Making sense of GC flow calculations - part 1

Introduction

Customers have often asked about the difference in measured flow rate to theoretical flow rate based on nominal column diameters and lengths. This article attempts to discuss the theoretical flow formula and explain the significance of various parameters used. A summary of the outcomes of changing column dimensions and carrier gas is outlined below.

- Changing the column internal diameter by 2% will change the column flow rate by 8%
- Cutting 5 m off a 30 m column will increase the flow rate by 17%
- Changing the carrier gas from helium to hydrogen will more than double the flow rate

The flow rate equation begins with the standard Poiseuille Flow calculations for incompressible fluids and is modified to take into account compressible gases. This short article is Part 1 of a two part series. By providing examples, the importance of various factors such as column internal diameter and length will be explained. Part 2 of this series will consider carrier gas velocity.

A modification of Poiseuilles Formula

Equation 1:

$$V_o = \frac{3.75\pi r^4}{\eta l} \cdot \frac{\{p_i^2 - p_o^2\}}{p_o} \cdot \frac{p_o}{p_m} \cdot \frac{T_m}{T_o}$$

The formula above, for the flow per minute, was the derived from first principles, and is correct provided a consistent set of units is used. The formula below is a modification to allow the use of more practical units in everyday use.

Equation 2:

$$V_o = 50747 \cdot \frac{d^4}{\eta l} \cdot \frac{\{(p_i + 14.7)^2 - (p_o + 14.7)^2\}}{(p_o + 14.7)} \cdot \frac{p_o}{p_m} \cdot \frac{(t_m + 273)}{(t_c + 273)}$$

where:

- V_o is the carrier gas volume flow rate in mL per minute
- d is the internal diameter of the capillary column (including the internal coating) in mm
- η is the dynamic viscosity of the carrier gas at the operating temperature, in micropoises
- l is the length of the capillary column in metres
- p_i is the carrier gas inlet pressure in psi (above atmospheric)
- p_o is the carrier gas outlet pressure in psi
- p_m is the pressure at which the measurement is made
- t_c is the temperture of the column in Celsius
- t_m is the temperature at which the measurement is made (outlet temperature)

Calculating flow rate using the modified Poiseuille equation

GC users are increasingly using software programs to calculate flow rate. Values obtained are sometimes compared with measured flow rates obtained by a bubble meter so we decided to compare the two. Equation 2 is a modification of Equation 1 and allows the use of everyday units such as psi for pressure, meters for length and Celsius for temperature.

The length and diameter of a well-used BPX5 column were measured and found to be 27.55 m and 0.245 mm ID, respectively. The column length was measured by counting the number of coils and using Equation 3 *(see next page)*. The internal diameter was measured using a light microscope. This column had begun life with a nominal length of 30 m but several cuts had reduced this to 27.55 m. The nominal diameter of the column was 0.25 mm. The inlet pressure was set at 20 psi and the viscosity of helium was calculated as 208 micropoise using the Helium Viscosity Equation *(refer next page)*. The flow was measured at atmospheric pressure and 25°C. An oven temperature of 50°C was set.

The measured flow rate using the bubble meter was 2.03 mL/min is close to the calculated flowrate of 1.98 mL/min using the modified Poiseuille equation.

$$50{,}747 \cdot \frac{0.245^4}{208 \times 27.55} \cdot \frac{\{(20 + 14.7)^2 - (0 + 14.7)^2\}}{14.7} \cdot \frac{14.7}{14.7} \cdot \frac{(25 + 273)}{(50 + 273)} = 1.98\,\text{mL/min}$$

It is important to remember that this is the flow rate at the column outlet. To optimize chromatography, one is really interested in the average linear carrier gas velocity and the inlet pressure needed to obtain this value for a column of certain dimensions. This discussion will be continued in part 2.

The effect of internal diameter and length on column flow rate

It can be clearly seen from an examination of Equation 1 that volumetric flow is directly proportional to the fourth power of the radius (diameter/2). Thus a small change in internal diameter can make a significant difference in calculated flow. For example, a deviation of only 5 µm in a column of internal diameter of 250 µm (a 2% change) will change the flow by 8%.

Table 1. Data showing calculated flows (mL/min) of helium at various internal diameters and lengths. An inlet pressure of 10 psi was used in the modified Poiseuille Equation 1.

Column ID (mm)	Column length (metres)		
	25	30	35
0.245	0.69 mL/min	0.57 mL/min	0.49 mL/min
0.250	0.75 mL/min	0.62 mL/min	0.53 mL/min
0.255	0.81 mL/min	0.67 mL/min	0.58 mL/min

Gas viscosity is taken as 228.1 micropoise at 100°C (reference CRC Handbook of Chemistry and Physics 59th edition)

Mathematically, it appears from Equation 2 that column flow rate is inversely proportional to column length. This is true provided that the inlet to outlet pressure differential remains constant. In a practical sense though, it is true because as the length increases so does the restriction and therefore the pressure must rise to maintain the same flow rate.

If we examine the data in Table 1, decreasing the column length from 30 to 25 m will increase the flow rate from 0.62 to 0.75 mL/min. Column length can be calculated by counting the number of turns and using Equation 3. For example, for a 17.5 cm cage, a 25 m column should be 45.5 turns or 55 cm per turn.

Equation 3:

$$\text{Length} = (\text{no of turns}) \cdot \pi \cdot (\text{diameter of column in cage})$$

The effect of temperature and pressure

A close examination of the modified Poiseuille equation shows that the pressure and temperature of both the outlet and the column are critical. Column temperature will affect gas viscosity and because gases become more viscous as they are heated, the flow rate will decrease as the viscosity and temperature increase.

The temperature of the outlet is also critical. Using Equation 2, for a 30 m x 0.25 mm ID column, a measured (outlet) temperature of 25°C and an oven temperature of 200°C will give a theoretical flow rate of 1.05 mL/min. This will be close to the value of the measured flow rate at this temperature as demonstrated above. However, if the actual measured (outlet) temperature is 200°C, the theoretical flow rate will now be 1.66 mL/min. This is a more realistic flow rate of the carrier gas as it passess through a hot detector and a measurement of flow rate with a bubble meter will give a misleading result.

The following Viscosity Equations may be used to calculate the viscosity of the carrier gas at any temperature from 0 to 300°C.

For Nitrogen

$$\text{Viscosity } (\eta) = 15.43 \cdot \sqrt{t_c + 273} - 89.4 \quad \mu\text{poise (correcct to within} \pm 0.5\%)$$

For Hydrogen

$$\text{Viscosity } (\eta) = 7.42 \cdot \sqrt{t_c + 273} - 39.5 \quad \mu\text{poise (correcct to within} \pm 1\%)$$

For Helium

$$\text{Viscosity } (\eta) = 16.5 \cdot \sqrt{t_c + 273} - 87.8 \quad \mu\text{poise (correcct to within} \pm 0.8\%)$$

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