INNOVATIONS IN ANALOG MASS FLOW CONTROLLER DESIGN

N. Alu, M.G. Zebaze Kana, A.A. Oberafo and D. Obi
Physics Advanced Laboratory, Sheda Science and Technology Complex (SHESTCO), Sheda, P.M.B. 186, Garki, Abuja, Nigeria.
E-mail: aaoberafo@yahoo.com

(Submitted: 6 October,2007;Accepted:4 April,2008)

Abstract

An analog Mass Flow Controller has been designed and fabricated. The special features include, its multilocular nature and integrability on a common platform, an additional innovation is *the use of a 0.88mm diameter tube sealed at both ends and perforated at two points as a valve pin in place of the traditional needle valve. These design features reduce the need for precision engineering of valve components. A further feature is its relatively low cost. A calibration experiment was carried out on one of the five gas exit (process) lines of the fabricated five-port mass flow controller. The results confirm the expected geometric dependence of flow rate on gas pressure.*

Keywords: *Mass flow controller, gas flow metering,gas flow instrumentation, gas pressure regulator and chemical vapor deposition control.*

1.0 Introduction

In spite of the recognition of its major role on socio-economic development, research and development (R&D) work in science and technology (S&T) continues to be poorly funded. The matter is further aggravated by the fact that the facilities and tools for carrying out effective S&T, R&D programmes are usually very expensive and accessible only to few Laboratories. Consequently, researchers have devised various means of accomplishing their tasks. Such methods include centralization of facilities, pooling of resources, formation of R&D groups, technology adaptation and innovations. This is no less so than in Materials Science which is a field that embraces, for example, energy and diversification of energy sources, as well as materials and electronic components and devices.

A major energy source which has remained relatively untapped is solar energy. In spite of the wide spread nature and abundance of solar energy, and a well established technology for converting it to electricity, the bulk of Mankind's energy needs is still sourced from fossil fuels with attendant deleterious effects on the environment. The reason for this is the high cost of producing crystalline and polycrystalline silicon-based solar photo-voltaic (PV) cells which has remained the dominant technology till date. The production of silicon solar cells requires very precise conditions and is energy intensive and complex. Recent research on solar-electric conversion has therefore focused on alternative materials to silicon and less complicated thin film deposition technologies. One such technique is the chemical vapor deposition (CVD) technique (Schropp et al., 2000) which involves depositing a solid material from a gaseous phase .In a CVD process , precursor gases (often diluted in carrier gases) are delivered into the reaction chamber at approximately room temperature. As they pass over a heated substrate, they react or decompose forming a solid layer onto the substrate.

A critical requirement of the CVD process is accurate metering of the process gases. This is usually accomplished with a mass flow controller (MFC). The MFC is essentially a gas admittance valve for venting a vacuum chamber or for regulating the rate at which a gas (precursor gas) is released into a chamber (or vacuum chamber). It consists essentially of a number of gas pressure regulators (six in this case), a gas filter, a gas distributor, five open tube manometers and five Venturi flow devices. The filtered inlet carrier gas (usually air or inert gas) is passed through a pressure regulator before being distributed into channels (five in this case). Each channel gas was passed through a pressure regulator and thence through a Venturi flow meter-manometer assembly from where it exits the system at a pre-set flow rate whence it is bubbled through a volatile precursor (which may be heated to increase the vapor pressure). The exiting precursor-rich gas now proceeds to the deposition head of the CVD reactor. In the CVD chamber, the precursor gas reacts with a heated substrate surface (or reacts with other precursor gases from other channel ports at the heated substrate surface), thereby causing a thin layer of an element or compound, as appropriate, to be deposited on the substrate.

Apart from its use in reactive coating, the MFC is also used in sputtering, calibration of mass spectrometers, and pumping speed tests.

In this work, we report the design and fabrication of a five-port analog mass flow controller. The special features of the MFC include, the combination of five mass flow controllers in one unit, thus resulting in substantial savings in materials as all the units share a common platform, and an innovative design of a single-stage pressure regulator (basically a spring-loaded check valve (EIGA, 2006) that requires much less tooling than conventional designs. Furthermore, the overall simplicity of the design lends itself to easy fabrication using simple tools. Such an analog mass flow controller can be used, for example in the process line of chemical vapor deposition of thin film coatings for aesthetic products and electronic components and devices, including solar cells.

2.0 Description and Theory

The complete five-port analog MFC system is shown in Figure 1. This version consists essentially of (a) six single-stage gas pressure regulators, (b) gas filter, (c) gas distributor, (d) open tube manometer and (e) Venturi flow meter. The gas pressure regulators are distributed thus: one (R_1) for the gas-inlet, and five (R_i, $i = 2,3,4,5,6$) for the gas-outlet ports of the gas distributor.

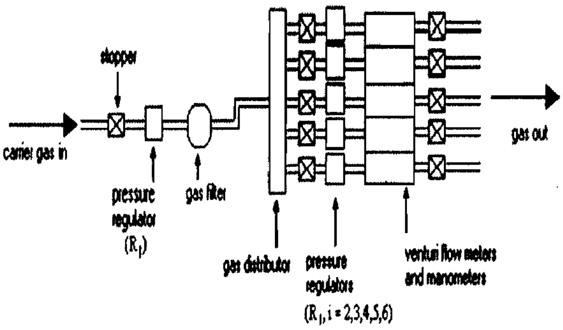


Fig. 1: Mass flow controller assembly

2.1 The Gas Pressure Regulator

Figure 2 is a single stage gas pressure regulator. It was designed for use with air or inert gases. It consists of a chamber (A) sealed at one end by the lip of a diaphragm (5) in an inverted position with respect to its base (4). The chamber is connected directly to the gas outlet (8). Pressure variations in the outlet stream cause the diaphragm to move up and down. This movement is transmitted to the valve pin

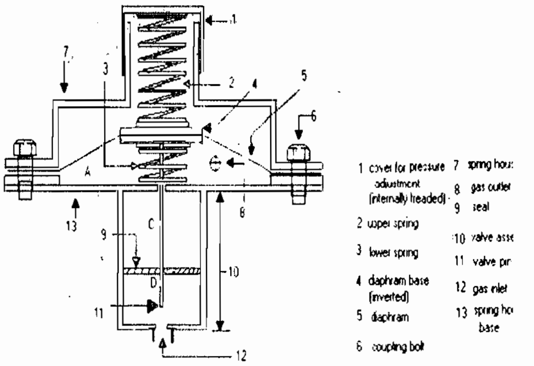


Fig. 2: The pressure regulator (single stage)

(11) which is directly attached to the diaphragm base 4. The valve pin is simply a 0.88mm diameter tube sealed at both ends and perforated at points C and D. The pin moves up (down) through the fixed seat (9), thereby closing (opening) D from accessing the gas issuing in from the inlet port (12). (The carrier gas (or incoming gas) is connected to the gas pressure regulator via port 12.) Thus, gas enters through D and gets out through C into the diaphragm chamber from which it is expelled through 8 to, for example, the gas filter in Fig. 1. Pressure regulation is effected by loading the diaphragm with a spring (2). A threaded knob (1) controls the tension in the spring. When the pressure in the chamber A is less than the tension exerted by spring 2, the diaphragm falls. This movement is transmitted to the valve pin which moves down through 9 and opens D to let in more gas and restore the equilibrium. Conversely, when the pressure rises beyond the tension in spring 2, the diaphragm moves upwards thereby shutting the supply of gas. The gas pressure is varied (regulated) by turning the threaded knob 1, while the gas is expelled through the outlet port 8.

2.2 The Manometer

The manometer (Fig. 3) is of the open tube type. The working fluid is water coloured with a hydrophilic dye. For such a system, pressure differential (Δp) at points A and B causes the fluid to rise to a height h, which gives a measure of gas flow rate (q).

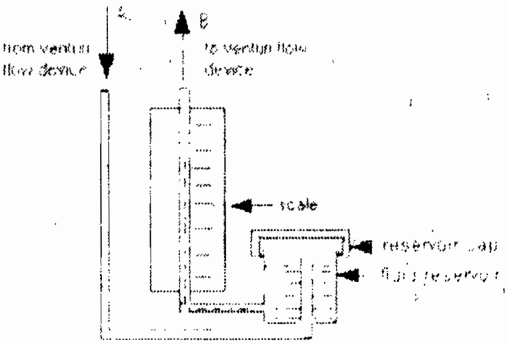


Fig. 3: Schematic of the manometer

2.3 The Venturi Flow Meter

The Venturi flow meter is essentially a constricted tube which serves as a gauge in a flow pipe to measure the flow speed of a fluid. In the version shown in Fig. 4, we have introduced a thin solid rod, or capillary tube closed at both ends, as an insert for adjusting the throat diameter.

Theory

The Venturi flow meter (Fig. 4) works on the principle that a fluid passing through a constriction experiences change in velocity. This change in velocity creates a pressure differential between the low and high velocity regions. For the Venturi flow tube (Fig. 4), the pressure differential between the portions labelled X and Z is directly proportional to the fluid velocity (Evwaraye and Inyang, 1989). For an ideal fluid, the Bernoulli equation states:

$$p_1 + \tfrac{1}{2}\rho v_1^2 + \rho g y_1 = p_2 + \tfrac{1}{2}\rho v_2^2 + \rho g y_2 \quad (1)$$

where p_1, p_2 are pressure at points X and Z, respectively, and v_1, v_2 are the corresponding velocities; ρ is density of the fluid, g is acceleration due to gravity, and y_1, y_2 are vertical elevation of points X and Z, respectively.

If the fluid is moving in a horizontal tube, $y_1 \approx y_2$, *and* the Bernoulli equation simplifies to

$$p_1 + \tfrac{1}{2}\rho v_1^2 = p_2 + \tfrac{1}{2}\rho v_2^2 \quad (2)$$

From the continuity equation, the gas flow rate q gives:

$$q = v_1a_1 = v_2a_2 \qquad (3)$$

where q is flow rate, and a is flow cross-sectional area.

Combining (2) and (3) and assuming $a_2 < a_1$ we get the "ideal" equation

$$q=a_2\left\{\frac{2(p_1-p_2)}{\rho\left(1-\left(\frac{a_2}{a_1}\right)^2\right)}\right\}^{½} \qquad (4)$$

For a given geometry, the flow rate can be determined by measuring the pressure difference p_1-p_2 (International Organization of standards (ISO 5167 1, 2003)). Equation 4 is for an ideal fluid. For real fluids, a small amount of energy is converted into heat within the viscous boundary layers. A discharge coefficient c_d is typically introduced to account for the viscosity of the fluid; and c_d is found to depend on the Reynolds number and usually lies between 0.9 and 0.98 for smoothly tapering Venturis (Wright, 1998), so that equation 4 becomes,

$$q=c_da_2\left[\frac{2(p_1-p_2)}{\rho\left(1-\left(\frac{a_2}{a_1}\right)^2\right)}\right]^{½} \qquad (5)$$

By converting area to diameter, eqn (5) becomes,

$$q=\frac{c_d\pi}{4d_2^2}\left[\frac{2(\Delta p)}{\rho(1-d^4)}\right]^{½} \qquad (6)$$

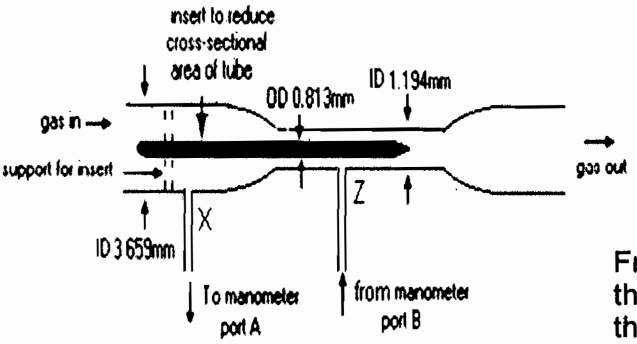


Fig.4: The modified Venturi flow meter

where d_1 is upstream and downstream pipe diameter; d_2 is orifice, Venturi, or nozzle inside diameter:

$d(=d_2/d_1)$ is diameter ratio

$\Delta p = p_1$-p_2 and $\pi = 3.142$.

Equation(6) can also be modified to mass flow rate (m) for fluids by simply multiplying with the density ρ to get

$$m=\frac{c_d\pi\rho}{4d_2^2}\left[\frac{2(\Delta p)}{\rho(1-d^4)}\right]^{½} \qquad (7)$$

when measuring the volume or mass flow rate in gases, it is necessary to consider the pressure reduction and change in density of the fluid. The formula above can be used with limitations for applications with relatively small changes in pressure and density. The pressure differential (Δp) causes the fluid in the manometer to rise to a height, h.

$$h=\Delta p/(\rho_l-\rho)g \qquad (8)$$

where P_L is the density of fluid in the manometer.

Combining Eqn (5) and (8), we get

$$q=h^{1/2}a_2\left[\frac{2(\rho_l-\rho)g}{\rho\left(1-\left(\frac{a_2}{a_1}\right)^2\right)}\right]^{½}=Kh^{½} \qquad (9)$$

where

$$K=a_2\left[\frac{2(\rho_l-\rho)g}{\rho\left(1-\left(\frac{a_2}{a_1}\right)^2\right)}\right]^{½} \qquad (10)$$

From the foregoing, we can conclude that there is a geometric relationship between the mass flow rate q, and the manometer reading h.

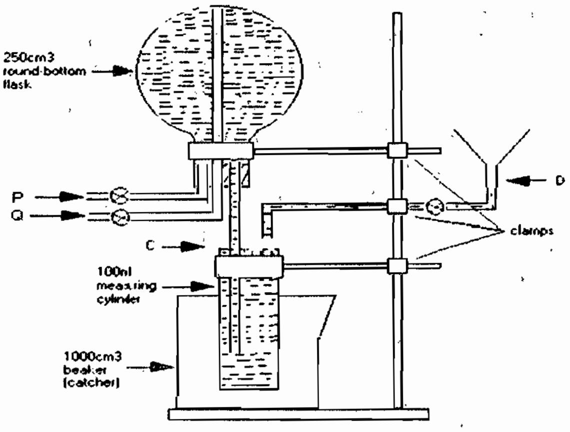
3.0 Experimentation.

3.1 Calibration of the mass flow Controller.

The MFC is calibrated for dry air with the set-up in Fig. 5.The calibration procedure is the "timed collection method" (International Organization of standards (ISO 5167 4, 2003) which involves measuring the time it takes to collect a known volume of gas, and runs as follows:

(i) Port P valve is locked and port Q valve is opened. The measuring cylinder is completely filled with water through the funnel, D.

(ii) Suction is applied at Q and this transfers water from the measuring flask into the inverted round-bottom flask. Simultaneously more water is poured into the measuring cylinder through D to keep it topped up. This procedure fills the round-bottom flask with water.



(iii) Port Q is then closed.

(iv) Gas (dry air in this case), from any of the five mass flow controller exit ports in figure 1, is introduced via valve P into the round-bottom flask to displace the water in the flask. The flow rate is determined by adjusting the appropriate port regulator (similar to that of figure 2) to obtain some height differential *h* on the manometer (Fig. 3) which is attached to the Venturi flow meter (Fig. 4). The displaced water is collected in the catcher. A timer is started at the commencement of the discharge of the water from the flask.

(v) The end point is when the round-bottom flask is evacuated of water down to the water level C in the measuring cylinder at which point the timer is then stopped.

(vi) The time *t* in seconds is recorded.

(vii) The volume of water in the catcher is measured. (The volume of gas collected in the round-bottom flask is equal to the volume of water collected in the catcher, less the partial volume of water vapor at that particular temperature and pressure).

(viii) The experiment is repeated keeping *h* constant, and the readings averaged.

(ix) Next, the mass flow controller is adjusted (by adjusting the regulator) to obtain a different manometer reading *h* and processes (i) to (viii) are repeated to obtain volume flow rate-manometer height data.

Processes (i) to (ix) are carried out in calibrating each of the outlet ports of the mass flow controller.

3.1.1 Pressure Corrections

Since the gases were collected over water in the above experiment, it is necessary to correct for the partial pressure of water. The saturation vapor pressure over water is given (in hectopascal (hPa)) by (Olsen and Baumgarten, 1971) as

$$P_w = 6.1121\exp\left[\frac{17.502T}{240.97+T}\right] \qquad (11)$$

where *T* is the temperature of the water Over which the gas was collected. Thus, the partial pressure of the gas is

$$p_c = p - p_w. \qquad (12)$$

Correcting to standard temperature (273K) and pressure (760mm (Hg)) and using the ideal gas equation, the final volume V_2 is given by

$$V_2 = {p_1V_1T_2}\big/{p_2T_1} \qquad (13)$$

where initial pressure $p_1 = p_c$, final pressure p_2 = 760mm(Hg) , since level C of the measuring cylinder in figure 5 is at atmospheric pressure. Initial volume V_1 is the evacuated volumetric flask volume, T_1 is the temperature of the gas collected in the round bottom flask and $T_2 = 273K$ is the standard temperature.

3.2 Results and Discussion

Figures 6a and 6b show the five-port gas distributor system and the five associated gas pressure regulators, respectively which were constructed in our laboratory in accordance with the description in the main text. A calibration experiment was carried out for one of the ports of the five-port MFC. Using equation (11) with laboratory temperature of 29°C (= 302K), we get

$$p_w = 40.058hpa$$

= 30.046mmHg (since 1 *hpa* = 0.75006183mmHg) Thus, for our evacuated volumetric flask, volume 250cm^3 of air was collected at 29 °C and pressure of 760 mm Hg over water, the corrected gas pressure (from equation (12) is given by

$$p_c = p - p_w$$

= (760 30.046) mm Hg
= 729.954 mmHg

This is the partial pressure of the gas. Correcting to standard temperature (273K) and pressure (760 mm Hg), and using the ideal gas equation, the final volume, V_2 is given (from eqn 13) by

$$V_2 = \frac{p_1 V_1 T_2}{p_2 T_1} = 217.06cm^3$$

since $p_1 = p_c = 729.954$ *mmHg*, $p_2 = 760.000$*mmHg*, *initial* volume $V_1 = 250cm3$, initial temperature $T_1 = 302K$ *and* final temperature $T_2 = 273K$

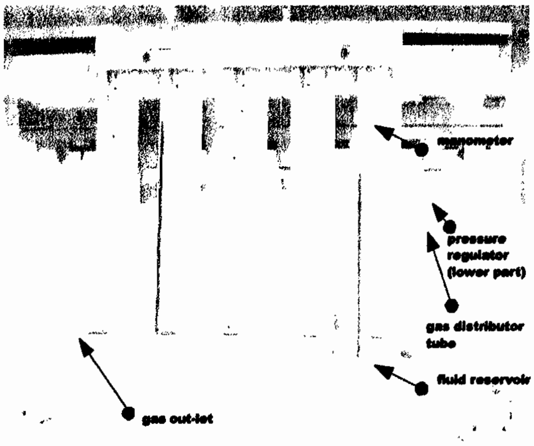


Fig.6a: Five-port gas distributor system of the constructed Mass flow controller, with the five associated manometers shown in the foreground

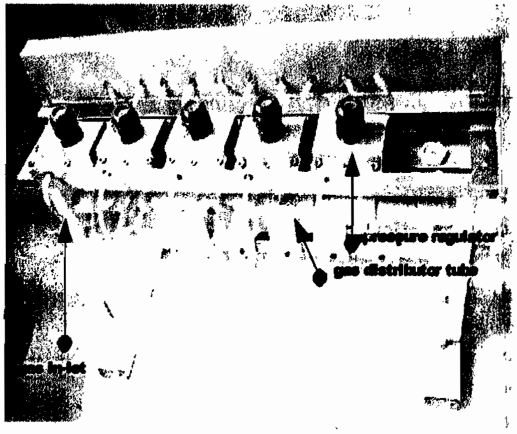


Fig.6b: Top back-view of the constructed Mass flow controller showing the five pressure regulators.

In carrying out the calibration process described in section 3.1, it should be noted that the volumetric flow rate *q* of equation 6 (now expressed in standard cubic centimeters per minute (SCC/M)) is given by V_2/t, with V_2 as given by equation 14. Furthermore, that V_2 is constant if *T* in (11) is constant, since $V_1 = 250cm^3$ is constant, and *t* (in minutes) is the average time of discharge for a given regulator setting or manometer height *h* (in centimeters).

Taking the natural logarithm of both sides of equation 9, we get

$$\ln q = \tfrac{1}{2} \ln h + \ln k$$

where *k* is given by eqn. *(*10*)*.

Figure 7 shows such a log-log plot for a set of (*q*, *h*) data for just one of the five exit ports of the MFC. The graph gives a slope of 0.926 and an intercept of 2.500 (= *ln k*) with a correlation coefficient of 0.998, which is indicative of a high linear correlation between *ln q* and *ln h* or a high non-linear correlation between *q* and *h*. This is in accord with the prediction of equation 9, and shows that the design does indeed function as a mass flow controller.

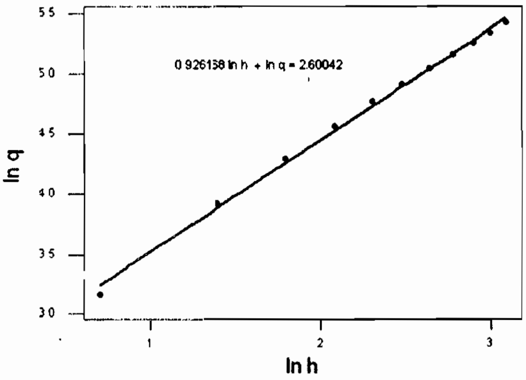


Fig. 7: Log - Log plot of volumetric flow rate *q* against manometer reading *h*

For multicomponent thin film coatings, the mass flow controller functions essentially to regulate the amount of precursor gas in one process line which is released for reaction with other appropriate precursor gases from other process lines in a chemical vapor deposition chamber to produce thin film layers and coatings. Such coatings could be used, for example, for fabrication of micro and nano-mechanical and electronic materials and components, and also of devices like electronic detectors (sensors), and energy transducers, including solar (PV) cells.

4.0 Conclusion

A functional Analog Mass Flow Controller has been designed and fabricated. The special features include its multilocular nature, integrability on a common platform, simplicity and ease of fabrication and its relatively low cost. Calibration data on one of the ports confirms the expected geometric relationship between the flow rate and the manometer height differential. The equipment has the potential to stimulate activity in Materials Science and Renewable Energy research and development work.

References

European Industrial Gases Association *(EIGA) (2006):* Safety Newsletter. *Safe operation of pressure regulators,* 1-4

Evwaraye, A.O., Inyang, A.E., (1989): *Introduction to mechanics and properties of matter,* 1st ed. African-FEP Publishers Limited, Onitsha, Nigeria, p. 363.

International Organization of standards (ISO 5167 1) (2003*): Measurement of fluid flow by means of pressure differential devices, part 1: Orifice plates, nozzles, and Venturi tubes, inserted in circular cross-section conduits running full.*

International Organization of standards (ISO 5167 4) (2003*): Measurement of fluid flow by means of pressure differential devices inserted in circular cross-section conduits running full- part 4: Venturi tubes.*

Olsen, L. and Baumgarten, G.(1971): *Gas Flow Measurement by Collection Time and Density in a constant volume flow: its Measurement and Control in Science and Industry.* ISA,. 1287-1295.

Schropp, R.E.L.; Stannowski, B., Brockhoff, A.M., Van Veenendaal P.A.T.T., and Rath, J.K. (2000): *Hot wire CVD of heterogeneous and polycrystalline silicon semiconducting thin films for application in thin film transistors and solar cells.*Mater.Phys.Mech.1.(online), 73-82.

Wright J. D., 1998. *The Long Term Calibration Stability of Critical Flow Nozzles and Laminar Flowmeters.* NCSL Conference Proceedings, Albuguerque, New Mexico, U.S.A., 443 - 462