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The Volume Measurement of Air Flowing through a Cross-section with PLC Using Trapezoidal Rule Method

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Abstract – In industrial control systems, flow measurement is a very important issue. It is frequently needed to calculate how much total fluid or gas flows through a cross-section. Flow volume measurement tools use simple sampling or rectangle methods. Actually, flow volume measurement process is an integration process. For this reason, measurement systems using instantaneous sampling technique cause considerably high errors. In order to make more accurate flow measurement, numerical integration methods should be used. Literally, for numerical integration method, Rectangular, Trapezoidal, Simpson, Romberg and Gaussian Quadrature methods are suggested. Among these methods, trapezoidal rule method is quite easy to calculate and is notably more accurate and contains no restrictive conditions. Therefore, it is especially convenient for the portable flow volume measurement systems. In this study, the volume measurement of air which is flowing through a cross-section is achieved by using PLC ladder diagram. The measurements are done using two different approaches. Trapezoidal rule method is proposed to measure the flow sensor signal to minimize measurement errors due to the classical sampling method as a different approach. It is concluded that the trapezoidal rule method is more effective than the classical sampling.

Keywords: Flow measurement, PLC, Trapezoidal integral method

1. Introduction

High-precision measurement of air flow volume is a necessity to provide the functionality and optimization in many industrial applications. The flow rate of liquid or gas in some pipes is not needed to precisely measure in most applications but is almost vital to obtain it by using most accurate way in some industries such as pharmaceutical, food and petrochemical. Accurate determination of the amount of aerosol is quite important particularly in pharmaceutical industry. Besides, inhalation of high rates of harmful substances can trigger critical diseases. A defined minimum gas volume is needed to ensure the desired performance of a system that particularly consumes compressed air. In addition, some processes must also be protected to prevent damage due to the excessive air supply. In most cases, manufacturer's warranty depends on the provision of this condition [1]. The accurate measure of flow rate is also quite important to use the preventive maintenance which is consumption-related [2]. Instead, consumption-related replacement improves the process reliability and decreases total operating cost [3]. Industrial production processes are considerably complex and firstly need some parameters to be accurately measured such as pressure, temperature, volume etc. These parameters are often controlled to achieve the most acceptable results. Therefore, prevalence studies are currently conducted on flow measurement. These studies in the literature can be classified by four groups: Sensor design [4-5], Comparison of sensor characteristics [6-11], Developments of flow measurement methods [12-14], Flow measurement applications [15-18].

However, the studies for the flow measurement using various methods in industrial control systems are very much limited. There are restrictions on defining of sampling interval at high velocity applications and performing calculations with some numerical integration methods. In addition, they don't provide a significant improvement in the value of accuracy at low velocities. But the trapezoidal rule method is very convenient and adopted particularly for the portable flowmeters with low power consumption for both high and low velocities.

The pitot tubes, laser doppler and thermal mass types of flowmeters are often used to measure flow volume measurement. Pitot tubes anemometer is far less expensive and easier to operate, but is difficult to use if air/gas velocities are less than about 3m/s and due to the need of calibration every six months. Laser doppler anemometer accurately measures between 0.1-100 m/s velocities. Since it provides noncontact anemometry, it is usable at high temperatures. Its primary disadvantages are cost and complications associated with properly seeding the flow with particles. Thermal mass flowmeter is affected by the upstream flow but it is calibrated with a perfect fully developed up-stream flow [19]. For this reason, Thermal

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mass flow meters are preferred for most applications. Therefore, this type of a transducer is used in the setup.

In this study, the volume measurement of air flowing through a cross-section by means of PLC using both a classical and trapezoidal rule method is realized. It is shown that trapezoidal rule method is more accurate and usable especially for portable flowmeters.

2. Design Parameters

Volume measurement can simply be implemented by sampling the signal at Δt time intervals. This method is known as cumulation of flow instantaneous values. When the flow decreases, the volume is over-measured. The measured value is oppositely below the true value when the flow increases as shown in Fig. 1. The other method is based on sampling the flow signal with uniform time intervals, summing and averaging the successive values respectively. In this process, the latest volume value is added to the previous value and consequently the average is achieved and so on. It is known as trapezoidal rule method and gives better results [19].

In this study, various measurements of the air volume which is pumped through a duct are made by using classical and the trapezoidal method. If a flow is sampled with (Δt) time intervals and the volume is calculated for each interval, the whole air volume flowing through a duct during this sampling time can be given as follows:

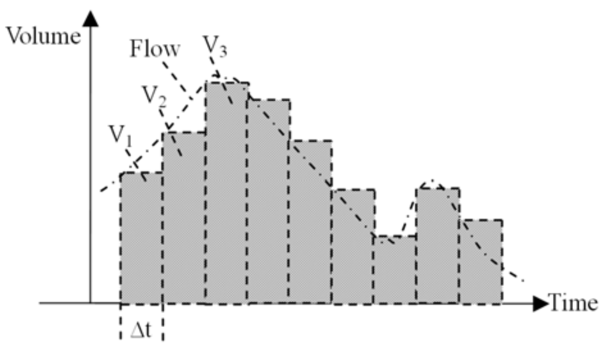


Fig. 1. A classical flow measurement

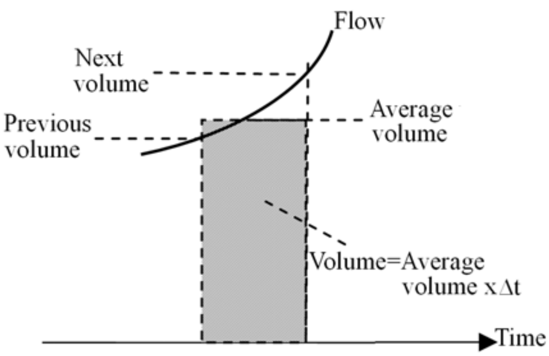


Fig. 2. Trapezoidal integration method [19]

$$V = \Delta t . s . v / 60 \tag{1}$$

Where V denotes flow volume in m^3 (But this unit is too big, so liter as unit is preferred for measuring the volumes in this work); Δt is sampling period in seconds; s is cross-section of the air duct in m^2. The measurement is made by sampling the signal, summing the successive two values and taking average respectively. The average volume is multiplied by Δt to find the final value. The representation of trapezoidal rule method is shown in Fig. 2. The measurement of the air volume for an air duct is made by using a PLC ladder diagram for both methods and ultimately, they were compared to each other in terms of errors for both increasing and decreasing flow values. The algorithm can be written as in the following.

Initial volume = 0 {Initial value is assigned}
  Read new data from the Data Acquisition card.
Wait Δt second
  Averaged vol.= (new vol.+ previous vol.).Δt /2
Calculate flow volume during Δt time interval
  ΔV = Δt. s. flow speed; {new volume in m^3}
  Total volume = Total volume+ ΔV
  Initial volume = total volume
  Return to the second step.

As a matter of fact, calculating total volume from flow rate is an integration operation. It is utilized in several applications such as providing distance from speed and speed from acceleration by using double integration. How this operation could be achieved by using ladder diagram is shown in Figs. 4-9.

3. Experimental Setup and Application

The experimental setup and schematic diagram are given in Fig. 3. Because the fan motor is one phase asynchronous, 0.5kW, 1500 rpm, 5A, therefore 0.8 kW with one phase inverter is selected. A flow s is also used to read the flow rate continuously.

In order to minimize errors which are caused of environment, measurement tool or measurement method, the circular air duck is used and the thermal mass flow transducer is set up 20 times the diameter of the air duck

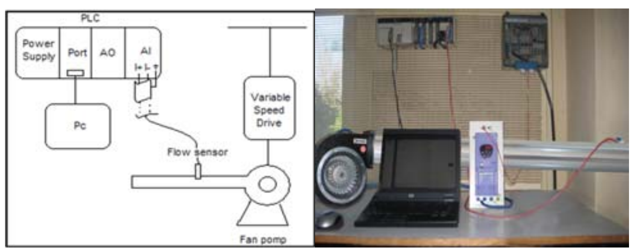


Fig. 3. Schematic diagram and the experimental Setup

Table.1 The Flow transducer technical data

Sensor	Thermal silicon chip sensor, mass flow principle
Media	Compressed air, air, nitrogen, non-corrosive gases
Measuring	0 to 80 Nm/s, min. 1 Nm/s or 0 to 150 Nm/s, min. 2Nm/s
Accuracy	±3 % of reading, ±0.4 % of final value For flows < 10 Nm/s: pressure influence 0.3 % of reading per bar
Temp. dependency	Compensated at 25 °C, deviating temperatures: 0.1% of reading/Kelvin
Response time	t90 approx. 0.5 seconds
Voltage supply	12 to 24 V DC ±10 %, power consumption < 100 mA (starting curre briefly 500 mA)
Electrical connection	Precision plug connection for distributor box, 0699 6445/4 or for cable 0699 6445/5
Analog output	4 to 20 mA=0 to 80 or 0 to 150 Nm/s, 4-wire, max. load = 500 ohm
Pulse output	Floating contact, 12 to 24 V DC switching voltage from external meter, corresponding to S0 meter signal (DI N 43864).
Standard reference	Standard flow rate (e.g. Nm/s) and standard volumetric flow rate (e.g. Nm^3/h) are based on DIN ISO 2533, 1 5 °C, 1013.25 mbar, 0% RH

away from the fan to prevent upstream effect in the setup.

Scan time is an important criteria for the flow measurement applications. The sampling times of two sequential data with one second interval varies between 1.00 s and 1.02 s for the case of typically 20 ms scan time of PLC. Two percent deviation of sampling interval may occur in this condition. This deviation can be decreased by selecting a longer sampling interval but it causes a degradation in the measurement responds. The sampling interval may be between 1-30 s depending on the size of the duct. The circular air duct which has 113 mm diameter is used in this application. One second sampling interval is selected referring to the size of the duct. The output of flow transducer is connected to the analog input channel 3. Technical Data of the flow transducer used in the experimental setup is given in Table 1.

The process of flow rate reading is realized by the PLC ladder diagram that consists of three steps as shown in Fig. 4. Some PLCs have system bits driven by the PLC itself. Oscillator bit P_1s in Omron PLC that is an example of them. These oscillator bits allow timers to operate independently from scan time and the sub-routine files to be executed with definite time intervals Network 0, moves #0000 value to the address of the analog channel.

Network 1, reads the flow value which is sampled in every 1s interval, then it is moved to D100 address. A sample is summed with the previous value, then averaged flow rate can be attained by dividing by 120 in Network 3 as seen from Block 2.

Another issue to be considered in analog data process is sensitivity of floating point numbers. Because the flow rate data taken from analog channel 3 is generated by a 12-bit ADC, it is not necessarily an integer. Therefore, these calculations need floating process. A typical floating point number has 7-digit sensitivity.

A 12-bit ADC is used in the measuring system. Due to the nature of ADC, it contains a quantization error on $\varepsilon = \mp \frac{1}{2} LSB$ value and this error is small enough to be ignored for flow measurement. The error in the addition may be small but it may cause considerable deviations in results due to the cumulative nature

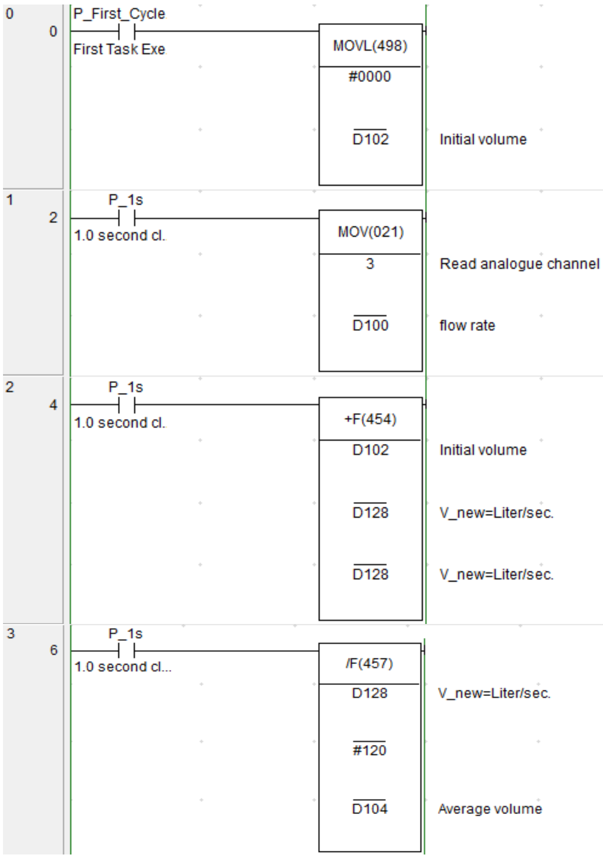


Fig. 4. The sum of trapezoidal flow

The total volume is represented by 7 digits, so 4 digits are assigned for the integer and 3 digits for the fractional part. 4-20 mA current signal in the range of 0.1 - 10 m/s that is produced by the flow transducer is connected to the analog input card in this application. The Analog card which has 12-bit resolution produces BCD values between #0000 and #4095. In order to detect any fault that may occur during the measurement, the flow rate signal is converted to a BCD value between #820 and #4095 by the analog input card. The analog card input function is shown in Fig. 5. for this conversion.

The $I_{in,}$ signal which is applied from the input channel is

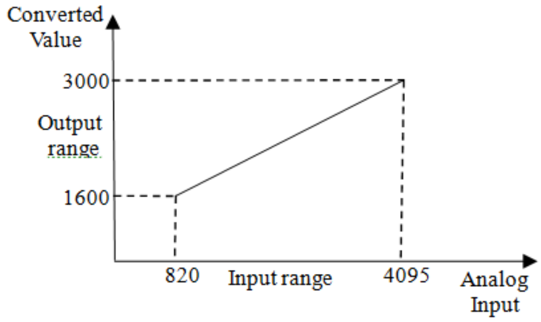


Fig. 5. 4 -20 mA input signal to the BCD value conversion.

converted to a BCD value as in Eq. (2). B and I denote the digital output value and the input current of the Analog input card respectively in Eq. (2).

$$B_o = B_{\min} + \left(I_{in} - I_{\min}\right).\left(\frac{\Delta B}{\Delta I}\right) \qquad (2)$$

In general, the output signal of the card between the upper and lower limits is expressed as a linear equation $B_0 = ax + b$. A four-step process for conversion of an analog input value is used in the PLC software. As a change occurs between 0 and 100% in flow signal, in the range of BCD coded # 820 - # 4095 is produced in the Analog outputs. It corresponds to 4 to 20 mA output current range.

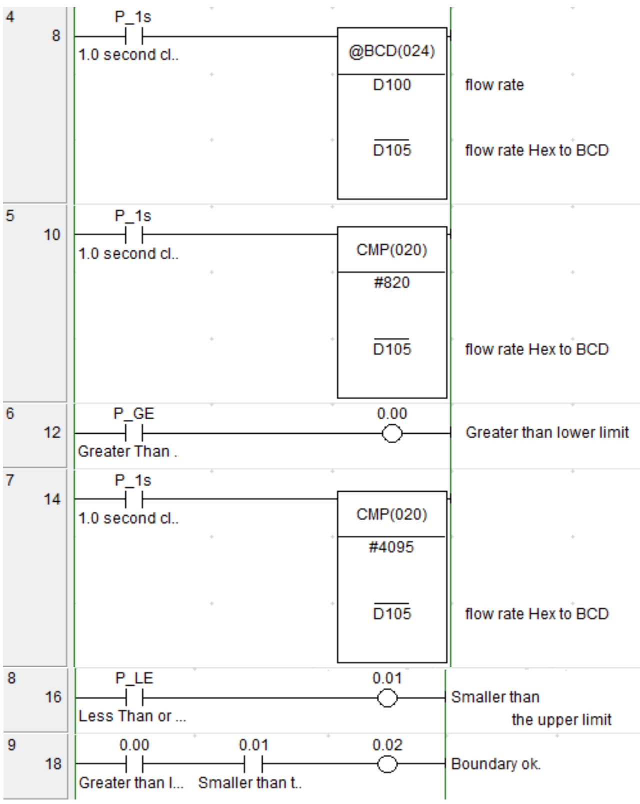


Fig. 6. Determining the data limits from the flow sensor.

$$\Delta B_{(BCD)} = \left(3000 - 1600\right) = 1400$$
$$\Delta I_{(BCD)} = \left(4095 - 820\right) = 3275$$
$$B_{\min(BCD)} = 1600 \;\; I_{\min(BCD)} = 820 \qquad (3)$$

$I_{\min(BCD)}$ and $B_{\min(BCD)}$ represent the smallest input current and the minimum BCD value respectively in Eq.3. The slope of the input signal (ΔB/ΔI) is calculated by the PLC in first scan time. Before starting the conversion process, It must be determined whether the data from the flow sensor is within the expected range. This process is carried out with networks 4-9 in Fig. 6. Network 7 checks if the input signal is within the expected range. If the measured value is within the limits of measurement, Linearization process is carried out according to Eq.3 between networks 10-15 as illustrated in Fig. 7.

Networks 10 - 12 calculate the slope $\Delta B / \Delta I$ of the line

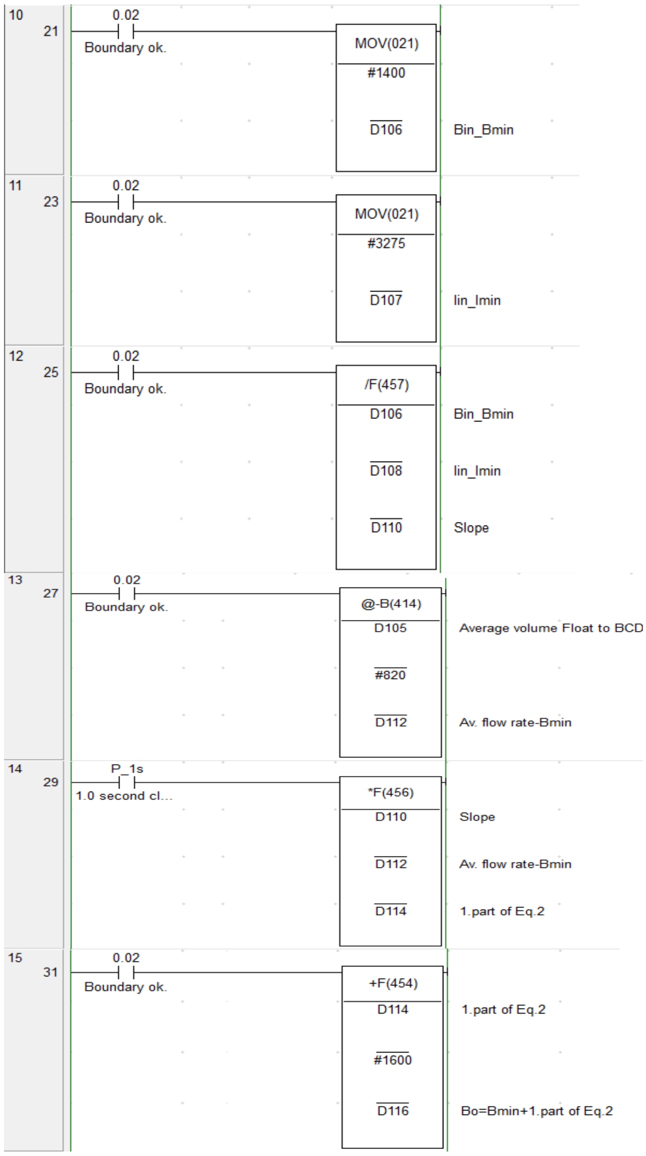


Fig. 7. The realization of the conversion process.

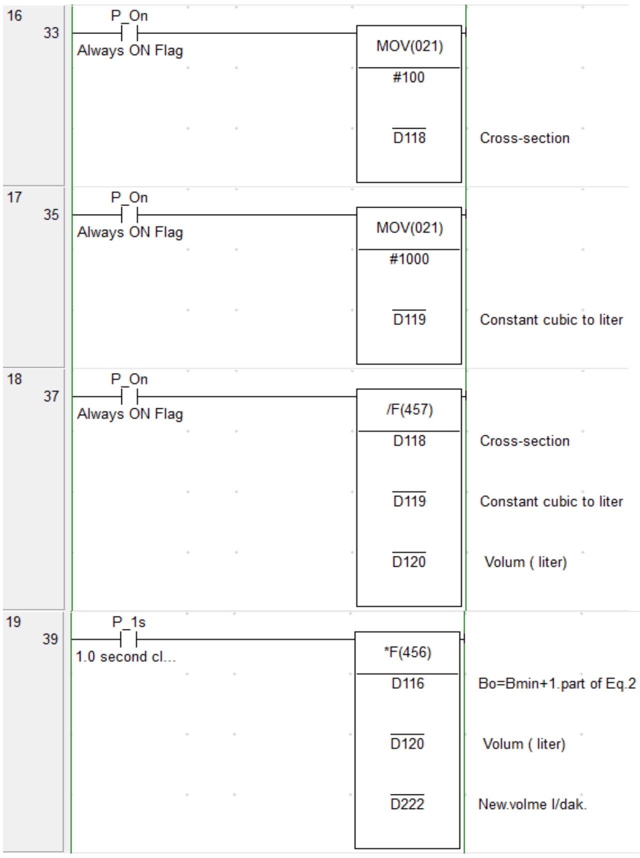


Fig. 8. Cross-section calculation of the Air duct

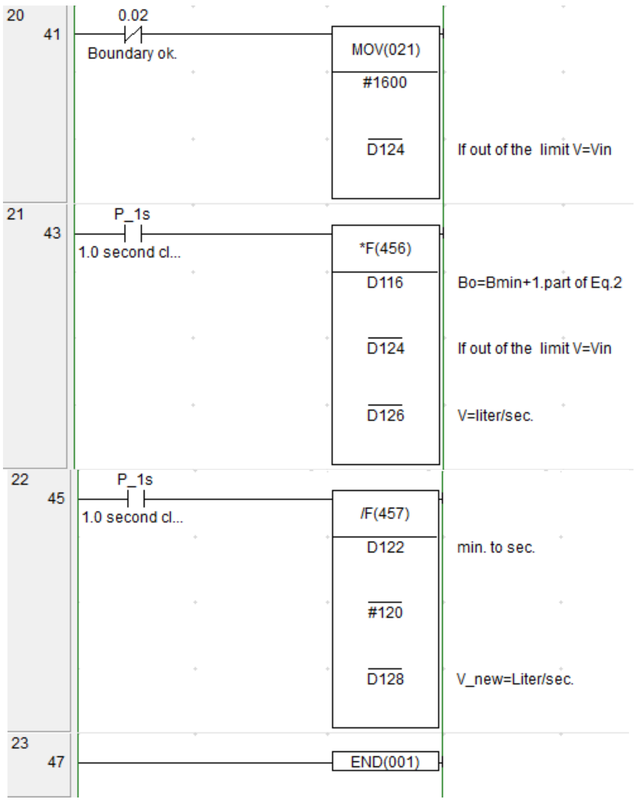


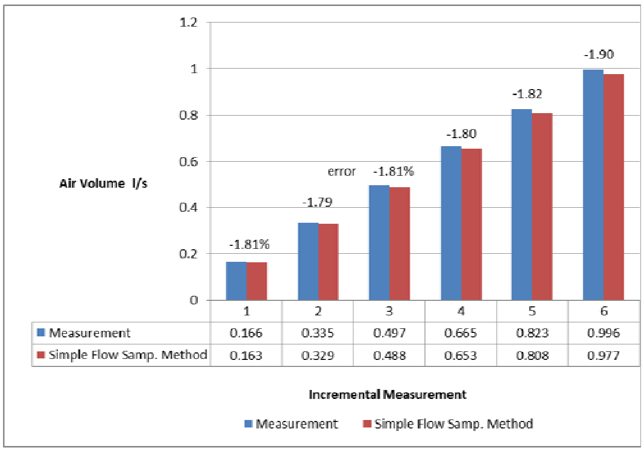
Fig. 9. Calculation of the Air volume (L/d)

to be used the conversion. Network 13 calculates $(I_{in} - I_{\min})$ value. Network 14 performs the operation of $(I_{in} - I_{\min})\left(\Delta B/\Delta I\right)$. Network15 performs the addition of the value of $B_{\min}$ to k which is obtained in Network 14, so Bo in Eq. 3 is yielded.

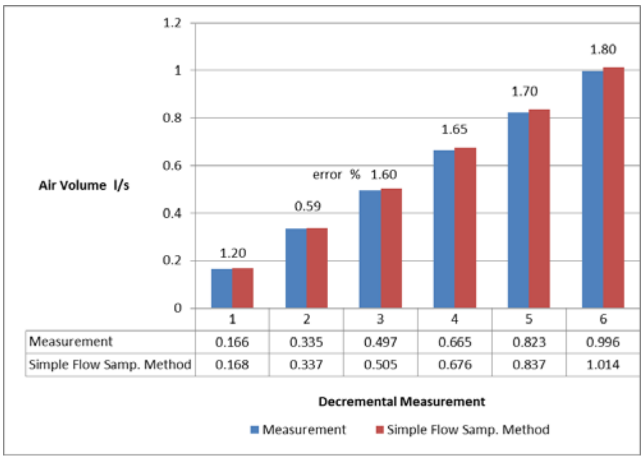
The volume of air passing through the air duct is calculated as air duct cross-section multiplied by the average speed. The calculation of the air duct cross-section is made by Networks 16-19 in Fig. 8. If the measured input signal is out of the measuring range, Network 20 first moves #1600 to D116 to check if this is a real situation or an error condition. Networks 21-23 in Fig. 9 calculate the volume of air flowing through the duct in l/min.

4. Experimental Results

Any temperature or pressure value in an industrial process can be examined by using digital input modules in a digital format, but the value cannot be measured accurately. In such cases, Analog I/O cards are utilized to



(a) Incremental air flow



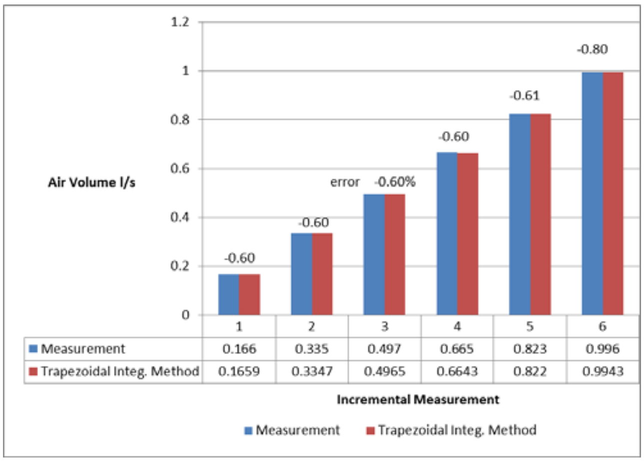
(b) Decremental air flow

Fig. 10. Classical Sampling Method error values

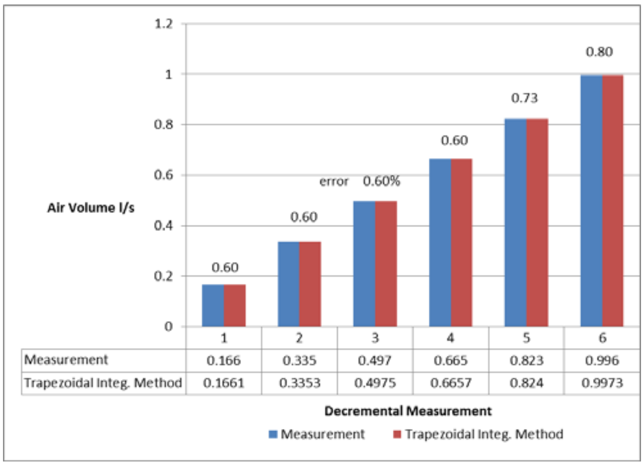
monitor and control specific parameters continuously between the upper and lower limits. In this study, The air flow rate was linearly changed by a fan driven with an inverter throughout the range of 1 to 6 Nm/s at atmospheric pressure to obtain the error rates for both increasing and decreasing regions. For every air velocity, air volume value is calculated via fan speed and displacement volume of the fan. The Air volume is then measured severally applying classical sampling method and trapezoidal rule method. Finally, the performance of the both measurement methods are evaluated via the following equation;

$$\varepsilon = 100 \times (y(k) - \hat{y}(k)) / y(k) \qquad (4)$$

Where ε represents relative error and $y(k)$ and $\hat{y}(k)$ denote the calculated volume and the measured, respectively. These calculated values are compared with the measured outputs by using both methods. By reference to the calculated air volume values, error values which are acquired from Eq. 4 are given in Fig. 10 and Fig. 11. When



(a) Incremental air flow



(b) Decremental air flow

Fig. 11. Trapezoidal Rule Method error values

air is changed in direction of volume increase in classical sampling method, relative error changes between -1.81% and -1.90%. When is changed in decrease direction, is determined that relative error changes between 1.20% and 1.80%. When air volume increment is changed in direction of volume increase in Trapezoidal rule, relative error changes between -0.6% and -0.8%. When is changed in decrease direction, is determined that relative error changes between 0.6% and 0.8%. The air volume values which is obtained by trapezoidal rule method yield approximately three times more accurate results than that of by classical method for both increasing and decreasing flow rates.

5. Conclusion

In this study, it was shown how to achieve the measurement of air volume in a closed air duct by using the simple flow sampling and the trapezoidal rule methods by means of a PLC. The results for both methods are also compared to each other in order to obtain the relative flow rate errors in the range of 1 to 6 Nm/s. The flow rate is linearly adjusted in the range of 1 to 6 *N*m/s for monitoring the relative error of volume measurements in this work.

In measurements using the trapezoidal rule method, the error values which decrease with increasing flow values are 3-2.37 times lower than that of in classical method. Similarly, in decreasing flow region, the error values obtained by the trapezoidal rule method are two times lower than by the classical. It is concluded that the measurement using the trapezoidal rule method can be made in higher accuracy especially in low velocities and is convenient especially for portable flowmeters that are allowable to consume low.

References

[1] T. M. I. Mahlia, R. Saidur, M. Husnawan, H. H. Masjuki, M. A. Kalam, October 2011, An approach to estimate the life-cycle cost of energy efficiency improvement of room air conditioners. Energy Education Science & Technology, Part: A Energy Science and Research, Volume 26 1-11.

[2] C. Gungor, D. Kaya, October 2009, Experimental investigation of the effect of absorber pre-cooler to the performance of the absorption cooling system. Energy Education Science & Technology, Part: A Energy Science and Research, Volume 24 71-83.

[3] Bob Steinberg, Thermal mass flowmeters, September 2004, Flow control.

[4] Tong Zhao, Masahiro Takei, Kenta Masaki, Ryoji Ogiso, Koji Nakao, Akira Uchiura, 2007, Sensor design and image accuracy for application of capacitance CT to the petroleum refinery process, Flow Measurement and Instrumentation, Volume 18,

Issues 5-6, Pages 268-276.

[5] Jung-Yoon Kim, Tae-Zi Shin* and Myung-Kook Yang, Design of a Smart Gas Sensor System for Room Air-Cleaner of Automobile, (Thick-Film Metal Oxide Semiconductor Gas Sensor), Journal of Electrical Engineering & Technology, Vol. 2, No. 3, pp. 408~412, 2007.

[6] A. Svete, J. Kutin, I. Bajsić, December 2009, Static and dynamic characteristics of a hydraulic Wheatstone bridge mass flowmeter, Flow Measurement and Instrumentation, Volume 20, Issue 6, Pages 264-270.

[7] Feasibility of an accurate dynamic standard for water flow, I.I.Shinder, M.R.Moldover, Flow Measurement and Instrumentation, Volume 21, Issue 2, Pages 128-133, 2010.

[8] Richard Steven, Andrew Hall, August 2009, Orifice plate meter wet gas flow performance, Flow Measurement and Instrumentation, Volume 20, Issue 5, Pages 141-151.

[9] Richard Steven, Horizontally installed cone differential pressure meter wet gas flow performance, Flow Measurement and Instrumentation, Volume 20, Issue 5, Pages 152-167.

[10] Yuxing Li, Jun Wang, Yanfeng Geng, Flow Study on wet gas online flow rate measurement based on dual slotted orifice plate, Measurement and Instrumentation, Volume 20, Issue 5, Pages 168-173.

[11] Rajesh Kumar Singh, S.N.Singh, V.Seshadri, 2010, CFD prediction of the effects of the upstream elbow fittings on the performance of cone flowmeters, Flow Measurement and Instrumentation, Volume 21, Issue 2, Pages 88-97.

[12] W. A. S. Kumara, G. Elseth, B. M. Halvorsen, M. C. Melaaen, 2010, Comparison of Particle Image Velocimetry and Laser Doppler Anemometry measurement methods applied to the oil-water flow in horizontal pipe, Flow Measurement and Instrumentation, Volume 21, Issue 2, Pages 105-117.

[13] H. Baha and Z. Dibi, ANN Modeling of a Gas Sensor, Journal of Electrical Engineering & Technology Vol. 5, No. 3, pp. 493~496, 2010.

[14] Byoung-Kon Choi, Hsiao-Dong Chiang, Yinhong Li, Yung-Tien Chen, Der-Hua Huang and Mark G. Lauby, Development of Composite Load Models of Power Systems using On-line Measurement Data, Journal of Electrical Engineering & Technology, Vol. 1, No. 2, pp. 161~169, 2006.

[15] Gregory-Smith, March 2006, An automated instrumentation system for flow and loss measurements in a cascade, Grant Ingram, David Flow Measurement and Instrumentation, Volume 17, Issue 1, Pages 23-28

[16] Edson da Costa Bortoni, December 2008, New developments in Gibson's method for flow measurement in hydro power plants, Flow Measurement and Instrumentation, Volume 19, Issue 6, Pages 385-390

[17] S. A. Hosseini, A. Shamsai, B. Ataie-Ashtiani, March 2006, Synchronous measurements of the velocity and concentration in low density turbidity currents using an Acoustic Doppler Velocimeter, Flow Measurement and Instrumentation, Volume 17, Issue 1, Pages 59-68

[18] John R. Hackworth and Frederick D. Hackworth 2008, Programmable Logic Controllers Programming Methods and Applications, Prentice Hall. 2nd Edition,

[19] John G. Olin, Industrial thermal mass flowmeters, m&c measurements & Control, Isue 193-194, 1999

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