a liquid (usually water) and supplied gas displaces the fluid. The fluid enters the first chamber if the pressure of the gas is higher than the pressure at the outlet of the pipe to the meter. As gas flows into one compartment, pressure builds up. This pressure is released as another compartment is allowed to discharge gas to the atmosphere. Consequently a rotary force is created. A needle-dial is connected to the drum that allows recording the volume of gas as it fills the drum.

III. Experimental

Experiments were comprised of orifice plate meters, various sized rotameters, a wet gas meter and a soap bubble meter setups. The fluids used in the experiments were either water or compressed air. The compressed air was assumed to be an ideal gas.

A. Soap Bubble Meter Experiment

Fig. 3 shows the Soap bubble meter experimental setup. This consisted principally of a tube reservoir, a manometer, and a rotameter.

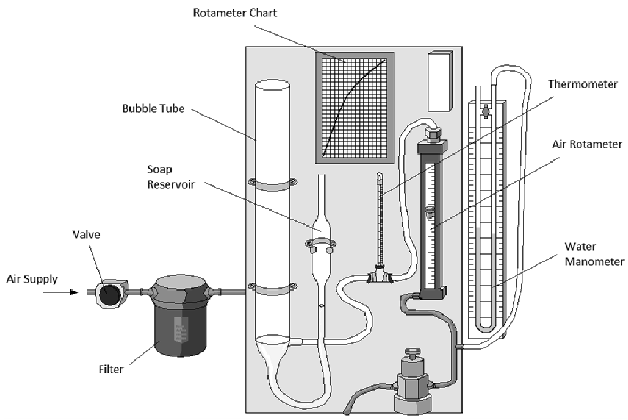

Fig. 3 Soap bubble meter setup

The experimental procedure was as follows:

1. The ambient air temperature (°C) and pressure (Pa) were recorded. This was done for all the experiments;
2. Dimensions of the soap-bubble meter were taken: the radius (m) and the height between the two referential points (mm);
3. After valve 2 and 3 were fully opened, valve 1 was then opened allowing the flow to enter the set-up;
4. The time taken for one specific bubble to rise between the two referential marks was recorded;
5. The difference in height (mm) between the two heads of fluid in the manometer was also recorded;
6. Steps 4 and 5 were repeated for various rotameter heights.

To check for reproducibility the overall experiment was repeated three times. Averages times and related rotameter heights were used in the flow rate calculations. It should be also noted that the inner wall of the soap-bubble meter was wetted to ensure the soap film to travel smoothly up the tube without being captured. The soap reservoir height was as well constantly adjusted.

B. Wet Gas Meter Experiment

Fig. 4 shows the experimental setup used for the wet gas meter, whose major components were rotameter 7A, orifice plate 1/8", manometer and the measuring cylinder.

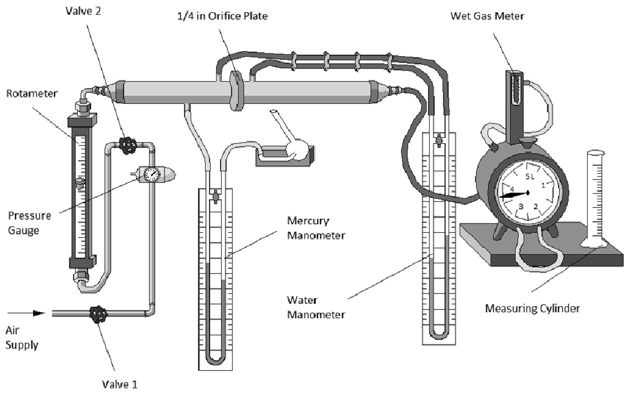

Fig. 4 Wet gas meter setup

To calibrate the wet gas meter, the following procedure was followed:

1. Valve 1 was completely opened during all the experiment;
2. Valve 2 was slightly adjusted to allow more air to flow through the system, and therefore to cause the rotameter float to move up;
3. Rotameter float heights (mm), were read at the widest part of float;
4. The manometer 1 pressure (mm) and manometer 2 pressure (mm Hg) were recorded;
5. Using a stopwatch, the time taken for the needle on the wet gas meter screen to complete one full revolution, equivalent to 5 litres water displacement, was recorded;

The experiment was repeated 2 to 3 times for reproducibility.

C. Rotameters and Orifice Plate Meter Experiments

The experimental setup of rotameters and orifice plate meter experiments is shown in Fig. 5. It consisted of two rotameters (10S and 14S) and one orifice plate 1/4". Each rotameter as well as the orifice plate were calibrated using the 'bucket-and-stopwatch' method. The flow to other pieces of equipment was kept closed, while one piece of equipment was calibrated. Valve 1 remained open throughout the experiment.

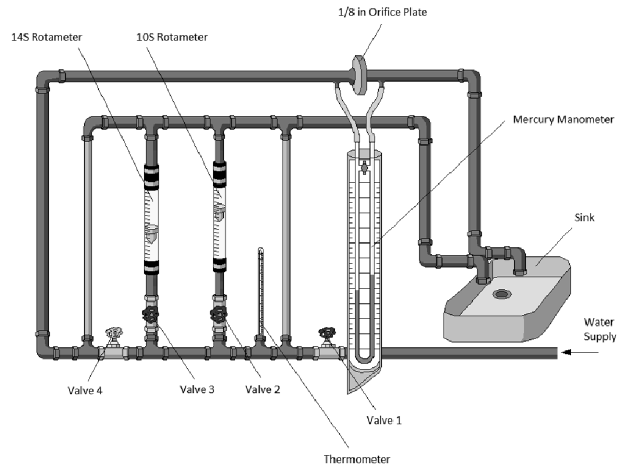

Fig. 5 Rotameters-orifice plate meter setup

To calibrate rotameter 1 (10S), the following procedure was followed:

1. Valves 1 and 2 were opened, whilst valves 3 and 4 were closed. Valve 2 was used to adjust the float height of rotameter 1 (10S);
2. A measuring cylinder was placed under the outlet of pipe 1 and the time taken to fill a certain volume of the cylinder was recorded;
3. The experiment was repeated three times at various float heights to see the deviations.

A similar procedure was used to calibrate the rotameter 2 (14S), and the 1/4" orifice plate. For rotameter 2 (14S), valves 1 and 3 were opened, whilst valves 2 and 4 were closed; and for 1/4" orifice plate valve 1 and 4 were opened, whilst valves 2 and 3 were closed.

IV. Results and Discussions

The general parabola equation $(y+a)^2 = 4p(x+b)$ was used to find the best fit line of the experimental data collected in the least square sense. Random values of a, b and p were substituted into the parabola equation. The error for the x and y values were then determined by substituting (x_i-x) and (y_i-y) into the S_{App} equation given as follows:

$$S_{App} = \Sigma_i \left(\left(\frac{(\Delta x_i)^2}{\sigma x_i^2} \right) + \left(\frac{(\Delta y_i)^2}{\sigma y_i^2} \right) \right) \tag{11}$$

where xi and yi are the experimental values; x and y are respectively the rotameter reading and the volumetric flow rate. Solver, an in-built Microsoft Excel function was used to minimize SApp by changing the variables a, b and p. Finally, the estimate of the errors between experimental and theoretical data was done using the Simpson's rule of numerical integration. This method approximates the value of a definite integral by using quadratic polynomials. Mathematically, the Simpson's rule is given as follows:

$$\text{Area} = \int_{x_1}^{x_3} f(x)dx = \frac{h}{3}(f(-x_1) + 4f(x_2) + f(x_3)) \tag{12}$$

where

$$h = \frac{x_3 - x_1}{2}$$

The error (E) between the manufacture's model values and experimental values are calculated as follows:

$$E(\%) = \frac{\left| \text{Area}_{\text{experimental}} - \text{Area}_{\text{manufacture's}} \right|}{\text{Area}_{\text{experimental}}} \times 100 \tag{13}$$

A. Experimental Conditions

All the experiments were performed under the laboratory conditions recorded in Table I, which were assumed to be constant.

TABLE I
EXPERIMENTAL CONDITIONS

Atmospheric Pressure (kPa)	84.2
Ambient Temperature (oC)	17
Volume between A and B (L)	0.998

B. Soap-Bubble Meter Experiments

Soap bubble meter experiments were conducted in order to investigate the effect of rotameter float height on the flow rate using the soap bubble meter. The results are shown in Fig. 6. It can be seen that with an increase in flow rate, the soap bubble meter data readings exhibit a higher percent error (about 17%) as compared to the manufacture's curve. This was believed to be caused by the flow meter installation default. Changes in pipe direction and valves positioning did not allow laminar fluid to flow out of the pipes and were instead causing turbulence. This type of turbulence accounted of about 50% errors in the readings of most flow meters [4].

Moreover, the discrepancy between theoretical and experimental data was also attributed to bubble instabilities and shape changes. [5] Experiments showed that the bubble dynamic was hysteretic: on increasing the forcing pressure, the bubble exhibited non-spherical oscillations and shrunk. Reference [6] stated that the bubble could resume spherical oscillations if the forcing pressure is slowly decreased. Reference [6] further showed that the bubble behaviour is also affected by the viscosity changes expressed as the Rayleigh-Taylor instability. The latter appears only weakly in low viscous fluids, as opposed in highly viscous fluids where it occurs even at a smaller driving pressure. This problem was surmounted by preparing a low viscous soap solution of small enough radius that the driving pressure increase wouldn't affect. However, experiments showed that bubbles from the low viscous soap solution were still distorted and rotated slightly during the up-rising movement. It was assumed that bubbles didn't experience the Rayleigh-Taylor instability during the experiments.

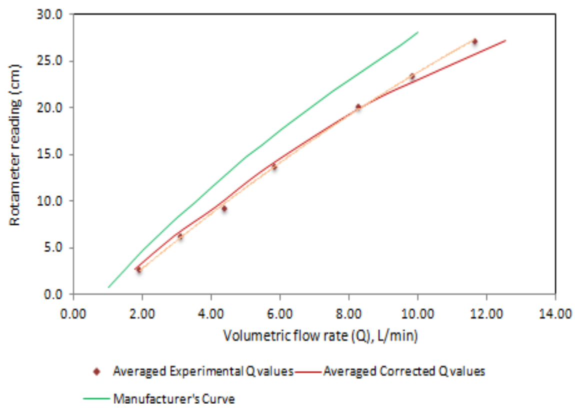

Fig. 6 Calibration chart of the 7A air rotameter

In Table II, a model that describes the relationship between rotameter float height and the flow rate was developed from experimental data, using the least squares regression

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technique. This model shows the mathematical behaviour of the rotameter float as affected by different fluid flow rates.

TABLE II
MATHEMATICAL MODELS FOR 7A AIR ROTAMETER

Instrument	Method	Model
Rotameter (7A)	S simple	$Q = 0.003037\left(h + 49.76\right)^2 - 6.40$
	S app	$Q = 0.003189\left(h + 49.75\right)^2 - 7.00$

C. Wet-Gas Meter Experiments

Fig. 7 displays the effect of rotameter float height on the flow rate, through the 1/8"orifice plate and the 14XK rotameter. The average error in the flow rate obtained with the wet gas meter was calculated using the Simpson rule of numerical integration. The error percent obtained was negligent and within a reasonable degree of approximation at low and moderate flow rates, respectively about 0.68% and 4.04%; however, at high flow rate, the percent error was relatively significant at about 19.44%. This was understandable since the experimental wet gas meter used had a capacity of only 5 litres. The flow rate range 0.96 m^3/hr to 4.10 m^3/hr was outside of the specified manufacturer's reliability range. This could explain the big margin error obtained at high flow rate. With respect to the orifice meter, the error increased with an increase in flow rate, and as well as the increase in float height fluctuations. The average relative errors were 2.83% at low flow rates and 39.67% at high flow rates respectively.

In Fig. 7, only three points (at low flow rate) were used to derive the model describing the behaviour of the 14XK rotameter since the rotameter reading data deviated significantly from those of the manufacturer's. The mathematical model developed is shown in Table III. The mathematical model for the 1/8" Orifice Plate was also developed.

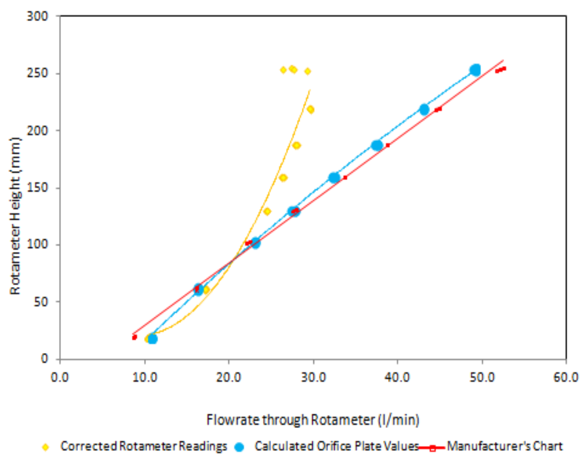

Fig. 7 Comparison chart between 14XK rotameter and 1/8" orifice plate

TABLE III
MATHEMATICAL MODELS FOR 14XK ROTAMETER 14XK AND 1/4" ORIFICE PLATE

Flow Meter Type	Model
14XK Rotameter	$h = 6.53Q - 6.53$
1/8" Orifice Plate	$h = \sqrt{8421.2\left(Q + 29.2\right)} - 559.5$

D. Rotameters-Orifice Plate Meters Experiments

Flow measurement tests were conducted using two different types of rotameters and an orifice plate meter to investigate the relationship between the experimental data and the theoretical predicted data.

Fig. 8 shows the results obtained with use of the rotameter 1 (10S). One can see that the experimental results differ from the theoretical predictions only at about 2.3%. The difference was relatively negligible and could have completely disappeared if more measurement were taken. The measurements also agreed with the Bernoulli's equation prediction and the manufacturer calibration curve.

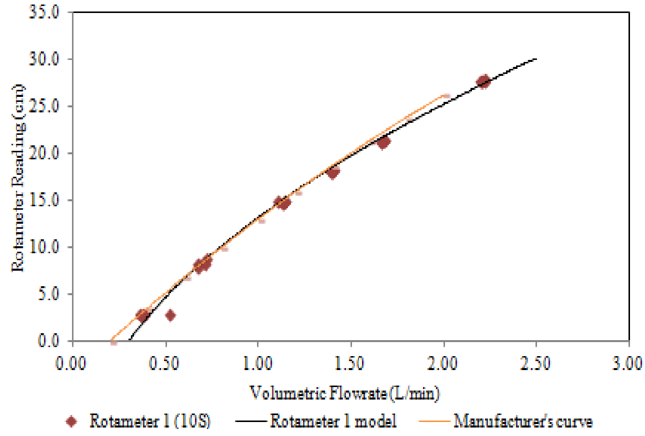

Fig. 8 Calibration chart of rotameter 1 (10S)

The results obtained with the rotameter 2 (14S) are shown in Fig. 9. It can be seen that the average % of deviation of the experimental data from the theoretical predictions was only 0.91%. This indicates that measurements taken were precise and reasonably accurate.

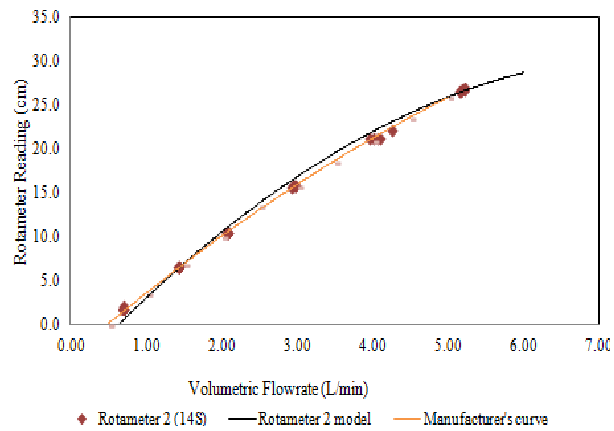

Fig. 9 Calibration chart of rotameter 2 (14S)

Flow measurement tests were also conducted with the orifice plate meter. The results presented in Fig. 10, provided more realistic readings for a large range of flow rates. The average percentage error associated with this experiment was approximately 6 %. This significant deviation from the theoretical predictions was believed to be due to the wear out of the orifice device with time [7]. Ideally, the orifice diameter should always be re-checked before taking any measurement.

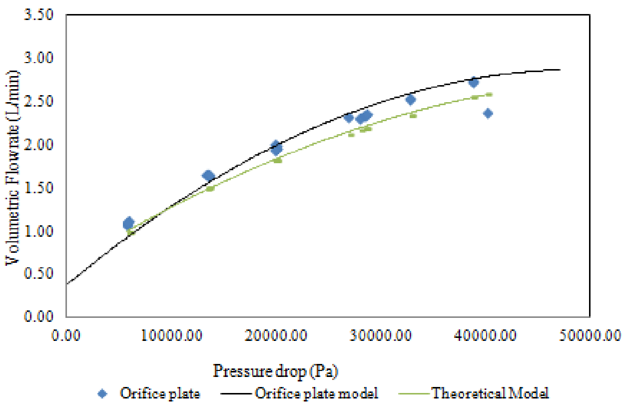

Fig. 10 Calibration chart of ¼ "orifice plate

Mathematical models were also developed for rotameter 1 (10S), rotameter 2 (14S) and orifice plate 1/4", using the least squares regression technique. The results are shown in Table IV.

TABLE IV
MATHEMATICAL MODELS FOR ROTAMETERS-ORIFICE PLATE METER

Instrument	Model	S_{App}
Rotameter 1 (10S)	$Q = 0.00118(h + 16.0)^2$	0.258
Rotameter 2 (14S)	$Q = 0.00315(h + 14.2)^2$	0.367
Orifice plate 1/4"	$Q = 0.505h^{\frac{1}{2}}$	1.910

The errors associated to these models were also evaluated using the Simpson's rule, as shown in Table V. It was assumed that the errors in Q and h formed a normal distribution curve and subsequently S_{App} was minimized to find a best fit model for the experimental values.

TABLE V
ERROR ANALYSIS USING SIMPSON'S RULE

Instrument	% error from Manufacture's chart
Rotameter 1 (10S)	2.3
Rotameter 2 (14S)	0.91
Orifice plate 1/4"	6.0

The relative error of the experiments was due to both the measurement reading errors and to the quality of the equipment. The results can be substantially improved if the follows are enhanced:

- Use of automated valve systems to allow precise and accurate regulation of the flow of fluids;
- Use of high-accuracy electronic flow meters that provide instantaneous flow readings;
- Use of a much elaborated soap in terms of viscosity and bubble shapes;
- Use of realistic compressible air characteristics in the calculations.

V. CONCLUSION

The laboratory flow measurement tests helped at understanding the reliability and accuracy ranges, as well functioning of various flow measurement devices. The soap bubble meter and wet gas meter were found to be better for measuring low flow rates with a smaller RMS error. As far as the rotameters are concerned, it was found that the greater the diameter of the rotameter the more accurate and precise the flow measurement readings. In addition, water flow system measurements were found to be more accurate than air flow ones using similar measurement systems. The orifice plate was less accurate and more limited, compared to rotameters, due to their arbitrary calibration and their wear over time.

Finally, rotameters are generally good choice as measuring devices that are able to cover wide ranges of flow rates. However, the proven need, the cost and the application should prevail in the choice of each and every device.

NOMENCLATURE

SI units except where otherwise indicated:

A_0 – Area of Orifice (m^2)
A_1 – Cross Sectional area of tube (m^2)
A_2 – Cross Sectional Area of Annulus (m^2)
Cal – Calibrated Reading
C_D – Coefficient of discharge
D – Diameter (m)
g – Gravitational acceleration constant (m/s^2)
G – Mass Flow Rate (kg/s)
h –Height Difference on Manometer (m)
M – Molecular Weight (kg/kmol)
p – Pressure (Pa)
Q – Volumetric flow rate (L/s)
R – Gas Constant (J/(mol.K))
RMS– root mean square
Rot – Experimental Reading
Sapp – Sum of squared errors
T – Temperature (ºC)
t – Time (s)
u – velocity of fluid (m/s)
V – Volume (L)
Δp – Pressure change
µ – Viscosity of water (Ns/m2)
ρ – Density (kg/m^3)

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