COMPRESSIBLE FLUID FLOW IN TUBES: A DEMONSTRATION OR LABORATORY MODULE

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INTRODUCTION

Anecdotally, our experience in engineering education is that students use the constant density form of Bernoulli's equation as a universal fluid flow equation. In the students' defense, incompressible flow equations are heavily emphasized in the engineering curriculum, appearing in numerous courses from Introduction to Engineering through General Thermodynamics to Senior Unit Operations Courses. Also, several standard engineering laboratory modules reinforce the use of incompressible fluid flow forms of Bernoulli's theorem. As engineers, we acknowledge that the mechanical-energy form of Bernoulli's theorem that accounts for friction losses written for incompressible fluids does have a wide range of applicability for both liquid and gas flow problems. However, the application of incompressible flow equations in situations when the fluid undergoes substantial decompression can lead to component failure or significant errors (Table 1).

Therefore, presented here is a laboratory module that introduces or reinforces compressible gas flow concepts for enhanced student learning. The module reduces safety concerns by using vacuum instead of compressed gases. The learning objectives are adjustable. Herein, we present material that will allow instructors to include learning objectives from the following author-suggested list, depending on the program/course objectives:

After completion of the laboratory, a student will be able to:

- Determine if the best flow model is incompressible, isothermal compressible, or adiabatic compressible
- Perform isothermal and adiabatic calculations for compressible flow systems
- Calculate Mach numbers and the speed of sound for given flow conditions
- Demonstrate self-learning of the governing equations for the isothermal compressible and adiabatic compressible fluid flow systems
- Write the following elements into a spreadsheet program:
  1. "If-Then" and "Nested If-Then" Statements
  2. Macros and the use of VBA in Microsoft Excel®
  3. Graphical User Interface (GUIs)

We developed prototype equipment and a beta-teaching module for compressible gas flows. Juniors/seniors in a unit operations laboratory class used the prototype equipment. The material presented below includes insights learned from this beta-testing of the teaching module/equipment. The evaluation of the beta-teaching module, which improved the presented teaching module, included post-course interviews with the students.

This manuscript will first discuss the construction of an experimental or demonstration apparatus for a compressible flow teaching module. The discussion covers apparatus construction and specification details, in addition to why the apparatus should generate vacuum flow regimes. The next section reviews the relevant fluid flow theory and equations. The manuscript covers examples of experimental assignments, including representative results reported by students who participated in the beta-testing. Finally, the manuscript discusses computer coding for evaluating generated experimental data.

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The literature on demonstration/laboratory equipment for teaching undergraduates compressible fluid flow is limited and typically uses nozzles, high speed air flow over vehicle components, and wind tunnels.[1] Undergraduate demonstrations or laboratory equipment in compressible fluid flow are, in general, expensive and, therefore, not feasible for some institutions.[2] One exception is the draining of a water tank through an open channel flow nozzle or conduit. This setup uses the water table analogy to illustrate fluid temperature changes and Mach numbers in adiabatic compressible flows via analogous changes in the free-surface water flow depths. While the water table analogy works for demonstrating adiabatic compressible flow, presented below is relatively inexpensive equipment for giving undergraduates experience with isothermal compressible flows in addition to incompressible and adiabatic flow conditions.

APPARATUS DESIGN AND CONSTRUCTION

Advantages/Disadvantages of Using Vacuum Instead of Compressed Gases

The teaching module described in this manuscript uses vacuum flow conditions instead of compressed gas flow. The use of vacuum flow makes system control difficult when using manual valves. However, the control disadvantage is offset by advantages in system safety and ease of producing compressible gas flow regimes. The ease of producing compressed gas flow regimes is not self-evident. To illustrate, consider a 1 ft (30.5 cm) length of 1/16 inch interior diameter (ID) tubing. With compressed gas feed, the exit tube pressure is atmospheric or higher (≥ 760 mmHg-abs). For a vacuum system, the tube exit pressure is set at pressures below atmospheric (≤ 760 mmHg-abs). Table 1 shows the modeled flow regime and pressure drop for a constant molar flow rate through the tube of 2 SLPM (standard liters per minute with T = 0 °C and P = 1 atm); while Table 2 gives the gas flow rate, in SLPM, required to cause a transition from incompressible to isothermal gas flow regimes. Compressible gas velocities, for constant mass flow and cross-sectional area systems, are inversely related to the absolute pressure of the gas. Therefore, Table 1 illustrates that pressure drop and, therefore, the compressible gas density change, is directly related to the gas velocity-squared, which is related to the exit absolute pressure of the flow system.

Apparatus Set-Up and Materials

Figure 1 shows the proposed experimental apparatus setup. The majority of the materials are standard plumbing, tubing, fittings, valves, pressure gauges, and manifolds. The hollow-fiber membranes and their plumbing into the experimental apparatus are non-standard.

The air flows through the equipment starting in the upper left-hand corner of Figure 1, where it enters a flow meter at atmospheric pressure. A needle or metering value controls either the flow rate or the pressure ("Press. In") of the entrance header. Ball or plug valves allow the direction of airflow through only one tube level. When open, the ball/plug valves give unrestricted flow from the header through the selected tubing and into the exit manifold, allowing one to assume the pressures of the header and exit manifold are the pressures, respectively, of the constriction entrance to the tubing and the expansion exit from the tubing. Because of the low operating pressures, having ball or plug values at both the entrance and exit is advisable to ensure complete isolation of the desired tube levels. A Proportional-Integral-Derivative (PID) controller/metering value is optional but

TABLE 1
Pressure Drop and Flow Regime for 2 SLPM of Air Flow at 25°C in a 1-foot length of 1/16 inch ID Tubing as a Function of the Tubing's Exit Absolute Pressure

Exit Absolute Pressure (mmHg)	Pressure Drop in the Tube (mmHg)	Flow Regime	%-Density Change	%-difference of compressible vs incompressible calculation
Compressed Gas Feeds				
4500 (i.e., 6 bar)	2.0	Incompressible	0.04%	-0.05%
2250 (i.e., 3 bar)	4.0	Incompressible	0.18%	-0.01%
760	12	Incompressible	1.5%	0.3%
Vacuum Systems				
560	16	Incompressible	2.8%	0.6%
400	22	Isothermal Gas	5.2%	1.3%
200	43	Isothermal Gas	18%	5.4%
130	61	Adiabatic	32%	-23%

TABLE 2
25°C Air Flow at which the Flow Regime Transitions from an Incompressible to Isothermal Gas Model Along with the Modeled Pressure Drop for a One-Foot Length of 1/16 Inch ID Tubing as a Function of the Tubing's Exit Absolute Pressure.

Exit Absolute Pressure (mmHg)	Transition Flow (SLPM)	Pressure Drop in the Tube (mmHg)
Compressed Gas Feeds		
4500 (i.e., 6 bar)	97.7	237
2250 (i.e., 3 bar)	45.3	118
760	3.4	40.3
Vacuum Systems		
560	2.4	29.6
400	1.9	21.1
200	0.6	11.5
130	0.2	7.1

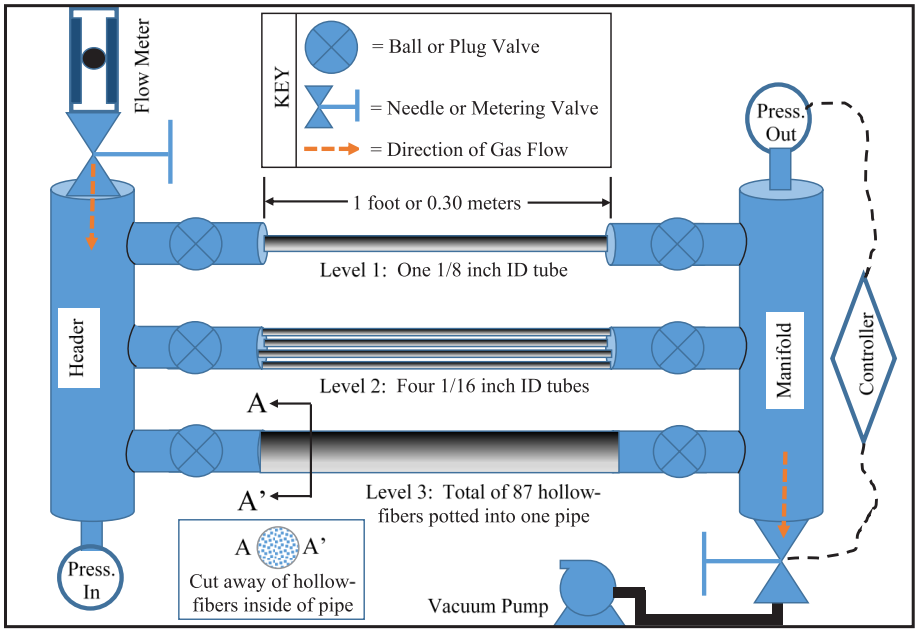


Figure 1. *Sketch of Laboratory Setup. See Figure 2 for illustration of how to fabricate the hollow-fiber tube bundle (Level 3).*

recommended for ease of running experiments. After exiting the isolated tube level, the air flows through the exit manifold, through the exit metering valve, and finally into the vacuum pump.

Table 3 summarizes our recommendation for the composition of the three levels of tubes illustrated in Figure 1. In Figure 1, Level 3 is a bundle of hollow-fiber membranes. While it is possible to design the laboratory equipment around any existing hollow fiber membrane module, we found it easier to repurpose the hollow-fibers from inside a compressed gas dehydration membrane module. The hollow-fibers we had access to had the outer and inner diameters (OD and ID) shown in Table 3. If alternative hollow-fibers are used, then the total number of fibers (i.e., tubes) would need to be adjusted to keep the cross-sectional flow areas equal between all the levels.

Fabrication of Hollow-Fiber Tube Bundles or Membrane Module

The hollow-fibers should be sealed inside a larger diameter pipe or housing. The sealing component is called the tubesheet, and it forms an air-tight barrier between the individual hollow-fibers, the hollow-fiber bundle, and the housing. The following two references discuss two options for the housing:

- One larger diameter PVC pipe, Wan et al.[3]
- Multiple 3/8 inch copper tubes, Scovazzo and MacNeill[4]

In addition to the housing, the following materials are needed:

- Two-part setting epoxy, such as Poly-Optic® 1411 Clear Casting Resin, EPON 826, or J-B Weld Industro Cold Weld®
- Tube cutter, saw, and wood chisels
- Mold-Release (for example Frekote®)
- Mold

The J-B Weld Industro Cold Weld can form a vacuum-tight bond with copper tubing.[4] The mold-release stops the

epoxy from forming a bond with surfaces, such as the outside of the pipe or the mold for holding the epoxy during its curing period.

Figure 2 shows the tubesheet fabrication process for one side of the membrane bundle. First, cut and bundle membranes in lengths longer than the housing. Spray the outside of the housing and the inside of the mold with mold-release. *Be careful not to spray mold-release on the inside of the housing*. Insert the membranes inside the housing; the plughole on the side of the housing prevents the build-up of air pressure during the fabrication. The plughole should be sealed after fabrication and prior to the experimental apparatus use. Put the housing containing the membrane bundle inside of the mold. Pour the epoxy (following the epoxy mixing) into the mold and allow it to travel up the inside of the housing and around the hollow-fibers.[3] After the epoxy cures, remove the mold and cut off the end of the housing. The ends of the hollow-fibers may have been closed by the cutting process in which case a wood chisel can be used to open the ends.[4]

TABLE 3
Specifications of Tubes. The Levels are Counted from Top to Bottom

Level	Assumed OD	Assumed ID	Number of Tubes	Total Cross Section Area (m^2)
1	1/4 inches	1/8 inches	1	7.9×10^{-5}
2	1/8 inches	1/16 inches	4	7.9×10^{-5}
3	650 micrometers	350 micrometers	87	7.9×10^{-5}

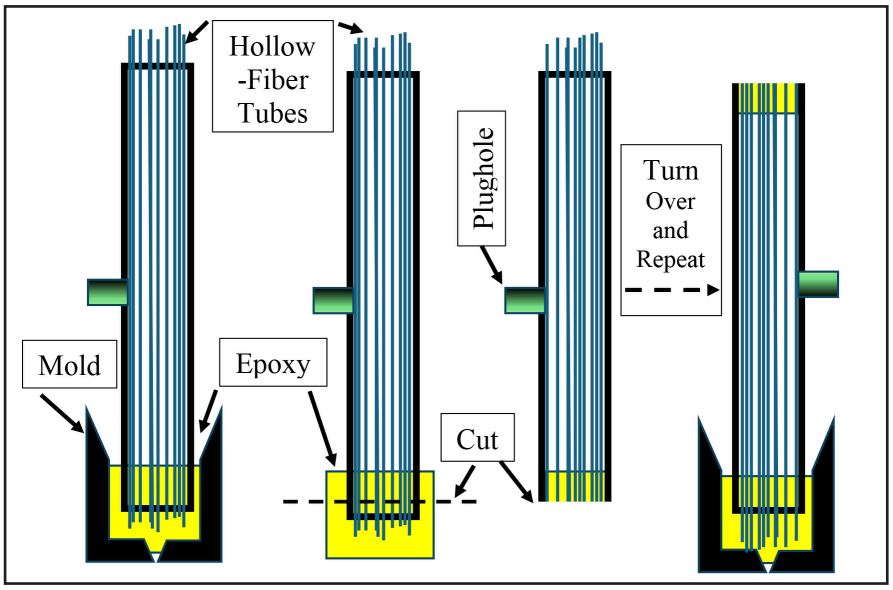


***Figure 2**. Illustration of how to fabricate the hollow-fiber tube bundle (Level 3 in Figure 1 and Table 3).*

The reader is directed to Wan et al.,[3] Section 4. 2 Formation of Tubesheets, for more details on the fabrication of hollow-fiber modules. It is important to prevent the epoxy from traveling up the inside of the hollow fibers via capillary action when the membrane bundle is in the mold for epoxying. To this end, sealing the ends of the membranes, prior to placement into the mold, is beneficial, either with a little rubber cement, polyurethane, or a hot wire. Scovazzo and MacNeill [4] give details on the fabrication of bundles with a copper housing. Copper tubing 3/8 inch in diameter can hold about 40 hollow-fibers, meaning that two or three copper tubes will be needed for Level 3 in Figure 1. However, the advantage of 3/8 inch copper tubing is that compression fittings, such as Swagelok®, can be used to make a vacuum tight manifold. If compression fittings are used, replace the metal ferrules with nylon ferrules to avoid destruction of the epoxy potting.[4]

THEORY AND EQUATIONS

In this laboratory module, students will use equations to model gas flow. The following relevant equations are modified from the development in *Unit Operations of Chemical Engineering*, 7th ed., McCabe, Smith, and Harriet (MSH).[5] Starting with total friction loss, N_f:

$$N_f = \frac{f(L)}{r_H} + K_c + K_e \tag{1}$$

where f = Fanning friction factor (unitless) averaged over the length of the tube, L is the total length of the tube (m), r_H is the hydraulic radius of the tube (m), K_c is constriction loss coefficient (at tube entrance), and K_e is expansion loss coefficient (at tube exit). The equation for incompressible fluid flow, assuming horizontal flow, is

$$P_{in} - P_{out} = \rho N_f \frac{v^2}{2} \tag{2}$$

where P_{in} is the fluid pressure in the entrance manifold, P_{out} is the fluid pressure in the exit manifold, ρ is the fluid density (assumed constant for incompressible flow), and v is the fluid velocity in the tube. For isothermal compressible flow, ρ and v are no longer constant in the tube, and the model for pressure drop is

$$(P_{in})^2 - (P_{out})^2 = \frac{G^2 RT}{M_w}\left[2ln\left(\frac{P_{in}}{P_{out}}\right) + N_f\right] \quad (3)$$

where G is the mass velocity, M_W is the averaged gas molecular weight, R is the ideal gas constant, and T is the absolute temperature.

Mach number, like Reynolds number, is an important parameter for compressible fluid flow modeling. The dimensionless Mach number, Ma, is

$$Ma \equiv \frac{v}{s} \quad (4)$$

where s is the speed of sound in the fluid at the system temperature, T,

$$s = \sqrt{\frac{kRT}{M_w}} \quad (5)$$

and k is the ratio of the specific heat capacities at constant pressure to constant volume for the compressible gas (i.e., for air k = 1.4). Because fluid velocity, v, is not constant in compressible flow, the Ma will be different at the entrance and exit of the tube. This difference in Ma is included in the adiabatic compressible flow model. For clarity, we present below the adiabatic flow model as a system of equations

$$C_{in} = 1 + \frac{k-1}{2}(Ma_{in})^2 \quad (6)$$

$$C_{out} = 1 + \frac{k-1}{2}(Ma_{out})^2 \quad (7)$$

$$N_f = \frac{1}{k}\left\{\frac{1}{(Ma_{in})^2} - \frac{1}{(Ma_{out})^2} - \frac{k+1}{2} ln\left[\frac{(Ma_{out})^2 C_{in}}{(Ma_{in})^2 C_{out}}\right]\right\} \quad (8)$$

where N_f has the definition in Eq. 1. Trial and error, or Goal Seek in Excel, using Eq. 6-8 calculates Ma_{out} from Ma_{in} or vice versa. With knowledge of both the entrance and exit Ma numbers, the ratio of P_{in} to P_{out} results from (Eq. 6.39, page 147, MSH 7th ed.[5]):

$$\frac{P_{in}}{P_{out}} = \frac{Ma_{out}}{Ma_{in}}\sqrt{\frac{C_{out}}{C_{in}}} \quad (9)$$

We point out to students that a variation in a system parameter could be neglected if it causes less than 1% error in the final answer. In the reduction-to-practice, this general 1% error recommendation can vary. For example, the recommendation for using incompressible vs compressible models varies by engineering discipline and application (i.e., enclosed channel flow versus semi-infinite flow over a surface). For this module, we chose a criterion that recommends using the incompressible flow model if the density change is less than 5%. Table 1 shows the %-difference in the final answers between the compressible versus incompressible models for a range of flow conditions along with the resulting percentage of density change. The data in Table 1 indicate that the reduction-to-practice recommendation of using incompressible flow models for density changes below 5% is consistent with the general engineering 1% error recommendation.

For enclosed channel flow with low Mach numbers (Ma ≤ 0.3), McCabe, Smith, and Harriet state that the adiabatic modeled pressure drops follow closely the results of the simpler Isothermal Model.[5] Therefore, combining the 5% density change recommendation with the low Mach number agreement between isothermal and adiabatic models results in an algorithm (Figure 3) for determining if the most appropriate model is incompressible, isothermal, or adiabatic.

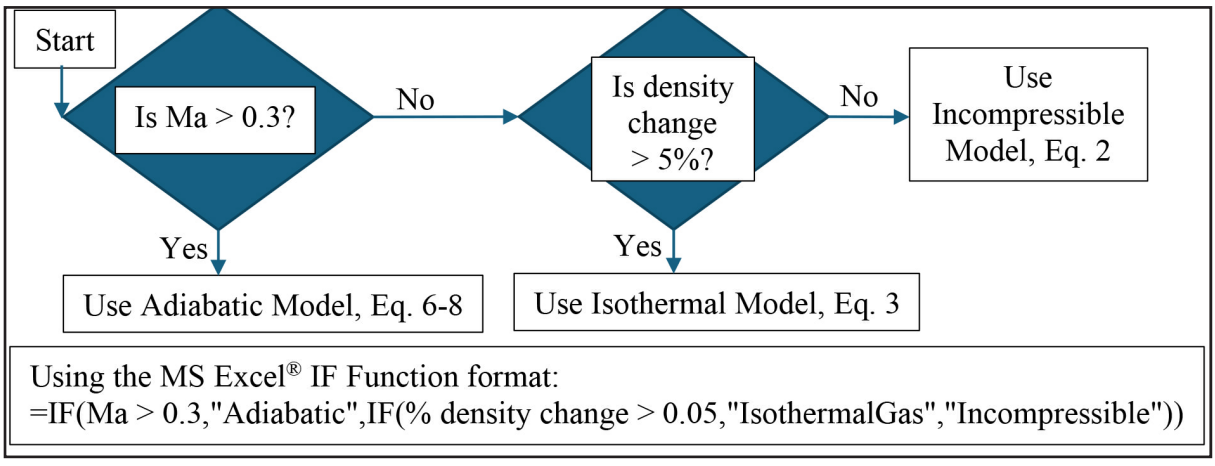


Figure 3. *An algorithm for determining if the best flow model is Incompressible, Isothermal, or Adiabatic. Shown in both Microsoft Excel equation and flow diagram formats.*

EXAMPLES OF EXPERIMENTAL ASSIGNMENT

Consider the three variables: molar flow rate, Q; entrance pressure, P_{in}; and exit pressure, P_{out}. For a given piping system and system temperature, that is not in choke flow conditions, two variables are independent.

For an experimental setup with a PID controller on the exit pressure, we suggest that the students use Q and P_{out} as the independent variables and calculate/measure P_{in}. This allows the PID controller to control the exit metering valve in Figure 1 as a student adjusts the entrance needle valve to obtain a specified set of molar flow rates. This would also allow pre-experiment calculation of the maximum Mach number since this is set by the exit conditions for compressible flows.

Alternatively, the students could set the P_{in} condition manually and measure P_{out}. This is the method we used for the initial beta-testing of the experiment in an undergraduate unit operations laboratory. As illustrated by the data presented in the next section, it was difficult for the students to maintain the pre-specified Q or P_{in} when trying to set other variables. This is why we recommend a PID controller.

Beta-Test Assignment

The following were the required deliverables for the students working on the beta-module and prototype equipment:

1. Pre-laboratory memo report (one to two pages) on modeling pressure drop in confined fluid flow (i.e., pipe flow) for incompressible, isothermal, and adiabatic gas systems. Include criteria for when the flow transitions from one system to another (i.e., isothermal vs. adiabatic). In your literature search for this memo report, you can use any source for the incompressible systems. For the compressible flow systems, consider textbooks by authors such as McCabe, Smith and Harriott.
2. For compressible fluid experiments with identical gas flow (≈ 5 SLPM) and an entering pressure of -100 mmHg (660 mmHg-abs), write a memorandum report that contains the following for each tube level:
    a. Actual gas molar flow rates (in SLPM)
    b. Absolute pressures in the Entrance Header and Exit Manifold
    c. Entering air temperatures
    d. Entering and exiting:
        i. Velocities in the tubes (m/s)
        ii. Speed of sound in the tubes (m/s)
        iii. Mach numbers in the tubes
    e. Best model for calculating pressure drops (Incompressible, Isothermal, or Adiabatic)
    f. Comparison of your measured pressure drops with those predicted by theory
    g. Comment on the impact of pipe diameter on compressible fluid dynamics
3. Create a spreadsheet/VBA program with the following features:
    a. Coding for evaluating incompressible gas flow data
    b. Coding for evaluating isothermal gas flow conditions
    c. Algorithm and coding to determine the appropriate model (incompressible, isothermal, or adiabatic) for the entered gas flow conditions with a text response
    d. Coding for comparing isothermal vs. incompressible results
    e. GUIs for activating program macros after the entry of known flow conditions
    f. Extra credit for other good programming elements; such as, drop down menus, changing cell references from alpha-numeric to variable names, etc.
4. Using error propagation, calculate the percent and absolute errors in the Mach numbers for the largest and the smallest diameter pipes at your highest gas flow rate.

The post-course interviews with the students included an evaluation of the self-learning elements of the experimental module; specifically, the first deliverable of a memo report on modeling fluid pressure drops. A representative response from the students for this line of questioning was "*I Googled a lot*." From the instructors' perspective, the students did self-learn about compressible flow. We did note a tendency for "Googling" to take some students to research journals, on-line calculators, lecture notes, and other secondary sources. This is why the problem statement for the first deliverable above implies that the literature search should start (and maybe end) with an established textbook to obtain the basic knowledge before "Googling."

Summary of Experimental Data and Calculations for Two Teams

Note, the beta-test equipment used tube lengths of 0.5 ft (0.15 m) instead of the 1 ft (0.30 m) recommended in Figure 1. There are significant differences between the experimentally measured and modelled pressure drops reported below. The precision of the pressure gages and rotameter combined with calculation error propagation accounts for some of these differences. However, the prototype nature of the beta-test equipment could have added flow resistances/issues not accounted for in the models. For example, the actual tube gas velocities could be greater than modeled because of unequal flow distribution between the tubes.

Team A: This team used a form of the target function that "did not converge completely" during "Goal Seek," resulting in a 30% lower calculated ΔP than the corrected calculations that appear in Table 4. This team did achieve a P_{in} (mmHg-abs) of 652 ± 19 and Q(SLPM) of 4.0 ± 0.3. Team A concluded that even with identical total cross-sectional areas, similar molar flow rates would have a higher pressure drop in a tube system with smaller tube diameters.

Team B: This team did achieve a P_{in}(mmHg-abs) of 677 ± 15 and Q(SLPM) of 4.8 ± 0.3 (Table 5). Team B noted the transition from incompressible to compressible flow conditions is a function of the tube system diameter for systems with similar mass flow velocities (i.e., G or Q/Area where Area = total cross-sectional area). Team B's spreadsheet/VBA coding did converge and forms the core of the spreadsheet/VBA program shown in Figure 4 and the Appendix.

EXCEL PROGRAM ANALYSIS OF THE DATA

The analysis of the data generated by the students using Eq. 1 - 9 could be done in a spreadsheet environment using trial and error or an automated iterative solution function, such as Goal Seek in Microsoft Excel. Because multiple calculations are needed, the use of Goal Seek could become tedious unless the student writes a macro or, better yet, uses a GUI to activate a macro. Therefore, this module could help with the Programming Learning Outcomes (i.e., spreadsheet and VBA) of the course and/or the degree program by having the students create programs with some or all of the following elements:

- Formulas including the use of cell names in place of absolute addressing
- IF/THEN statements
- Nested IF/THEN statements
- Iterative solutions (i.e., Goal Seek)
- Recording Macros
- Assigning Macro to a GUI control
- Using user-defined drop-down menus

Figure 4 shows a completed Excel spreadsheet illustrating these outcomes. This isothermal model spreadsheet has five sections. In the upper left is the section of independent variable inputs, such as temperature, feed molar flowrate, exit manifold pressure, tube inner diameter (ID), tube length, and manifold pipe ID. The middle section on the left calculates needed system properties from the INPUTS using standard equations. The bottom section on the left is for inputting system constants and the calculation of the Loss Coefficients, K_c and K_e.

The bottom section on the right solves Eq. 3 and compares the result to the incompressible model, Eq. 2. Finally, the upper section on the right gives the results and two text functions indicating if a new Goal Seek run is needed and what is the proper flow model to use. Note, if the proper flow model is not isothermal, then the results in the upper right section are incorrect.

Appendix A contains some of the spreadsheet formulas for Figure 4 along with the VBA coding for the macros assigned to the two GUIs: "Calculate Delta-P" and "Calculate required flow for target pressures."

CONCLUDING REMARKS

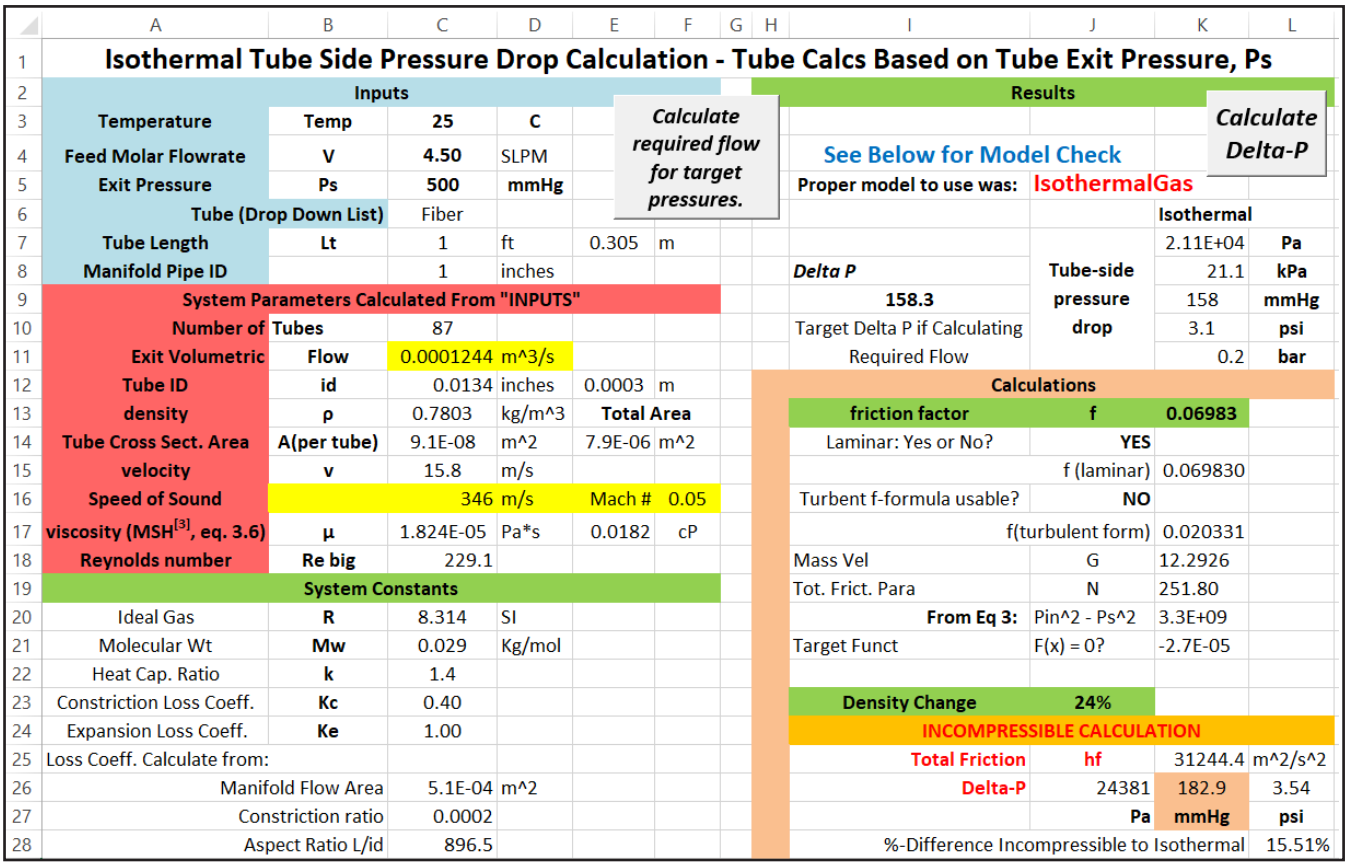
A compressible flow laboratory module is a counterbalance to numerous incompressible flow examples that appear in engineering curricula. We developed and beta-tested the compressible flow equipment discussed in this manuscript in order to increase the exposure of our graduates to appropriate gas flow models. Key advantages of the equipment

TABLE 4
Summary of Data and Calculations Produced by Team A

LEVEL	Q (SLPM)	P_{in} (mmHg)	P_{out} (mmHg)	% Δ-dens.	Ma in	Δ-Pres Obs'd	Δ-Pres Calc'd	Model Used
1/8" ID	3.95	633	633	0.2%	0.03	0	1.3	Incompressible
1/16" ID	3.7	652	645.7	0.5%	0.03	6.35	3.2	Incompressible
Fiber	4.4	671	506	9.6%	0.04	165.1	71.5	Isothermal

TABLE 5
Summary of Data and Calculations Produced by Team B

LEVEL	Q (SLPM)	P_{in} (mmHg)	P_{out} (mmHg)	% Δ-dens.	Ma in	Δ-Pres Obs'd	Δ-Pres Calc'd	Model Used
1/8" ID	4.94	669	656	0.3%	0.04	13	2.3	Incompressible
1/16" ID	4.94	695	669	0.6%	0.04	25	4.2	Incompressible
Fiber	4.39	669	491	9.6%	0.03	178	70.7	Isothermal



	A	B	C	D	E	F	G	H	I	J	K	L
1	**Isothermal Tube Side Pressure Drop Calculation - Tube Calcs Based on Tube Exit Pressure, Ps**											
2	**Inputs**								**Results**			
3	**Temperature**	**Temp**	**25**	**C**								
4	**Feed Molar Flowrate**	**V**	**4.50**	SLPM					See Below for Model Check			
5	**Exit Pressure**	**Ps**	**500**	**mmHg**					**Proper model to use was:**	**IsothermalGas**		
6	**Tube (Drop Down List)**		Fiber								**Isothermal**	
7	**Tube Length**	**Lt**	1	ft	0.305	m					2.11E+04	**Pa**
8	**Manifold Pipe ID**		1	inches					***Delta P***	**Tube-side**	21.1	**kPa**
9	**System Parameters Calculated From "INPUTS"**								**158.3**	**pressure**	158	**mmHg**
10	**Number of**	**Tubes**	87						Target Delta P if Calculating	**drop**	3.1	**psi**
11	**Exit Volumetric**	**Flow**	0.0001244	m^3/s					Required Flow		0.2	**bar**
12	**Tube ID**	**id**	0.0134	inches	0.0003	m			**Calculations**			
13	**density**	**ρ**	0.7803	kg/m^3	**Total Area**				**friction factor**	**f**	**0.06983**	
14	**Tube Cross Sect. Area**	**A(per tube)**	9.1E-08	m^2	7.9E-06	m^2			Laminar: Yes or No?	**YES**		
15	**velocity**	**v**	15.8	m/s						f (laminar)	0.069830	
16	**Speed of Sound**		346	m/s	Mach #	0.05			Turbent f-formula usable?	**NO**		
17	**viscosity (MSH[3], eq. 3.6)**	**μ**	1.824E-05	Pa*s	0.0182	cP				f(turbulent form)	0.020331	
18	**Reynolds number**	**Re big**	229.1						Mass Vel	G	12.2926	
19	**System Constants**								Tot. Frict. Para	N	251.80	
20	Ideal Gas	**R**	8.314	SI					**From Eq 3:**	Pin^2 - Ps^2	3.3E+09	
21	Molecular Wt	**Mw**	0.029	Kg/mol					Target Funct	F(x) = 0?	-2.7E-05	
22	Heat Cap. Ratio	**k**	1.4									
23	Constriction Loss Coeff.	**Kc**	0.40						**Density Change**	**24%**		
24	Expansion Loss Coeff.	**Ke**	1.00						**INCOMPRESSIBLE CALCULATION**			
25	Loss Coeff. Calculate from:								**Total Friction**	**hf**	31244.4	m^2/s^2
26	Manifold Flow Area		5.1E-04	m^2					**Delta-P**	24381	182.9	3.54
27	Constriction ratio		0.0002							**Pa**	**mmHg**	**psi**
28	Aspect Ratio L/id		896.5						%-Difference Incompressible to Isothermal			15.51%

Calculate required flow for target pressures.

Calculate Delta-P

Figure 4. *Spreadsheet for the isothermal model with incompressible model comparison.*

are its ease of construction and the lower safety concerns of using vacuum instead of compressed gases.

The compressible flow laboratory module can also be a vehicle to enhance other program/curriculum objectives, such as spreadsheet programming and self-learning. In the case of self-learning, we found that some students need guidance to begin the literature review by first learning the basics from a reference/textbook before "Googling" the latest research papers. We also learned of several misconceptions that students have about flow systems via student interviews. From these interviews, we compiled the following concept questions for future students to consider during or after working through the module:

1. For a tube with equal exit and entrance cross-sectional areas, is the exit velocity equal to the entrance velocity?
2. In tube bundles, does decreasing the tube diameters, while keeping the total cross-sectional area constant, increase or decrease the pressure drop through the tubes?
3. At constant mass flow, does decreasing the operating pressure, increase or decrease the pressure drop through tubes?
4. At constant mass flow, does decreasing pressure have an impact on Reynolds (Re)?
5. In tube bundles, does decreasing the tube diameters, while keeping the total cross-sectional area constant, decrease Re?
6. How is the Reynolds number for a tube bundle calculated?

REFERENCES

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Appendix A: Formulas and VBA Coding for the Excel Isothermal Model of Figure 4

While those schooled-in-the-art of spreadsheet programming can reconstruct the coding in the cells of Figure 4, the following are the less apparent codes; such as, If/Then statements:

TABLE A1
Formulas for the Excel Isothermal Model of Figure 4

Cell Address	Coding
C6	Drop down menu with the following choices that match the text strings in the coding of cells C10 and C12: Fiber, 1/16 in, or 1/8 in.
C10	=IF(C6=”Fiber”,87,IF(C6=”1/16 in”,4,1))
C12	=IF(C6=”Fiber”,340/1000/25.4,IF(C6=”1/16 in”,1/16,IF(C6=”1/8 in”,1/8,1/4)))
I4	**=IF(ABS(K21) < 0.0001, “See Below for Model Check”,”Need to Run a Calculation”)**
J5	**=IF(F16 > 0.3,”Adiabatic”,IF(J23 > 0.05,”IsothermalGas”,”Incompressible”))**
K13	=IF(Re_big<2100,K15,K17)
J14	=IF(C18<2100,”YES”,”NO”)
K15	=16/Re_big
J16	=IF(Re_big<2100, “NO”,IF(Re_big<100000,”YES”,”NO”))
K17	=0.0791/(Re_big^0.25)
K21	=K20*(760/101325)^2 - ((Ps+Delta_P)^2 -Ps^2)

VBA Coding For Macros Activated by GUIs

```
Sub CalcDeltaPIsothermal()
'
' CalcDeltaPIsothermal Macro
' Calculates the pressure drop for a given info entered in the isothermal model
'
' Keyboard Shortcut: Ctrl+Shift+Q
'
        Range("K21").Select
        Range("K21").GoalSeek Goal:=0, ChangingCell:=Range("I9")
End Sub

Sub FlowIsothermal()
"
FlowIsothermal Macro
' Calculated a required flow rate for a given delta-P
'
        Range("K21").Select
        Range("K21").GoalSeek Goal:=0, ChangingCell:=Range("C4")
End Sub
```