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A Novel Straightforward Practice for Rotameter Calibration in Gas Flow Measurement

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Rotameters for gas flow-rate measurements are calibrated and scaled by air or oxygen at standard atmospheric pressure and temperature in the fabrication plants. To utilize these rotameters for gas flow rate measurements at different conditions, they have to be recalibrated again. This is not an easy task in the labs environment and should be carried out with so much care to obtain accurate measurements at the specified operating conditions. A novel straightforward and reliable procedure for calibrating rotameters under specific lab conditions is introduced in this paper which enables researchers to practice it with usual limitations of time and budgets. The practice involves producing proper calibration curves based on the theoretical formulations. As an example, the principle of action and characteristics of an air calibrated rotameter is investigated, when it is going to measure oxygen flow rate at different pressure and temperature. It is shown that a linear function can be derived to estimate the true flow rates of gases based on the indicated flow rate readings on the rotameter scale and the corrected flow rate mentioned in the literature.

Keywords: Rotameter, Flow meter, Calibration

1 Introduction

Flow rate is the amount of a substance (liquid or gas) passing per unit time through a cross-section. The quantity of substance, passing through a cross section, could be measured in volume flow rate $\dot{Q}$ [m^3/s] or mass flow rate $\dot{m}$ [kg/s] by devices called flow meters.

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According to the principle of operation, the flow meters are categorized as: variable pressure drop, variable level, with constant pressure drop, velocity, power, electromagnetic, thermal, etc.[1-4].
The flow measurement devices, such as rotameter, have to be re-calibrated and/or their accuracy be verified before using in an application based on its operating condition[5-9] . This costly, time-consuming process typically involves sending flowmeters out for calibration or verifying them in-house.
Most of the researchers proposed the relationships mentioned in Section (3). But, when testing a ventilating system, that was obvious for us that getting a proper result on oxygen flow rate, only by using those relationships, is not a simple task due to the limitation in estimating actual operating conditions in the installed rotameter. Hence, a straightforward affordable calibration procedure is developed in this work with carefully-selected instruments and gauges, available in stores, to enable accurate calibration of rotameter for measuring flow rate of any gases at different pressure and temperature.

2 Working Principle of Rotameters

The rotameter is a robust and simple flowmeter for gases and liquids, and holds a large share of the market for pipe diameters smaller than about 100 mm [10, 11]. They belong to the group of devices working with a constant pressure drop (variable area flow meter) [9]. The rotameter is characterizes by simple and robust construction, high reliability, low pressure drop, uncertainty of 0.4 % to 4% of maximum flow, insensitivity to non-uniformity in the inflow[12]. A rotameter for air flow rate measurement is shown in Figure (1). Its main elements are a vertically positioned conical transparent tube and float. The input of the unit is supplied with fluid at a pressure P_O. In the absence of flow, when the throttle valve is closed, the float is located in the lower end position, completely closing the tube, and its middle surface should show zero mark on the scale. When opening the throttle, the flow forces overcome the weight of the float and move it vertically upwards. It opens passage section with an annular space defined by the difference of the diameters of the float and the tube for the particular position of the float. In the actual design the pipe and the scale are interchangeable depending on the scale of the device and the type of measured fluid [7].

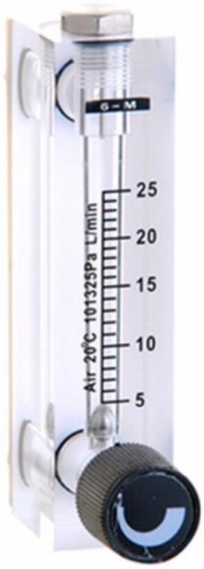

Figure 1 A scheme of a rotameter for measuring air flow rate

3 Flow Corrections

Each variable area flow-meter is designed to operate under a certain set of conditions which include the temperature, pressure and the type of gas [7, 13]. Usually, these conditions are documented directly on the tube enclosure of the variable area flow-meter, with the flow rate scales referenced in mm (millimeter).

A reference table is provided to enable operators to match the millimeter readings against the equivalent flow rates at the specified standard temperature and pressure. Otherwise, direct scale variable area flow-meters, such as shown in Figure (1), indicate the flow rates directly on the tube enclosure.

When calibrating variable area flow-meters, corrections must be applied to the indicated flow measurements in order to take into account the differences between the actual operating temperature, pressure and gas used versus the variable area flow-meter's specified temperature, pressure, and gas requirements [7, 13]. Volumetric flow rates through a rotameter can be estimated by the following equation [2, 14]:

$$\dot{Q} = CA_b \sqrt{\frac{2g\left[\frac{V_f(\rho_f-\rho)}{A_f}-\rho h_f\right]}{\rho\left[1-\left(\frac{A_b}{A_a}\right)^2\right]}} \tag{1}$$

Where $\dot{Q}$ is the volumetric flow rate; C is the discharge coefficient; A_a and A_b are flow areas at the bottom and top of the float; ρ_f, V_f, A_f, and h_f are density, volume, area and height of float. ρ is the density of fluid, and g is the earth gravitational acceleration.

To properly calibrate variable area flow-meters, the flow rate obtained from the above equation should be corrected by the following formula [7]:

$$\begin{gathered} Variable\ Area\ Flow\ Meter's\ Corrected\ Flow = \\ Variable\ Area\ Flow\ Meter's\ Indicated\ Flow * Correction\ Factor \end{gathered} \tag{2}$$

Correction factor could be calculated from;

$$X = \sqrt{A * B * C} \tag{3}$$

Where:

- A = Specific gravity of the calibration gas as specified by the variable area flow meter / Specific gravity of the operating gas
- B = Absolute operating pressure in PSIA during calibration / pressure in PSIA as specified by the variable area flow-meter
- C= Temperature in ^{o}K as specified by the variable area flow-meter / Surrounding temperature in ^{o}K during calibration.

During testing a ventilating system, remarkable differences between actual flow rate of oxygen and what was estimated by Equations (2) and (3) were observed. Investigating more the cases, it seems that the problem might be due to inaccuracy in measuring actual pressure in the rotameter. Frankly, getting a proper result for oxygen flow rate, only by using those relationships, could not be a simple task due to the limitation in estimating actual operating conditions in the installed rotameter.

4 Calibrating Apparatus Setup

Scheme of the experimental stand and nozzles are shown in Figure (2) and Figure (3). The names of required elements and their functions are as follows: 1- A cylinder filled by oxygen up to 100 bar ; 2- Regulating valve (reducing pressure to 4 bars gauge); 3- Needle valve to control the flow in rotameter; 4- An on/off valve; 5- Needle valve to control oxygen flow through the nozzle; 6- Rotameter (fluids: air, oxygen and similar gases, calibrated with air at standard atmospheric pressure and temperature, accuracy class: 2.5 L/M compared to the upper limit of the range, operating temperature: –30 °C to +120 °C, scale length: 100 mm, cone pipe designed for air flow rate of 2 to 25 L/M); 7- Nozzles with throat diameters of 0.5, 0.75, and 1 mm (shown in Figure (3)); 8- A transparent beaker to measure the gas volume displaced (V_6: scaled up to a maximum volume of 6 liters); 9- container (tub water); 10, 11, and 12 are Gauge Pressures; 13- Stainless steel tubes and fittings; 14- flexible connecting tube (hose) with an internal diameter $d \approx 8$ mm; 15- Thermometer (range: 0 to 50 °C; division value: 1 °C); 16- barometer; 17- Stopwatch-division value: 0.01 s.
Density of water is assumed to be 1000 kg/m^3; value of the gravitational acceleration is g = 9.80665 m/s^2; and volume of the beaker is V_6 = 5 liters. Standard atmospheric pressure and temperature are considered to be 1 atm and 25ºC.

5 Experiments Procedure

The calibration procedure is as follows. Lab absolute pressure and temperature were recorded by barometer and thermometer at the beginning of each test. Due to low flow rate and small gas velocity, the temperature of flowing gas is assumed to be constant and equal to the local lab temperature. Water density is assumed to be 1000 kg/m^3 and gravitational acceleration g = 9.80665 m/s^2. Standard atmospheric pressure and temperature are considered to be 101.325 kPa and 25ºC. Data from the experiment were recorded in Table (1). Experiments were carried out ten times and then the numerical results were averaged. There are three sets of data in this table. The operational condition of these sets are as follows;

- Set (1): Valves (2) and (4) were fully opened. Valve (3) was used to control the flow, and Valve (5) was closed. Hence, the pressure inside the rotameter is very close to the local atmospheric pressure.
- Set (2): Valves (2) and (5) were fully opened. Valve (3) was used to control the flow, and Valve (4) was closed. Nozzle (7) is not installed in the flow system. Therefore, the pressure in the rotameter is also close to local atmospheric pressure, but with a small amount l greater that those in Set (1).
- Set (3): Valves (2) and (5) were fully opened. Valve (3) was used to control the flow, and Valves (4) was closed. Nozzle (7) is installed in the flow system. Consequently, the pressure inside the rotameter is much higher than local atmospheric pressure due to pressure loss in the nozzle.

In each test, rotameter flow rate was directly read from the rotameter scale in units of liters/minutes. The absolute pressure in rotameter was obtained by reading gauge pressure (11), which is located just at the exit port of the rotameter, and adding it to the local atmospheric pressure measured prior to test. In case the pressure was very close to the atmospheric pressure, a water filled manometer was used for better accuracy.
Corrected volume flow-rates were obtained by applying Equations (2) and (3) for standards atmospheric conditions to the above reading indicated rotameter flow rate. Considering the constant temperature assumption, besides gas type, the only physical parameter affecting the volume flow rates would be the operating gauge pressures.

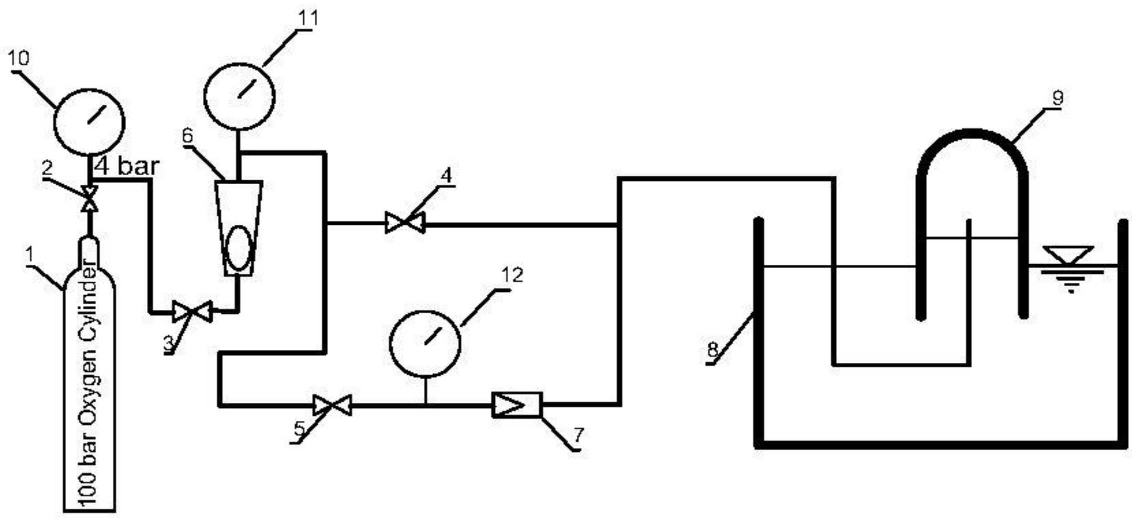

Figure 2 Scheme of experimental stand

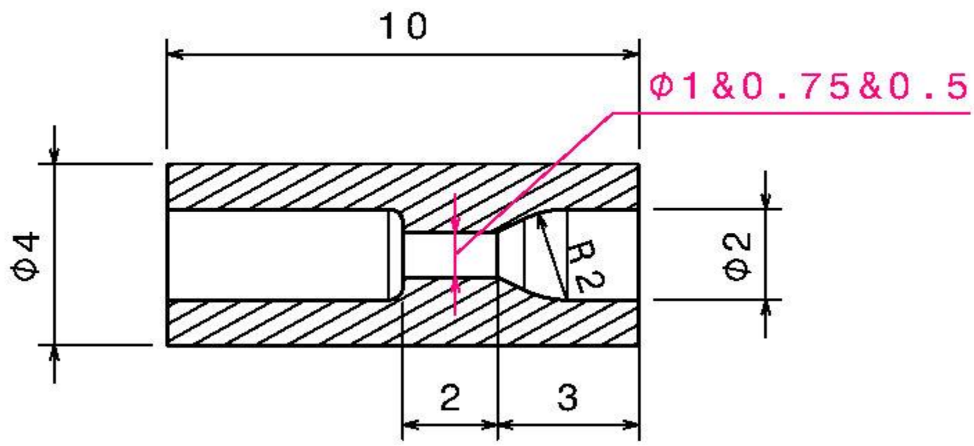

Figure 3 Shapes and Dimensions of the Nozzles

To measure the actual operating gas (oxygen) volumetric flow rate at lab atmospheric pressure and temperature, a downward beaker (No. (8)) was filled with water. After achieving stable conditions, the time needed for substitution 5 liters of water in beaker with flowing oxygen was measured by a stopwatch (No. (17)). The actual oxygen flow rate at local atmospheric pressure and temperature was determined by dividing the beaker volume (5 liters) to the measured time. This value was modified to standards atmospheric conditions.

6 Results

The results of measured as well as corrected calculated flow rates for three above mentioned tests sets are tabulated in Table (1).
The percentage of error between Measured Standards Oxygen Flow Rate and Corrected Standard Oxygen Flow Rate for different Rotameter Reading Flow Rate are plotted in Figure (4). As shown, the difference between measured (true) value with corrected value estimated by Equations (2) and (3) could be up to 35 %. Also, the error for Set (1) and Set (2) are almost similar, but that of Set (3) is quite different. This might be due to pressure in inside the rotameter, which is almost the same for Set (1) and Set (2).

Table 1 Rotameter flow-rates

Test Set	Rotameter Reading Flow Rate (L/M)	Rotameter Operating Absolute Pressure (kPa)	T_0 (K)	Measured Standard Flow Rate (L/M)	Corrected Standard Flow Rate (L/M)	Error(%)
Set 1	2	101.5	305.15	2.809	1.880	33
Set 1	3	101.5	305.15	3.823	2.820	26
Set 1	5	101.5	305.15	5.995	4.699	22
Set 1	7	101.5	305.15	7.910	6.579	17
Set 1	8	101.5	305.15	9.330	7.519	19
Set 1	10	101.5	305.15	12.083	9.399	22
Set 1	13	101.5	305.15	15.333	12.218	20
Set 1	13	101.5	305.15	15.949	12.218	23
Set 1	15	101.5	305.15	18.192	14.098	23
Set 2	5	103.03	304.15	5.889	4.742	19
Set 2	7	103.97	304.15	8.043	6.669	17
Set 2	10	103.30	304.15	12.550	9.497	24
Set 2	13	105.03	304.15	14.796	12.449	16
Set 2	15	103.70	304.15	17.507	14.273	18
Set 2	20	107.57	304.15	23.708	19.382	18
Set 3	5	112.63	304.15	5.677	4.958	13
Set 3	10	131.70	304.15	11.202	10.723	4
Set 3	15	159.69	304.15	15.929	17.712	11
Set 3	20	211.16	304.15	22.193	27.156	22

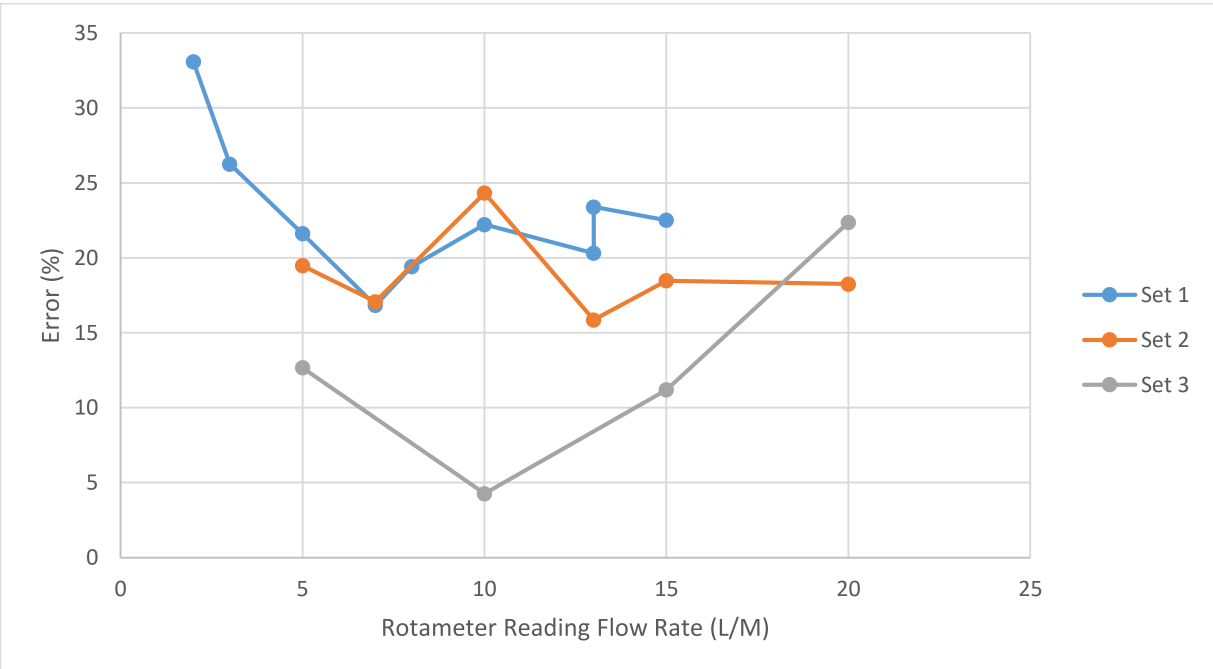

Figure (4) Variation of Error Percentage between Oxygen Standard Measured and Corrected Flow Rate with Rotameter Reading Flow Rate

According to ISO-5168 [15] and Kaizhong Guo, Shiyong Liu [16], three types of errors exist: *random errors*, which can be due to a large number of variables and cannot be controlled by the researcher, and that cause measurements to differ from the true value in a constant manner; *systematic errors*, which occur when all measures differ from the true value in a constant manner; and *spurious errors*, caused by human error or problems within the device. Systematic errors can be minimized with instrument calibration.
The variation of corrected and measured oxygen flow rates at standard atmospheric pressure and temperature versus oxygen flow rate readings by rotameter are shown in Figures (5) and (6), respectively. As can be seen Set (1) and Set (2) data are quite close and could be grouped in a single set, but Set (3) data have offsets, in particular as flow rates increase. This trend is more obvious in Figure (5). This is because of effective absolute pressures of gas in rotameter, which is almost similar for Sets (1) and (2), while in Set (3) is much higher than those of Sets (1) and (2), mainly because of installing a nozzle in the gas passage tubing.
For incompressible flow in a piping system the following equation could be derived from Bernoulli's and Darcy's equations [6];

$$\Delta p = f\rho \frac{L+\sum L_e}{D}\frac{V^2}{2g_c} = K_{total}\rho\frac{V^2}{2g_c} \tag{4}$$

from continuity equation;

$$\dot{m} = \rho AV = \rho\dot{Q} \tag{5}$$

hence,

$$\dot{Q} = \sqrt{\frac{2g_c A^2 \Delta p}{K_{total}\rho}} = C\sqrt{\Delta p} \tag{6}$$

For fluid flow of gases such as air, oxygen and steam, when density changes are small ($M<0.3$), the fluid flow may be considered as incompressible[6]. Since the maximum volumetric measured flow rate is almost *30 L/M* and the diameter of the piping system is *8 mm*, the above formulations are applicable in this research. Increasing volumetric flow rate is associated with increasing pressure drop in the piping system, but the relationship between these parameters is not linear. This is clearly shown in Figure (5) and is in agreement with Equations (1) and (2).
Variations of measured flow rates (actual values) versus corrected calculated flow rate are shown in Figure (7). Again Set (1) and Set (2) data are quite close, considering their almost similar operating pressures, and may be represented by a single curve. However, the slope of the curve for Set (3) is different, considering their different operation pressure. The linear correlation between standard measured and corrected oxygen flow rates for both constant and variable operating pressures in this drawing is quite appealing.
Although, basically, the measured and corrected flow rates at any particular operating pressure and temperature must be equal, Figure (7) clearly indicates that, indeed, it is not the case. The main reason for this offsets is the pressure changes of the gas as it passes through the rotameter. Measuring the pressure and temperature inside the rotameter are not easy tasks, but this is not really a challenging issue. In this investigation pressure was measured just at the exit port of rotameter. This can explain the difference between corrected and measured flow rates, as the corrected flow rates values are obtained based on the rotameter exit port pressure. Considering that the pressure at the exit of rotameter depends on downstream pressure losses up to beaker (atmospheric pressure), a linear relation exists between measured and corrected flow rates. Hence, Figure (7) could provide a proper and simple correlation for proposed method in Section (2).

For constant operating pressure of a rotameter, Figure (7) can be used to properly estimate true volumetric flow rate of oxygen based on corrected flow rates calculated by Equations (2) and (3). This expression is linear and can be derived by doing a few straightforward tests in the lab as will be outlined. This practice is also applicable for variable operating pressure conditions, albeit with more attentions.

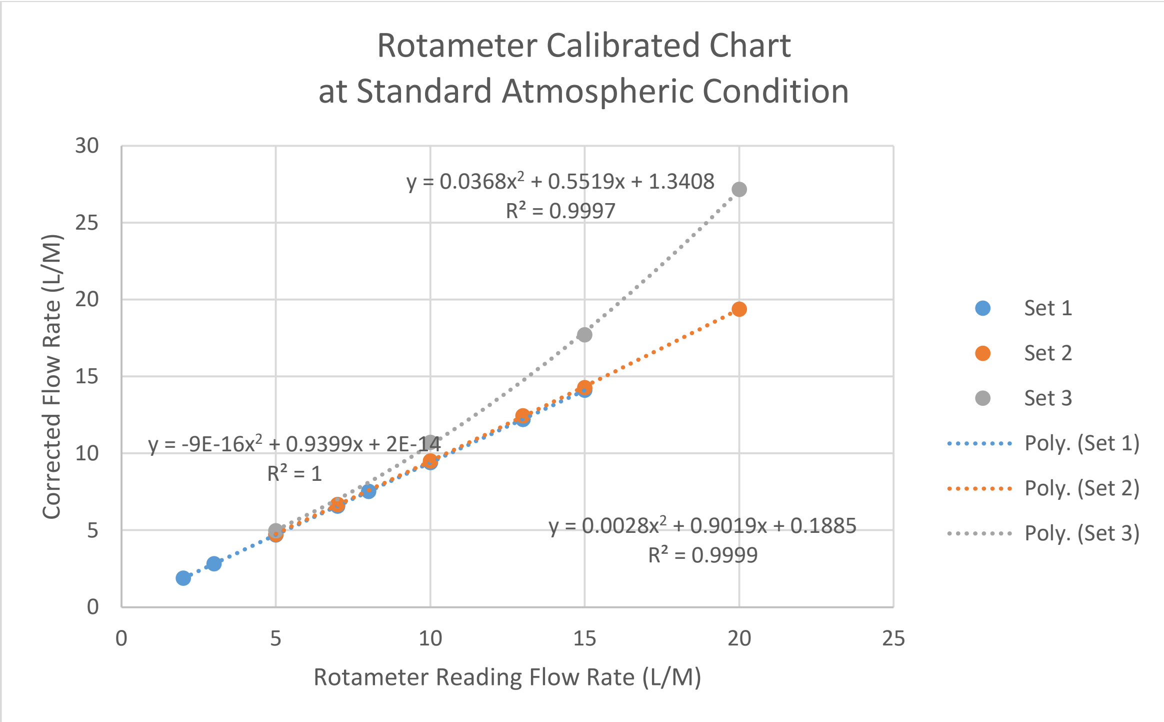

Figure 5 Variations of Corrected Flow Rates versus Rotameter Flow Rate Readings

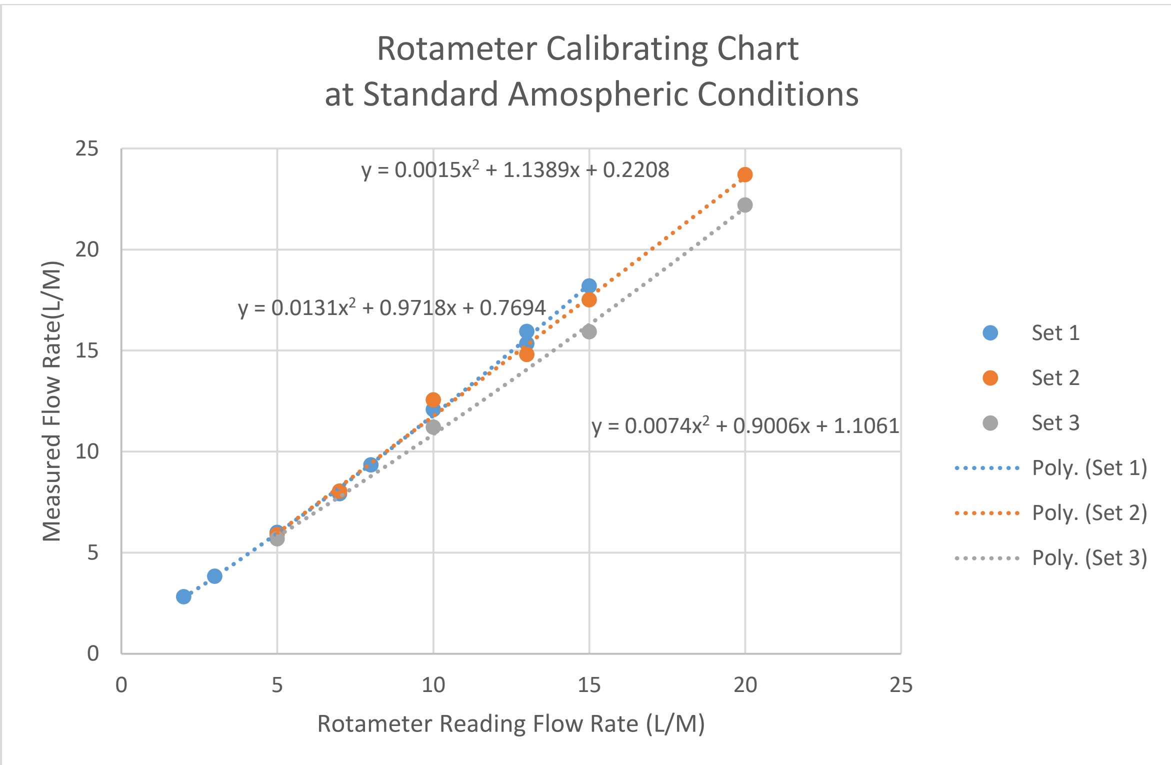

Figure 6 Variations of Measured Flow Rates versus Rotameter Flow Rate Readings

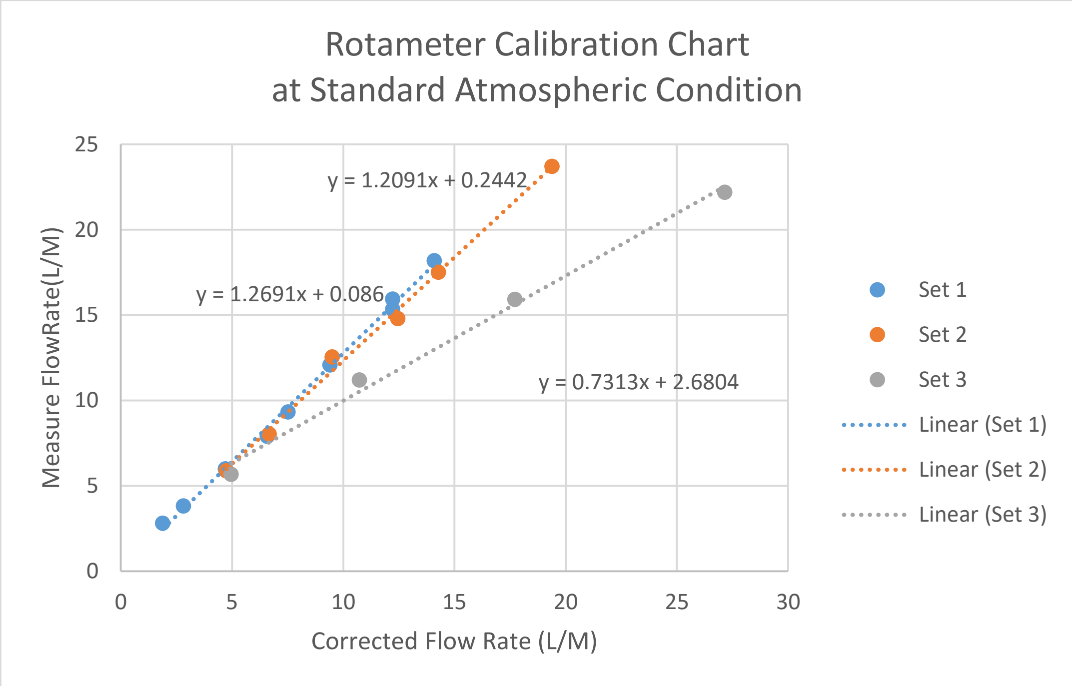

Figure 7 Variations of Standard Oxygen Measured Flow Rates versus Rotameter Corrected Flow Rates

In summary the proposed practice steps are as follows:

1- Install the designated rotameter in the system setup as explained earlier
2- Set the desired operating pressure on rotameter by adjusting pressure drop at its downstream
3- Measure and record lab local atmospheric pressure and temperature
4- Measure the time require to fill the beaker.
5- Calculate the actual flow rate, and modify it for standard atmospheric pressure and temperature
6- Obtain the correction factors for standard atmospheric pressure and temperature as well as the flowing gas molecular weight [7].
7- Calculate the corrected flow rate at Standard atmospheric conditions (Eq. (2) and Eq. (3)).
8- Re-produce Table (1) and Figure (6).
9- Obtain the linear correlation between measured and corrected flow rates (from re-produced Figure (6)). This is the calibration expression.
10- To use this rotameter in real tests or in operational units, read the scale on the rotameter and rotameter exit gauge pressure and temperature and repeat Steps (6) and (7), and obtain the actual flow rate from the correlation in Step (9).

7 Conclusion

The purpose of this research work was to present a practical affordable procedure for calibration of rotameters measuring gas flow rates in labs environment. The procedure was examined for measuring oxygen flow rates in an apparatus specifically designed and fabricated in this research. Based on the experimental results, a proper calibration curve for the rotameter was provided by plotting the measured flow rates (true values) versus the corrected flow rates (calculated by Equations (2) and (3)). A linear function could be derived by regression this graph which can be used to estimate the true flow rates of gases based on the indicated flow rate readings on the rotameter scale in practical applications. The proposed procedure is applicable for calibration of rotameters in the reference lab sites as well as university or industrial labs without worry about the exact value of pressure in the rotameter.

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