

# 26

## **Term Projects (6): Fluid Flow**

- 26.1 Pressure Drop – Velocity – Mesh Size Correlation
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## Term Project 26.1

### Pressure Drop – Velocity – Mesh Size Correlation

Figure 26.1 below provides information on pressure drop variation with velocity for different mesh-sized particles [1–4]. Using any suitable statistical technique [5], convert Figure 26.1 into equation form.

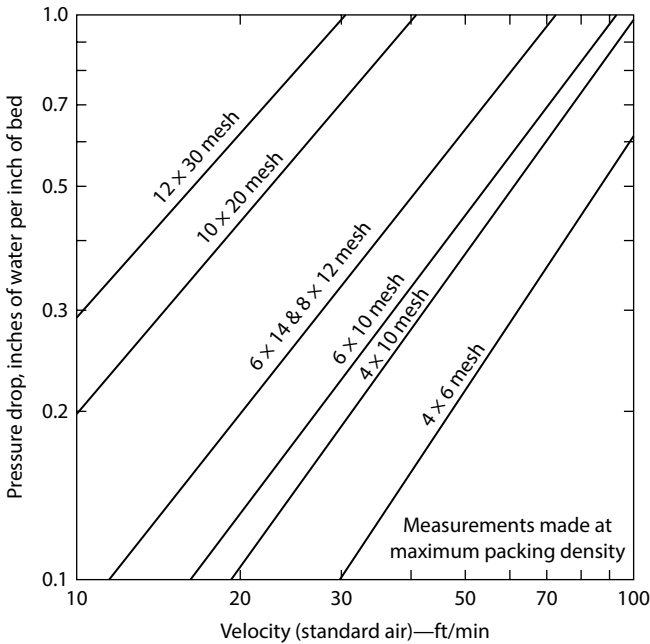


Figure 26.1 Pressure drop – mesh size graph

## Term Project 26.2

### Fanning’s Friction Factor: Equation Form

The effect of the Reynolds number on the Fanning friction factor is provided in Figure 26.2. In the turbulent regime, the “roughness” of the pipe becomes a consideration. In his original work on the friction factor, Moody [6] defined the term  $k$  as the roughness and the ration,  $k/D$ , as the relative roughness. Thus, for rough pipes/tubes in turbulent flow

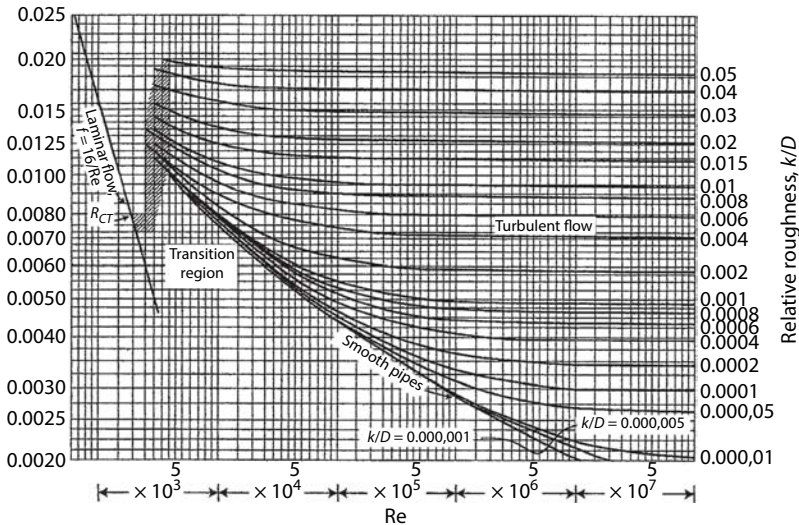


Figure 26.2 Fanning friction factor; pipe flow

$$f = f(Re, k/D) \tag{26.1}$$

This equation reads that the friction factor is a function of *both* the  $Re$  and  $k/D$ . However, as noted in chapter 5, the dependency on the Reynolds number is a weak one. Moody [6] provided one of the original friction factor charts. His data and results as applied to the Fanning friction factor, and as presented in Figure 26.2 also contains friction factor data for various relative roughness values.

The reader should note the following:

1. Moody’s original work included a plot of the Darcy (or Moody) friction factor, not the Fanning friction factor. His chart has been adjusted to provide the Fanning friction factor i.e., the plot in Figure 26.2 is for the Fanning friction factor. Those choosing to work with the Darcy friction factor need only multiply the Fanning friction factor  $f$  by 4, sin

$$f_D = 4f \tag{26.2}$$

2. The intermediate regime of  $Re$  between 2100 and 4000 is indicated by the shaded area in Figure 26.2.
3. The average “roughness” of commercial pipes is given in Table 26.1 [7,8].

4. Note in Figure 26.2 that the relative roughness lines are nearly horizontal in the fully turbulent regime to the right of the dashed lines.
5. Roughness is a function of a variety of effects—some of which are difficult, if not impossible, to quantify. In effect, the roughness of a pipe resembling a smooth sine wave exhibits different frictional effects than one resembling a sharp saw-tooth or step function.

In summary, for Reynolds numbers below 2100, the flow will always be laminar and the value of  $f$  should be taken from the line at the left in Figure 26.2. For Reynolds number above 4000, the flow will practically always be turbulent and the values of  $f$  should be read from the lines at the right. Between  $Re = 2100$  and  $Re = 4000$ , no accurate calculations can be made because it is generally impossible to predict flow type in this range. If an estimate of friction loss must be made in this range, it is recommended that the figures for turbulent flow should be used, as that provides an estimate on the high side [9].

Theodore [10] provides additional information.

Abulencia and Theodore [8] provide a number of models that have attempted to convert Figure 26.2 into equation form. This term project is

**Table 26.1** Average Roughness of Commercial Pipes

Material (new)	Roughness, $k$	
	ft	mm
Riveted steel	0.003 – 0.03	0.9 – 9.0
Concrete	0.001 – 0.01	0.3 – 3.0
Wood stove	0.0006 – 0.003	0.18 – 0.9
Cast iron	0.00085	0.26
Galvanized iron	0.0005	0.15
Asphalted cast iron	0.0004	0.12
Commercial steel (wrought iron)	0.00015	0.046
Drawn tubing	0.000005	0.0015
Glass	“smooth”	“smooth”

concerned with developing an improved model to describe Fanning's friction factor in terms of both the Reynolds number and the roughness factor.

## Term Project 26.3

### An Improved Pressure Drop and Flooding Correlation

Consider a packed column operating at a given liquid rate and the gas rate is then gradually increased. After a certain point, the gas rate is so high that the drag on the liquid is sufficient to keep the liquid from flowing freely down the column. Liquid begins to accumulate and tends to block the entire cross section for flow (a process referred to as *loading*). A further increase in the gas flow rate increases both the pressure drop and prevents the packing from mixing the gas and liquid effectively, and ultimately some liquid is even carried back up the column. This undesirable condition, known as *flooding*, occurs fairly abruptly and the superficial gas velocity at which it occurs is called the *flooding velocity*. The calculation of column diameter is usually based on flooding considerations, with the usual operating range being taken as 50 – 75% of the flooding rate.

One of the more commonly used flooding correlations is U.S. Stoneware's [11] generalized pressure drop correlation, as presented in Figure 26.3. The procedure to determine the column diameter is as follows: [12-14]

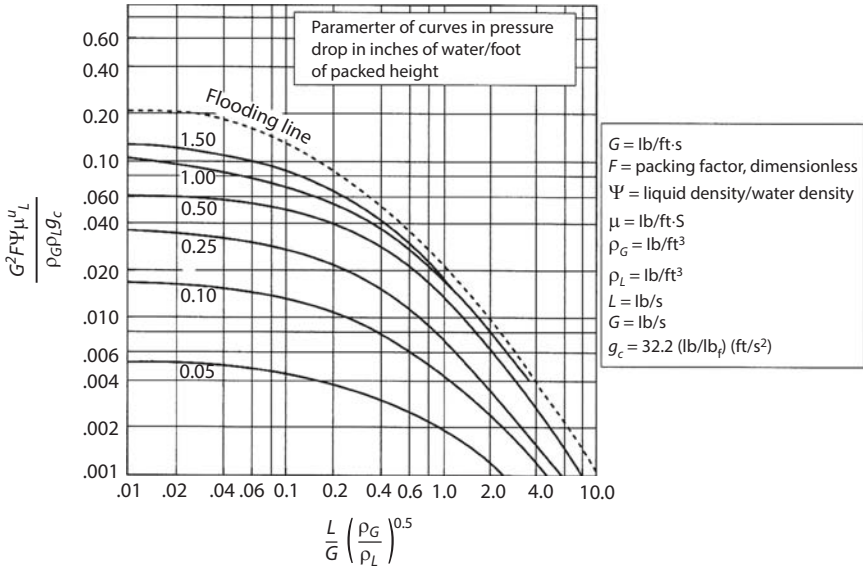
1. Calculate the abscissa,  $(L/G)(\rho_G/\rho_L)^{0.5}$ ; mass basis for all terms.
2. Proceed to the flooding line and read the ordinate (design parameter).
3. Solve the ordinate equation for  $G_f$  at flooding.
4. Calculate the column cross-sectional area,  $S$ , for the fraction of flooding velocity chosen for operation,  $f$ , by the equation:

$$S = \frac{W}{fG_f} \quad (26.3)$$

where  $W(\dot{m})$  is the mass flow rate of the gas in lb/s and  $S$  is the area in ft<sup>2</sup>.

5. The diameter of the column is then determined by

$$D = \left(\frac{4}{\pi} S\right)^{0.5} = 1.13S^{0.5}; \text{ft} \quad (26.4)$$



**Figure 26.3** Generalized pressure drop correlation to estimate column diameter

Note that the proper units, as designated in the correlation, must be used as the plot is not dimensionless. The flooding rate is usually evaluated using total flows of the phases at the bottom of the column where they are at their highest value.

- The pressure drop may be evaluated directly from Figure 26.3 using a revised ordinate that contains the actual, not flooding, value of  $G$  [14].

Chen [15] later developed the following equation from which the tower diameter can easily be obtained:

$$D = 16.28 \left( \frac{W}{\phi L} \right)^{0.5} \left( \frac{\rho_L}{\rho_G} \right)^{0.25} \tag{26.5}$$

where

$$\log_{10} \phi = 32.5496 - 4.1288 \log_{10} \left( \frac{L^2 A_v \mu_L^{0.2}}{\rho L^2 \epsilon^3} \right) \tag{26.6}$$

and (employing Chen's notation)  $A_v$  is the specific surface area of dry packing ( $\text{ft}^2/\text{ft}^3$  packed column),  $L$  is the liquid flux ( $\text{gal}/\text{min} \cdot \text{ft}^2$  of superficial

tower cross section),  $W$  is the mass rate of flow of gas (lb/h),  $\epsilon$  is the void fraction,  $\mu_L$  is the liquid viscosity (cP), and the density terms are in lb/ft<sup>3</sup>.

You have received the following assignment. Convert the U.S. Stoneware correlation for the flooding conditions and pressure drop into equation form. Use any suitable statistical technique [16,17] in solving the project.

## Term Project 26.4

### Ventilation Model I

Refer to Part II, Chapter 21, Illustrative Open-ended Problem 3.

Your consulting firm has received a contract from Theodore Industries (TI) to develop mathematical models describing the concentration of a chemical in a medium-sized ventilated laboratory room. The following information/data (SI units) all provided by TI:

$V$  = volume of room, m<sup>3</sup>

$q_0$  = volumetric flow rate of ventilation air, m<sup>3</sup>/min

$c_0$  = concentration of the chemical in ventilation air, gmol/m<sup>3</sup>

$c$  = concentration of the chemical leaving ventilated room, gmol/m<sup>3</sup>

$c_1$  = concentration of the chemical initially present in ventilated room, gmol/m<sup>3</sup>

$r$  = rate of disappearance of the chemical in the room due to reaction and/or other effects, gmol/m<sup>3</sup>·min.

Using the laboratory room as the control volume, one may apply the conservation law (see also chapter 3) for mass to the chemical [18-20], produced following the equation.

$$\frac{q_0}{V}(c_0 - c) + r = \frac{dc}{dt} \quad (26.7)$$

As noted earlier, the term  $V/q_0$  represents the average residence time that the chemicals reside in the room and is usually designated as  $\tau$ . The above equation may then be written as

$$\frac{dc}{dt} = \frac{c_0 - c}{\tau} - r \quad (26.8)$$

As an authority in the field, you have been requested to:

1. Obtain the equation describing the concentration in the room as a function of time if there are no "reaction" effects, i.e.  $r = 0$ .

2. Obtain the equation describing the concentration in the room as a function of time if  $r = -k$ . Note once again that the minus sign is carried since the chemical is disappearing.
3. Obtain the equation describing the concentration in the room as a function of time if  $r = -kc$ . Note once again that the minus sign is carried since the chemical is disappearing.
4. For Part 2, discuss the effect on the resultant equation if  $k$  is extremely small, i.e.,  $k \rightarrow 0$ .
5. Provide your comments on the validity of the above results.

## Term Project 26.5

### Ventilation Model II

Refer to the previous term project [21,22].

1. Qualitatively discuss the effect on the results if the volumetric flow rate,  $v_0$ , varies sinusoidally.
2. Qualitatively discuss the effect on the final equation if the inlet concentration,  $c_0$ , varies sinusoidally.
3. Discuss the effect on the results if both  $v_0$  and  $c_0$  vary sinusoidally.
4. Arbitrarily select a mode of variation for both  $v_0$  and  $c_0$ , and solve the problem
5. Present the results if both  $v_0$  and  $c_0$  are allowed to vary in an arbitrary manner.

## Term Project 26.6

### Two – Phase Flow

The simultaneous flow of two phases in pipes (as well as other conduits) is complicated by the fact that the action of gravity tends to cause settling and “slip” of the heavier phase with the result that the lighter phase flows at a different velocity in the pipe than does the heavier phase. The results of this phenomena are different depending on the classification of the two phases, the flow regime, and the inclination of the pipe (conduit).

As one might suppose, the major industrial application in this area is gas (G) – liquid (L) flow in pipes. The extension of much of this material to



flow in various conduits can be accomplished by employing the equivalent diameter [23,24] of the conduit in question.

The general subject of flashing and boiling liquids is also a consideration. However, when a saturated liquid flows in a pipeline from a given point at a given pressure to another point at a lower pressure, several processes can take place. As the pressure decreases, the saturation or boiling temperature decreases, leading to the evaporation of a portion of the liquid. The net result is that a one-phase flowing mixture is transformed into a two-phase mixture with a corresponding increase in frictional resistance in the pipe. Boiling liquids arise when liquids are vaporized in pipelines at approximately constant pressure. Alternatively, the flow of condensing vapors in pipes is complicated due to the properties of the mixture constantly changing with changes in pressure, temperature, and fraction condensed. Further, the condensate, which forms on the walls, requires energy in order to be transformed into spray, and this energy must be obtained from the main vapor steam, resulting in an additional pressure drop. Additional information is available in the literature [23].

The suggested method of calculating the pressure drop of gas – liquid mixtures flowing in pipes is essentially that originally proposed by Lockhart and Martinelli [25] nearly 60 years ago. The basis of their correlation is that the two-phase pressure drop is equal to the single-phase pressure drop for either phase (G or L) multiplied by a factor that is a function of the single-phase pressure drops of the two phases. That development was presented in Part II, Chapter 5, Illustrative Open-ended Problem 3. You have been requested to improve on the outdated method developed by Lockhart and Martinelli.

## References

1. L. Theodore and A. Buonicore, *Control of Gaseous Emissions*, USEPA/APTI, RTP, NC, 1982.
2. L. Theodore and J. Barden, *Mass Transfer Operations*, A Theodore Tutorial, Theodore Tutorials, East Williston, NY, originally published by the USEPA/APTI, RTP, NC, 1992.
3. S. Ergun, *Chem. Eng. Progr.* 48, 89, 1952; *Ind. Eng. Chem.*, New York City, NY, 41, 1179, 1949.
4. Union Carbide Corp., Linde division, Molecular Sieve Department, New York City, NY, Bulletin F-34.
5. S. Shaefer and L. Theodore, *Probability and Statistics Applications in Environmental Science*, CRC Press/ Taylor & Francis Group, Boca Raton, FL, 2007.

6. L. Moody, *Friction Factors for Dye Flow*, Trans. Am. Soc. Mech. Engrs., 66, 67 1-84, New York City, NY 1944.
7. I. Farag, *Fluid Flow*, A Theodore Tutorial, Theodore Tutorials, East Williston, NY, originally published by the USEPA/APTI, RTP, NC, 1996.
8. P. Abulencia and L. Theodore, *Fluid Flow for the Practicing Chemical Engineer*, John Wiley & Sons, Hoboken, NJ, 2009.
9. W. Badger and J. Banchero, *Introduction to Chemical Engineering*, McGraw-Hill, New York City, NY, 1955.
10. L. Theodore, *Chemical Engineering: The Essential Reference*, McGraw-Hill, New York City, NY, 2014.
11. Generalized Pressure Drop Correlation, Chart No. GR-109, Rev. 4, U.S. Stoneware Co., Akron, OH, 1963.
12. Personal notes: L. Theodore, East Williston, NY, 1979.
13. L. Theodore and J. Barden, *Mass Transfer Operations*, A Theodore Tutorial, Theodore Tutorials, East Williston, NY, originally published by the USEPA/APTI, RTP, NC, 1995.
14. Adapted from: L. Theodore and F. Ricci, *Mass Transfer Operations for the Practicing Engineer*, John Wiley & Sons, Hoboken, NJ, 2010.
15. N. Chen, *New Equation Gives Tower Diameter*, *Chem. Eng.*, New York City, NY, May 2, 1962.
16. S. Shaefer and L. Theodore, *Probability and Statistics Applications in Environmental Science*, CRC Press/ Taylor & Francis Group, Boca Raton, FL, 2007.
17. L. Theodore, *Chemical Engineering: The Essential Reference*, McGraw-Hill, New York City, NY, 2014.
18. L. Theodore, *Chemical Reaction Kinetics*, A Theodore Tutorial, Theodore Tutorials, East Williston, NY, originally published by the USEPA/APTI, RTP, NC, 1992.
19. J. Reynolds, J. Jeris, and L. Theodore, *Handbook of Chemical and Environmental Engineering Calculations*, John Wiley & Sons, Hoboken, NJ, 2004.
20. P. Abulencia and L. Theodore, *Fluid Flow for the Practicing Chemical Engineer*, John Wiley & Sons, Hoboken, NJ, 2008.
21. L. Theodore, *Chemical Reaction Kinetics*, A Theodore Tutorial, Theodore Tutorials, East Williston, NY, originally published by the USEPA/APTI, RTP, NC, 1992.
22. J. Reynolds, J. Jeris, and L. Theodore, *Handbook of Chemical and Environmental Engineering Calculations*, John Wiley & Sons, Hoboken, NJ, 2004.
23. P. Abulencia and L. Theodore, *Fluid Flow for the Practicing Chemical Engineer*, John Wiley & Sons, Hoboken, NJ, 2008.
24. L. Theodore, *Chemical Engineering: The Essential Reference*, McGraw-Hill, New York City, NY, 2014.
25. R. Lockhart and R. Martinelli, *Generalized Correlation of Two-Phase, Two-Component Flow Data*, *CEP*, New York City, NY, 45, 39-48, 1949.