GAS PRESSURE-DROP EXPERIMENT

William L. Luyben and Kemal Tuzla
Lehigh University • Bethlehem, PA 18015

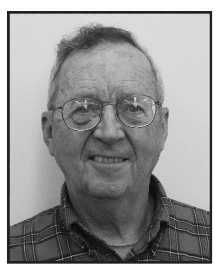
For many years, one of the most important experiments in the Lehigh Undergraduate Chemical Processing Laboratory has been a fluid mechanics experiment in which pressure drop through pipes of various diameters is measured over a range of velocities. The working fluid is liquid water, which is pumped from a holding tank by a centrifugal pump. The stream flows through a manual valve, a rotameter, one of three pipes with different diameters, through another manual valve, and back to the tank. Experimental data is used to calculate friction factor vs. Reynolds number, and results are compared to literature Moody diagram[1] predictions. Pump characteristic curves are also generated for different motor rotational speeds: pump head vs. flowrate and motor power vs. flowrate.

Regulating the flowrate is usually achieved by positioning the manual valve immediately after the pump. This means that the pipes are at a low pressure since they discharge back into the tank, which is at atmospheric pressure. In fact, under some conditions the pipes can be under vacuum because they are located at an elevation above the tank. This can lead to air being sucked into the impulse lines of the pressure gauges and can give faulty reading.

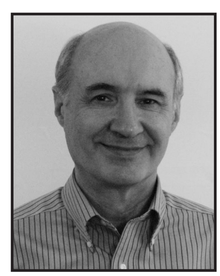
To prevent this, the valve downstream of the pipes before the tank can be used to set the flowrate. Then the pressure in the pipes is only slightly lower than the pump discharge pressure of about 45 psig.

Several years ago, a group of students took their data using the valve upstream of the pipes (low-pressure operation) and obtained some unreasonable data for pressure drops. The laboratory instructor suggested that they should have used the valve downstream of the pipes to have positive pressure in the test pipes. The response of the students was that they had to repeat all of their experiments. Of course, this is not true since liquid water is incompressible and pressure drop does not vary with pressure in the pipe.

This misconception by some bright students prompted us to design and build a new experiment in which the density of the fluid can be changed. Density affects both pressure drop and flow measurement, and understanding these concepts is very important to any engineer working with gas streams. In the current era of increasing importance of biomass gasifica-



***William L. Luyben** is a professor of chemical engineering at Lehigh University. He received his B.S. from Penn State and Ph.D. from the University of Delaware. He teaches Unit Operations Laboratory, Process Control, and Plant Design courses. His research interests include process design and control, distillation, and energy processes.*



***Kemal Tuzla** is a professor of practice and associate chair in the Department of Chemical Engineering at Lehigh University. He received his B.S. and Ph.D. from the Technical University of Istanbul. He teaches Unit Operations Laboratory, Fluid Mechanics, and Heat Transfer courses. His research interests include thermal energy storage and heat transfer in two-phase flows.*

tion and the hydrogen economy, the chemical engineer must be competent in dealing with gas flows through pipes.

There have been a number of papers discussing experiments in compressible flow systems. Aerospace departments use many experiments to illustrate compressible flow effects in converging-diverging nozzles, usually at high Mach numbers. Lam and Liu[2] provide a useful example of a simple laboratory set up. Forrester, et al.,[3,4] discuss experiments in which gas discharges from a pressure vessel or is fed into a vessel.

Despite the importance of gas flows in chemical engineering industrial processes, we are not aware of any student laboratory experiments dealing with the flow of compressible fluids through pipes.

DESCRIPTION OF EQUIPMENT

Figure 1 gives a schematic flowsheet. High-pressure air (85 psig) flows through a pressure regulator. This device holds a constant pressure at the down-stream rotameter, and this pressure can be adjusted to different levels. After passing through the rotameter, the piping consists of two parallel lines. One pipe is 1⁄4 inches in diameter and the other is 1⁄2 inches in diameter. There is a manual valve at the inlet of each line that is used to set the flowrate of air through the line in service. At the discharge end of each pipe is a back-pressure regulator that is adjusted to hold different pressures in the test pipe.

For example, suppose the supply pressure is 85 psig. The pressure at the rotameter could be 50 psig. The pressure at the beginning of the test pipe could be 26 psig, and pressure at the end of the pipe in service could be 25 psig due to the 1 psi pressure drop. Pressure gauges measure the total pressures at each end of test pipes, and a differential pressure measurement is made between the inlet and exit of each pipe.

GAS PRESSURE DROP

The first concept illustrated in this experiment is the effect of density on pipe pressure drop. The first task for students is to measure friction factors and compare the experimental values to Moody's data. Since the pipe is horizontal, the measured pressure drop across the pipe is assumed to be due to frictional pressure losses only. Any effects due to small pressure changes along the pipe associated with compressibility of the gas are assumed negligible.

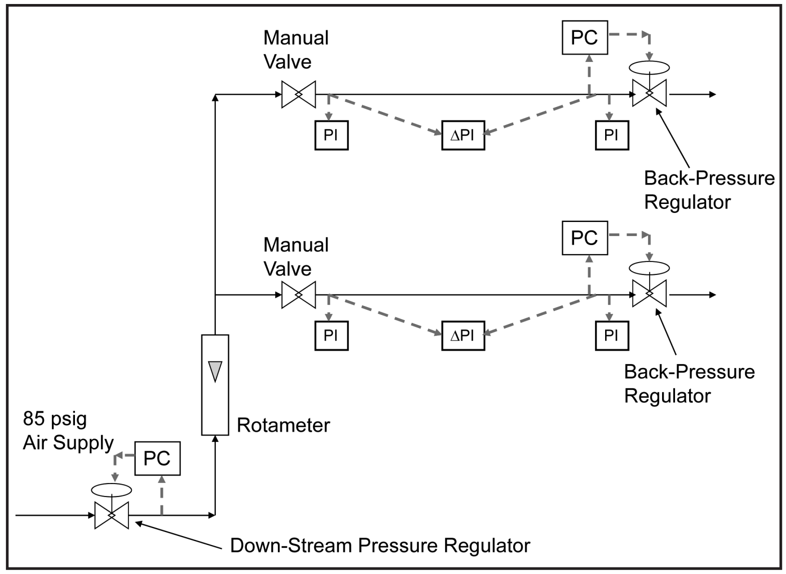


Figure 1. *Schematic of experimental test loop.*

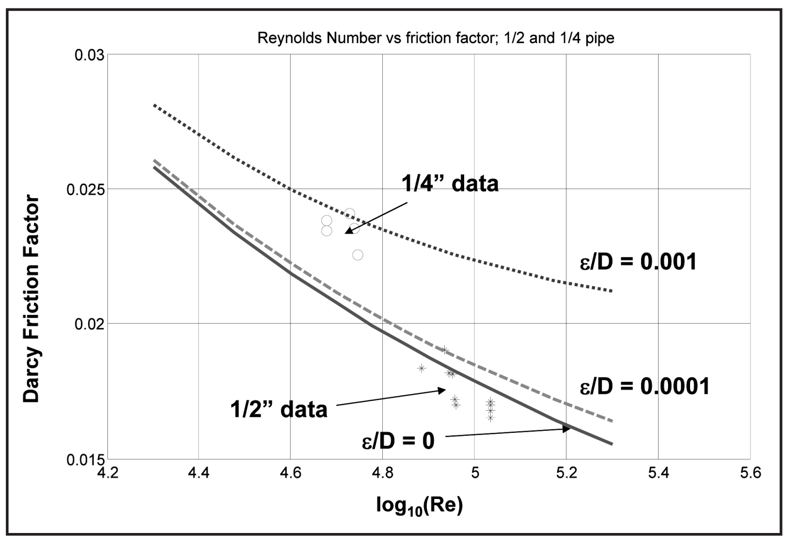


Figure 2. *Comparison of experimental data with Moody data for two pipe sizes.*

A sample comparison is presented in Figure 2. Experimental data for the 1⁄4" pipe agree with Moody's data for a roughness ratio of ε/D=0.0008. The data for the 1⁄2" pipe shows good agreement with Moody's at zero roughness. There are few points that show friction factors less than a smooth tube, which is obviously due to experimental uncertainty.

The apparatus permits pressure-drop data to be gathered with different pipe pressures. For the same mass flowrate, the pressure drop changes as pressure in the pipe changes. Pressure drop depends on kinetic energy, which is proportional to density (ρ) times the square of the velocity (V^2).

Higher pressure means higher gas density, but higher density decreases gas velocity. So density increases directly with line pressure, but velocity decreases directly with line pressure. The net effect is a linear inverse relationship between pressure drop and pressure in the pipe.

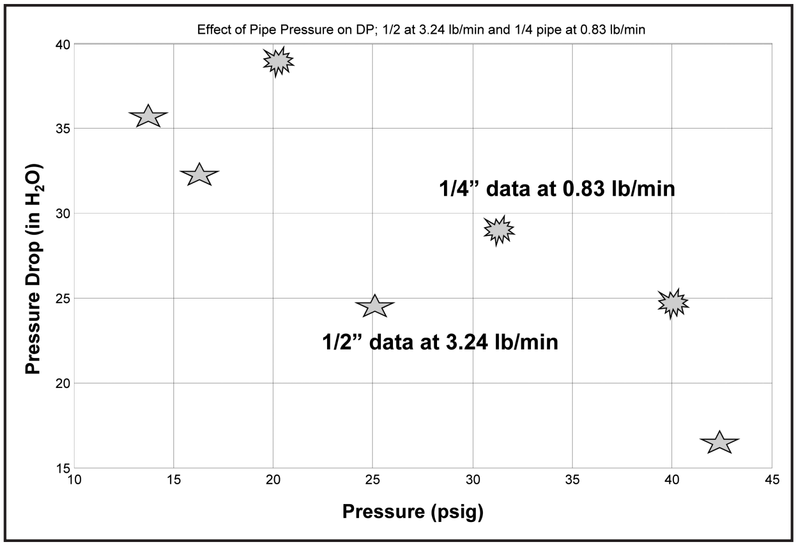


Figure 3. *Effect of line pressure on pressure drop at constant mass flowrate.*

Students are asked to verify this relationship by carrying out several tests at similar rotameter conditions, (*i.e.*, at same mass flow rate) but different pipe pressures as tabulated in Table 1. Note that there are three gas densities involved in the calculations: density at standard conditions, density in the pipe at pipe pressure, and density in the rotameter at rotameter pressure.

From the data of Table 1, the variation of pressure drop across the pipe is plotted as a function of pressure in the test pipe and is presented in Figure 3. For the 1⁄2 inch pipe that is 8 ft long, with a mass flowrate of 3.24 lb/min, the pressure drop is 24.5 inches of water when the average pressure in the pipe is 25.5 psig (arithmetic average of the inlet and outlet pressures in the pipe). With the same mass flowrate, the pressure drop decreases to 16.5 inches of water when the pipe pressure is increased to

TABLE 1
Experimental Data and Calculated Parameters

Pipe: 1⁄2 inch – Schd. 40.				
ID (inches)	0.622			
Pressure at Rotameter (psig)	50	50	50	50
Gas Density at Rotameter (lb/ft^3)	0.330	0.330	0.330	0.330
Rotameter Reading (SCFM)	20.6	20.6	20.6	20.6
Pressure at Inlet of Pipe (psig)	14.5	17.0	26.0	42.8
Pressure at Outlet of Pipe (psig)	13.0	15.5	25.0	42.3
Differential Pressure (inches H_2O)	35.6	32.3	24.5	16.5
Mean Gas Density in Pipe (lb/ft^3)	0.145	0.158	0.205	0.292
Mass Flowrate (lb/min)	3.24	3.24	3.24	3.24
Velocity in Pipe (ft/sec)	176	162	125	87.7
Darcy Friction Factor	0.0170	0.0167	0.0165	0.0158
Reynolds Number	109,000	109,000	109,000	109,000
Pipe: 1/4 inch – Schd. 40				
ID (inches)	0.364			
Pressure at Rotameter (psig)	45	45	45	
Gas Density at Rotameter (lb/ft^3)	0.306	0.306	0.306	
Rotameter Reading (SCFM)	5.5	5.5	5.5	
Pressure at Inlet of Pipe (psig)	40.5	32.0	21.0	
Pressure at Outlet of Pipe (psig)	39.5	31.0	19.5	
Differential Pressure (inches H_2O)	24.5	29.0	39.0	
Mean Gas Density in Pipe (lb/ft^3)	0.279	0.235	0.178	
Mass Flowrate (lb/min)	0.83	0.83	0.83	
Velocity in Pipe (ft/sec)	68.7	81.4	108.0	
Darcy Friction Factor	0.0235	0.0234	0.0239	
Reynolds Number	47,600	47,600	47,600	

42.5 psig. With the same mass flowrate, the pressure drop increases to 35.6 inches of water when the pipe pressure is decreased to 13.8 psig.

Note that there is a slight curvature in the data shown in Figure 3. In theory, the relationship between pressure drop and pressure should be linear. Pressure drop in a pipe can be calculated from the friction factor f.

$$\Delta P = f\left(\frac{L}{D}\right)\rho\frac{V^2}{2} \tag{1}$$

where L and D are the length and diameter of the pipe, ρ is density and V is velocity. When the mass flowrate of gas is constant in a constant-diameter pipe, the Reynolds number is constant. This means the friction factor is constant. Consider two pipes of the same diameter and length that operate with gases having different densities (ρ_1 and ρ_2) but with the same mass flowrate. The pressure drops through the pipe (ΔP_1 and ΔP_2) at these two conditions are

$$\Delta P_1 = f\left(\frac{L}{D}\right)\rho_1\frac{V_1^2}{2}$$

$$\Delta P_2 = f\left(\frac{L}{D}\right)\rho_2\frac{V_2^2}{2} \tag{2}$$

Taking the ratio of the pressure drops and expressing velocity as the mass flowrate F_{mass} divided by density ρ and pipe cross-sectional area A_{CS} give the effect of density on pressure drop.

$$\frac{\Delta P_1}{\Delta P_2} = \frac{f\left(\frac{L}{D}\right)\rho_1\frac{V_1^2}{2}}{f\left(\frac{L}{D}\right)\rho_2\frac{V_2^2}{2}} = \frac{\rho_1 V_1^2}{\rho_2 V_2^2} = \frac{\rho_1\left(\frac{F^{mass}}{\rho_1 A_{CS}}\right)^2}{\rho_2\left(\frac{F^{mass}}{\rho_2 A_{CS}}\right)^2} = \frac{\rho_2}{\rho_1} \tag{3}$$

If the two densities are different only because of differences in pressure (same molecular weight and temperature), the ratio of the pressure drops varies inversely with pressure P.

$$\frac{\Delta P_1}{\Delta P_2} = \frac{P_2}{P_1} \tag{4}$$

These experiments expose the students to the important observation that the density of the gas affects the pressure drop in the pipe. This knowledge is vital to any engineer involved in a process that handles gas flows. The density of the gas can change with pressure and temperature. Very importantly, it also can change with composition. Fuel gas in a plant is a common example. The fuel gas can come from various sources (purchased natural gas or gas produced in a process, for example hydrogen or propane). Therefore the composition of the gas changes as the flowrates from the various sources change. The laboratory experience provides the students with this important insight.

GAS FLOW MEASUREMENT

The second important concept illustrated in this experiment is how to correct gas flow meter constants for conditions different than used for their calibration. This is achieved by operating the flow measurement device at different pressures. The mass flowrate changes as the density of the gas in the flow-measuring device changes.

If a turbine meter is used, which is a volumetric device, it is straightforward to find the mass flowrate by simply multiplying the volumetric flow reading from the turbine meter by the actual density of the fluid in the device.

If the device is based on drag force (the case for a rotameter) or on Bernoulli's Principle (the case for the differential pressure in an orifice plate or Pitot tube), the calculation of flowrate is not as straightforward. The correction requires the use of the square root of the ratio of the density at actual flow conditions to the density at calibration conditions. The correction factor relationship is given in Eq. (5).

$$F_{actual}^{mass} = F_{cal}^{mass}\sqrt{\frac{\rho_{actual}}{\rho_{cal}}} \tag{5}$$

The F_{actual}^{mass} is the actual mass flowrate of gas flowing through the meter.

The term F_{cal}^{mass} is the mass flowrate that is calculated by using the flow meter reading (usually in volumetric units F_{cal}^{vol}) times the gas density at calibration conditions.

$$F_{cal}^{mass} = F_{cal}^{vol}\rho_{cal} \tag{6}$$

The gas densities ρ_{actual} and ρ_{cal} are at the actual and calibration conditions in the flow meter.

In the experiment, only gas pressure changes since the gas is air at ambient temperature. In this case, the correction factor is given in Eq. (7) in terms of pressures.

$$F_{actual}^{mass} = F_{cal}^{mass}\sqrt{\frac{P_{actual}}{P_{cal}}} \tag{7}$$

The students in the laboratory operate the rotameter at different pressures but with the same mass flowrate. They observe that the rotameter reading is different at different pressures because of the change in gas density with pressure. For the same mass flowrate, the rotameter reading increases as the pressure in the rotameter decreases because the lower density increases the gas velocity. The derivation of these equations for the rotameter used in the experiment is appended.

Consider a numerical example. A rotameter is calibrated for air under standard conditions (14.7 psia and 70 °F). The rotameter reading is 20.6 scfm. The flow meter is used with air at room temperature but with a pressure of 50 psig in the rotameter. We want to calculate the mass flowrate through the rotameter.

Assuming ideal gas behavior, the density of air (28.84 lb/lb-mole) at 70 ˚F and 14.7 psia is

$$\rho_{cal}=\frac{\left(28.84\ \mathrm{lb/lb-mol}\right)\left(14.7\ \mathrm{lb_f/in^2}\right)\left(144\ \mathrm{in^2/ft^2}\right)}{\left(1545\frac{\mathrm{ft\ lb_f}}{\mathrm{lb-mol\ ^\circ R}}\right)\left(460+70\,^\circ\mathrm{R}\right)}=0.0746\frac{\mathrm{lb}}{\mathrm{ft^3}} \tag{8}$$

The mass flowrate at standard conditions would be

$$F_{cal}^{mass}=F_{cal}^{vol}\rho_{cal}=\left(20.6\ \mathrm{scfm}\right)\left(0.0746\ \mathrm{lb/ft^3}\right)=1.54\ \mathrm{lb/min} \tag{9}$$

Using Eq. (7) to find the actual mass flowrate with the same molecular weight and temperature gives

$$F_{actual}^{mass}=\left(1.54\ \mathrm{lb/min}\right)\sqrt{\frac{14.7+50}{14.7}}=2.97\ \mathrm{lb/min} \tag{10}$$

CONCLUSION

This paper has described an experiment that illustrates several important issues associated with the fluid mechanics of gas flow in pipes at low Mach numbers, which is found in many chemical engineering processes. The experiment gives the students hands-on experience and understanding that:

- *For a given mass flowrate, pressure drop in a pipe varies inversely with gas density.*
- *Flow measurements using a variable area rotameter or differential pressures (orifice plates or pitot tubes) need to be properly compensated for densities that differ from those used for calibration.*

Although students are exposed to these concepts during their classroom studies, our experience shows that this experiment provides very helpful reinforcement for student understanding and retention of concepts.

ACKNOWLEDGMENT

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APPENDIX

Derivation of rotameter equations is summarized below. A schematic of a rotameter is shown in Figure A1. Suppose we carry out two experiments with different operating conditions in this rotameter, and the float stabilizes at the same level. Furthermore assume that one of the experiments is under standard calibration conditions (cal) with air (1 atm and 70 ˚F) at which the rotameter has been calibrated, and the other condition is at a different pressure and temperature (actual) and perhaps a different gas with a different molecular weight.

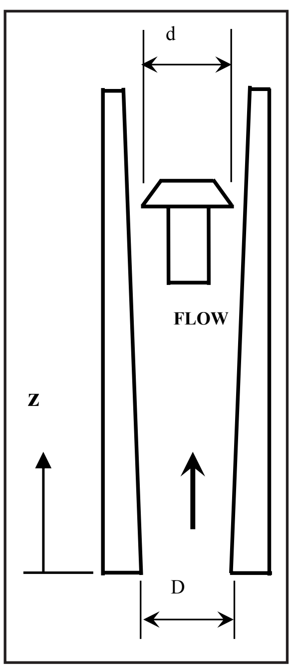

Figure A1. *Rotameter schematic.*

A force balance on the float would include the drag force, the buoyancy force of the fluid, and the weight of the float;

$$F_D+\rho_{Fluid}Vol_{Float}\frac{g}{g_c}=\rho_{Float}Vol_{Float}\frac{g}{g_c} \tag{A1}$$

where the drag force is defined as;

$$F_D=C_DA_{Float}\frac{\rho_{Fluid}\left(V_{Fluid}\right)^2}{2g_c} \tag{A2}$$

The drag coefficient, C_D, consists of both pressure drag and frictional drag. For the geometry of the float with a short aspect ratio, however, frictional drag is negligible for a wide range of Reynolds Numbers (between 1,000 and 250,000), and therefore pressure drag dominates the C_D. As a result, C_D becomes a constant, independent of Reynolds Number.

Combining Eqs. (A1) and (A2) gives the velocity and volumetric flow rate.

$$V_{Fluid}=\left[\frac{2gVol_{Float}}{C_DA_{Float}}\left(\frac{\rho_{Float}}{\rho_{Fluid}}-1\right)\right]^{1/2} \tag{A3}$$

$$F_{Fluid}^{Vol}=AV_{Fluid}=A\left[\frac{2gVol_{Float}}{C_DA_{Float}}\left(\frac{\rho_{Float}}{\rho_{Fluid}}-1\right)\right]^{1/2} \tag{A4}$$

where A is the annular area between the body of the rotameter tube and the float. When gases are used, the ratio of ρ_{Float} to ρ_{Fluid} is very large, so the term "-1" on the right-hand side of Eq. (A4) can be neglected;

$$F_{Fluid}^{Vol} = A\left[\frac{2gVol_{Float}}{C_D A_{Float}}\left(\frac{\rho_{Float}}{\rho_{Fluid}}\right)\right]^{1/2} \tag{A5}$$

If we consider the flowrate for two different experimental conditions, one with density at which the rotameter has been calibrated and the other at some other actual density, the ratio of the volumetric flowrates would be as given in Eq. (A6).

$$\frac{F_{actual}^{Vol}}{F_{cal}^{Vol}} = \frac{A\left[\frac{2gVol_{Float}}{C_D A_{Float}}\left(\frac{\rho_{Float}}{\rho_{actual}}\right)\right]^{1/2}}{A\left[\frac{2gVol_{Float}}{C_D A_{Float}}\left(\frac{\rho_{Float}}{\rho_{cal}}\right)\right]^{1/2}} = \left(\frac{\rho_{cal}}{\rho_{actual}}\right)^{1/2} \tag{A6}$$

The term F_{cal}^{vol} is the volumetric flowrate reading from the rotameter based on its meter constant. The ρ_{cal} and ρ_{actual} are the gas densities at standard calibration conditions and actual conditions in the rotameter, respectively. To calculate the mass flowrates, the corresponding densities are used.

$$\frac{F_{actual}^{mass}}{F_{cal}^{mass}} = \left(\frac{F_{actual}^{Vol}}{F_{cal}^{Vol}}\right)\frac{\rho_{actual}}{\rho_{cal}} = \left(\frac{\rho_{cal}}{\rho_{actual}}\right)^{1/2}\frac{\rho_{actual}}{\rho_{cal}} = \left(\frac{\rho_{actual}}{\rho_{cal}}\right)^{1/2} \tag{A7}$$

When the temperature and molecular weight of the fluid do not change, the relationship can be expressed in terms of pressures.

$$F_{actual}^{mass} = F_{cal}^{mass}\sqrt{\frac{P_{actual}}{P_{cal}}} \tag{A8}$$

NOMENCLATURE

A_{CS} – cross-sectional area
C_D – drag coefficient
D – diameter
F_D – drag force
F^{mass} – mass flowrate
F^{vol} – volumetric flowrate
g – gravitational constant
P – pressure
Re – Reynolds number
V – velocity
z – vertical position of rotameter float

Subscripts

actual – at operating conditions
cal – at calibration conditions
fluid – gas phase
float – rotameter float

Greek

ρ density
ε roughness factor
Δ difference in property between locations ❒