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DESIGN AND CALIBRATION OF A CAPILLARY FLOWMETER SET FOR MEASUREMENT OF GAS FLOWS

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ABSTRACT

In this study, design and calibration of a capillary flowmeter set was represented. The capillary flowmeters will be used for measurements of small gas flows having laminar flow regime. The gases (such as, nitrogen, argon, methane, hydrogen and carbon-dioxide) supplied from high pressure gas bottles and passed through capillary flowmeters (1 to 3) at various times. Each capillary flowmeter was made of glass and calibrated with one or two gases. Outlet of the capillary flowmeters were connected to the needle valves which have been used for regulating gas flowrates of the capillary flowmeters. Gases individually passed to a bubble flowmeter, and residence time of gases are recorded by using a stop watch. Then, from collected experimental results actual gas flowrates through the capillary flowmeters are calculated by using Hagen-Poiseuille equation.

Key Words : Capillary flowmeter, Measurement of small gas flows, Bubble flowmeter, Laminar flow

GAZ AKIŞ ÖLÇÜMLERİ İÇİN BİR KAPİLAR AKIŞMETRE SETİNİN DİZAYNI VE KALİBRASYONU

ÖZET

Bu çalışmada, kapilar bir akışmetre setinin dizaynı ve kalibrasyonu incelenmiştir. Kapilar akışmetreler laminer akışa sahip küçük gaz akış debilerinin ölçümü için kullanılmıştır. Gazlar yüksek basınçlı gaz silindirlerinden sağlanmış (azot, argon, metan, hidojen ve karbondioksit, v.s) ve farklı zamanlarda kapilar akışmetrelerden (1'den 3'e kadar) geçirilmişlerdir. Her bir kapilar akışmetre camdan yapılmış olup, bir yada iki gazla kalibre edilmiştir. Kapilar akışmetre çıkışları, kapilar akışmetre gaz akışlarını regüle eden ayar vanalarına birleştirilmiştir. Gazlar sırasıyle bir kabarcık akışmetresine geçirilmişlerdir ve gazların bu akışmetrede kalış süreleri, kronometre yardımıyle kaydedilmiştir. Sonra, biriktirilen deneysel ölçümlerden yararlanarak, kapilar akışmetrelerden geçen gerçek gaz debileri, Hagen-Poiseuille denklemi kullanılarak hesaplanmıştır.

Anahtar Kelimeler : Kapilar akışmetre, Küçük gaz akışlarının ölçümü, Kabarcık akışmetresi, Laminer akış

1. INTRODUCTION

The main purpose of this study is to design a capillary flowmeter set and calibrate it with various gases in laminar flows. Thus, measurements of any gas flows in laminar regime will be possible and so this or similar type experimental setups are more convenient for measurements of small gas flows.

Design of a laboratory flowmeter with bore capillaries and application of a laboratory pressure flowmeter were given by Croxton (1942), Brady and Carson (1942). A review of soap-film calibrators and various types of capillary flowmeters were presented by Gooderham (1947).

The theory of capillary flowmeters was reviewed by Herbo and for a given temperature between flow and

pressure an equation was derived for calculation of gas flows. He presented a capillary flowmeter and a bubble counter arrangement to detect small variations in composition of a flowing gas providing the constituents vary widely in viscosity (Herbo, 1942).

Applications of variable-orifice flowmeters and principles of flow measurements by capillary tubes given by Linford (Linford, 1943; Linford, 1944). Rimberg has studied pressure drop-across sharp-end capillary tubes (Rimberg, 1967).

A new displacement method for measuring gas flows, measurement of gas flows by the capillary tubes and determination of very small gas flows had been studied by Silvermann, and Thomson (1942), Sips (1943) and Wright, (1950, 1950a.).

Ergun (1953) purposed a mathematical procedure in the calibration of capillary flowmeters. The capillary flowmeter is identified by two constants, a and b, representing viscous and kinetic factors in the pressure loss. The method enables calculation of the precision of measurements made and serves as a guide in the design of laboratory capillary flowmeters. Pinkava (1963) has given a primitive method applicable to all gases, including corrosive substances.

A basic analysis of a capillary flowmeter was given by Bird et al. (1960). Velocity distributions and streamline flow in circular pipes and related equations are given in various literature (Bennett and Myers, 1982; Nevers, 1991; Mc Cabe et al., 1993).

The velocity profile in a round pipe is (Bennett and Myers, 1982; Bird et al., 1960; Coulson and Richardson, 1990),

$u = 2\,u_0 \left[1 - \frac{r^2}{a^2}\right]$ and the shear stress τ at the

wall $= -\,\mu \frac{du}{dr}$ at $r = a$;

The differentiation of u over r gives following result (Levent, 1994) :

$$\tau = -\,\mu \left[2\,u_0 \left[-\frac{2\,r}{a^2} \right] \right]_{r=a} = \frac{4\,\mu\,u_0}{a} \qquad (1)$$

A force balance over an element Δx; pressure forces = viscous forces,

$$\pi\,a^2\,dp = \frac{4\,\mu\,u_0}{a} \cdot 2\pi\,a\,dx$$

$$\frac{dp}{dx} = \frac{8\,\mu\,u_0}{a^2} \qquad (2)$$

The molar flow in the tube $= \pi a^2 \,.\, u_0 \,.\, \rho_{molar}$ .For an ideal gas PV = nRT ; or

$\rho_m = P / R\,T$.

Molar flow ;

$$M = \pi\,a^2\,u_0\,\rho_m = \pi\,a^2\,u_0\,\frac{P}{R\,T} \qquad (3)$$

$$u_0 = \frac{R\,T\,M}{\pi\,a^2\,P} \qquad (4)$$

If we put this value into equation (2), then;

$$\frac{dp}{dx} = \frac{8\,\mu}{a^2} \cdot \frac{R\,T\,M}{\pi\,a^2\,P} \qquad (5)$$

The integration of equation (5) gives the Hagen-Poiseuille Equation (Coulson and Richardson, 1990; Levent, 1994);

$$\frac{P_1^2 - P_2^2}{2} = \frac{8\,\mu\,R\,T\,L\,M}{\pi\,a^4} \qquad (6)$$

So the molar flow $= \left[\frac{P_1 + P_2}{2}\right]\left[P_1 - P_2\right] \frac{\pi\,a^4}{8\,\mu\,R\,T\,L}$

$$M = \left[\frac{P_1 + P_2}{2}\right]\left[P_1 - P_2\right] . K \qquad (7)$$

1. 2. Calibration of Capillary Flowmeters

The measurement of flow through the bubble flowmeter was Q_{BFMW} . The dry gas flowrate Q_{BFMD} was calculated at ambient temperature from the correction for water vapor;

$$Q_{BFMD} = Q_{BFMW} \cdot \frac{h_b - h_{H_2O}}{h_b} \qquad (8)$$

Then,

$\frac{Q_{BFMD}}{\frac{1}{2}\left[P_1 + P_2\right]}$ was plotted against Δh (Levent, 1994).

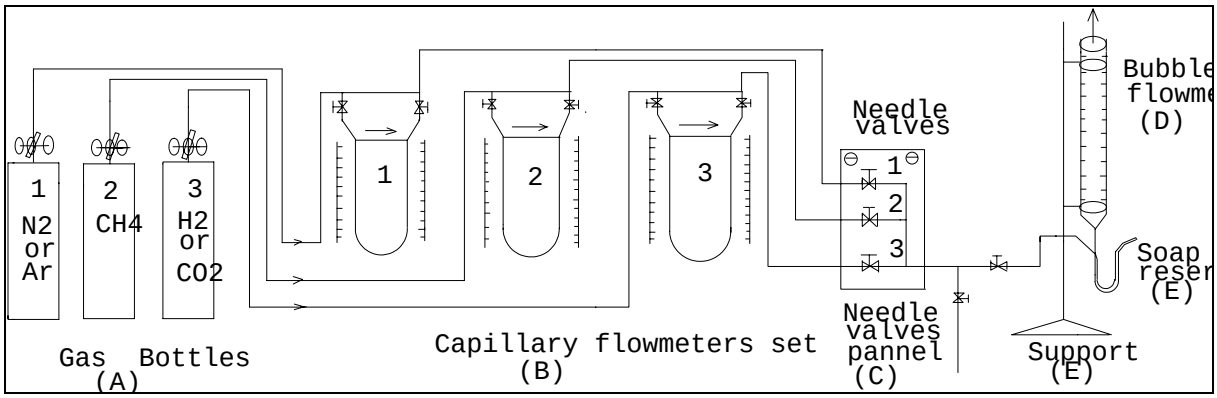

Figure 1. Schematic diagram of the capillary flowmeter set

2. EXPERIMENTAL SYSTEM

An experimental system was designed as Figure 1. The gases from high pressure bottles (A) are fed to the capillary flowmeters (B). At individual times, the gases passed through each capillary flowmeter (1 to 3). Each capillary flowmeter was calibrated with one or two gases and pressure drop in each capillary flowmeter was read by monitoring liquid level (water) in one of three manometers(1 to 3) which take place below the capillary flowmeters. The flow through the capillaries are adjusted with needle valves (C) which are installed on separate lines at downstream of capillary flowmeters. The outlet of the needle valves passed through a bubble flowmeter (D). Each time, flows of gases through the bubble flowmeter were recorded by using a stop watch.

3. RESULTS AND DISCUSSIONS

Figure 2 shows pressure difference (Δh) against mean flowrates of hydrogen, which are dry gas flowrates over mean pressure.

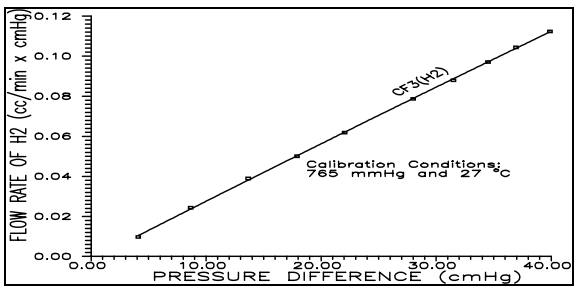

Figure 2. Calibration curve of the capillary flowmeter 3 for measurement of hydrogen flow

The pressure differences through the capillary flowmeter were drawn against mean flowrates of hydrogen. The resultant graph CF3 (H2) has a linear relation between pressure difference and flowrate of hydrogen. The calibration studies were carried out at 1181 mm Hg and 27 °C. From the calibration curve, mean flowrates of hydrogen will be determined according to pressure differences in the capillary flowmeter 3. In this graph, minimum pressure difference between up and downstream is 4.10 cm Hg and maximum pressure difference is 39.39 cm Hg (Levent, 1994). Minimum measurable mean flowrate was 9.7 x 10^{-3} cc/min x cm Hg and maximum flow of hydrogen was 112.3 x 10^{-3} cc/ min x cmHg as seen on Figure 2. Figure 3 shows calibration curve CF2 (CH4) of methane for capillary flowmeter 2 which was obtained from relation of up and downstream pressure difference and mean flowrates of methane. Minimum and maximum pressure differences through the capillary flowmeter 2 were 4 and 40.20 cm Hg and corresponding mean flowrates of methane were 8.4 x 10^{-3} and 93.25 x 10^{-3} cc/min x cm Hg (Levent, 1994). Calibration conditions were 1173 mm Hg and 25.8 °C. From extrapolation of measurements points, lower flowrates may be obtained, if calibration curve extended to origin of the Figure 3.

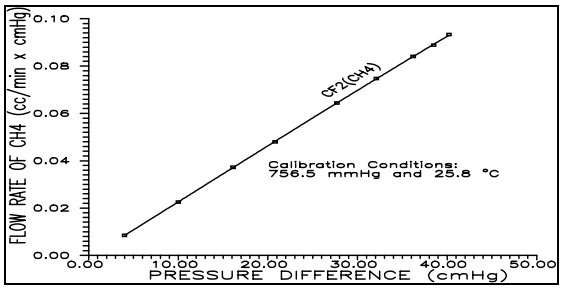

Figure 3. Calibration curve of the capillary flowmeter 2 for measurement of methane flow

Calibration graph of capillary flowmeter 3 for carbon dioxide CF3 (CO2) was shown on Figure 4.

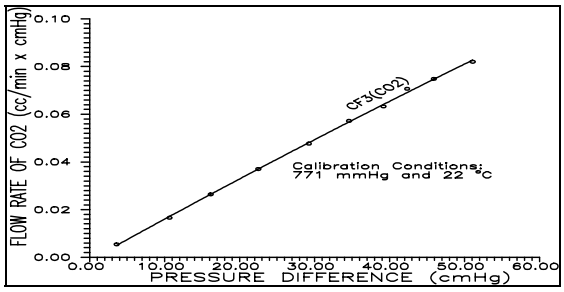

Figure 4. Calibration curve of the capillary flowmeter 3 for measurement of carbon dioxide flow

Flowrates of carbon dioxide and pressure differences through the capillary flowmeter 3 have been monitored and recorded. Then, mean flowrates are drawn against pressure differences.

From resultant calibration curve, flowrates of carbon dioxide at various experimental conditions will be determined. Calibration conditions for this experimental study were 1311 mm Hg and 22 °C. Minimum and maximum pressure differences were 3.60 and 51.10 cm Hg. Minimum and maximum mean flowrates of carbon dioxide were 5.47 x 10^{-3} and 82.05 x 10^{-3} cc/ min x cm Hg (Levent, 1994).

Figure 5 shows calibration curve of capillary flowmeter 1 for argon. As seen on graph, mean flowrate of argon was drawn against pressure difference in the capillary flowmeter. Calibration conditions of this experimental study were 748 mmHg and 18.5 °C.

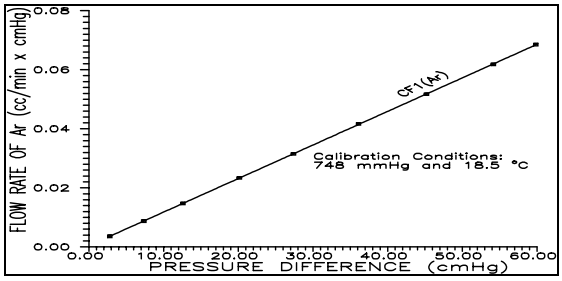

Figure 5. Calibration curve of the capillary flowmeter 1 for measurement of argon flow

Figure 6 shows calibration curves of the capillary flowmeter 1 for nitrogen and argon gases. Calibration conditions for this study were 752 mm Hg and 19 °C. As seen on graph, flowrate of argon through the capillary flowmeter 1 is less than flowrate of nitrogen because molecular weight of nitrogen is less than argon. From these curves, mean flowrates of nitrogen and argon will be determined without any trouble in the future by only measuring pressure differences of the capillary flowmeter.

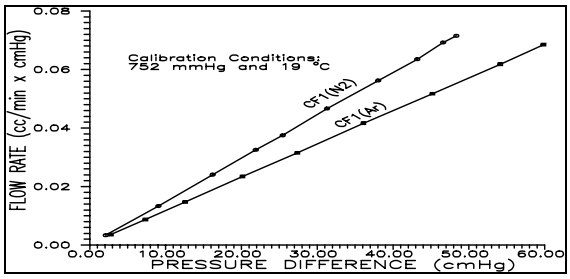

Figure 6. Calibration curves of the capillary flowmeter 1 for measurements of nitrogen and argon flows

Figure 7 shows calibration curves of the capillary flowmeters 2 and 3 for measurements of lower flows of hydrogen, methane and carbon dioxide. Calibration conditions of this experimental study were 764 mm Hg and 25 °C. As seen on graphs, hydrogen flow is higher than methane and carbon dioxide flows, because hydrogen is lighter than both

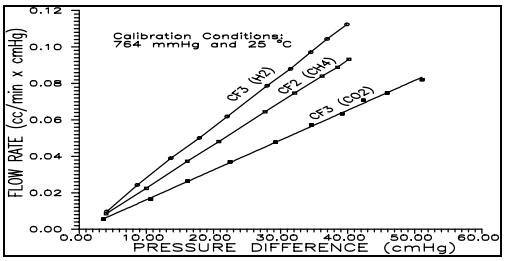

Figure 7. Calibration curves of the capillary flowmeters 2 and 3 for measurements of hydrogen, methane and carbon dioxide flowsgases.

By measurements of pressure differences of gases in same system, mean flowrates of hydrogen, methane and carbon dioxide will be determined without any trouble in the future. This capillary flowmeter system is very useful for measurements of lower gas flows of a reacting system and a diffusion system with same gases.

4. CONCLUSIONS

A capillary flowmeter set was designed and calibrated with different gases. This capillary flowmeter set is very useful for measurements of small gas flowrates in laminar flow regime. In this study, practical application of the Hagen- Poiseuille equation was demonstrated for various gases in laminar flows through the capillary flowmeters.

5. NOMENCLATURE

a	radius of the pipe (cm)
dp	pressure drop (cm Hg)

dx	length of unit element (cm)
h_b	barometric pressure (cm Hg)
h_{H2O}	water vapor pressure at the bubble flowmeter (cm Hg)
Δh	pressure difference of up and downstream pressures (cm Hg)
L	length of capillary (cm)
M	molar flow of fluid (mole/s)
P	partial pressure of gas (cm Hg)
P_1	upstream pressure at the capillary flowmeter (cm Hg)
P_2	downstream pressure through the capillary flowmeter (cm Hg)
Q_{BFMW}	wet gas flowrate at the bubble flowmeter (cc/min)
Q_{BFMD}	dry gas flowrate through the bubble flowmeter (cc/min)
R	ideal gas constant (cm Hg cm^3/mol.K)
T	temperature of gas (K)
u	velocity of flow at any cross-sectional of pipe (cm/s)
u_0	mean velocity of fluid (cm/s)
V	volume of gas (cm^3)
μ	viscosity of fluid (gr/cm.s)
ρ_m	molar density of gas (mol /cm^3)
τ	shear stress at the pipe wall (gr/cm.s^2)

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