2

Fluid Flow Fundamentals

Introduction

Fundamental to an investigation of the operation and attributes of the various flowmeter technologies is a working knowledge of the physical properties used to describe liquids and gases, as well as a basic understanding of some of the physical phenomena associated with flow in pipes. These physical properties need only be studied in a practical sense in order to understand the operation and limitations of various flowmeter technologies.

Units commonly used to describe physical properties of fluids are generally a combination of the English system, the SI system, and other unique systems often common only to particular industries. Vendor technical data on flow ranges, size, and the like, are typically expressed using the English system unless the manufacturer distributes the same literature in international markets, in which case SI information is also available. If the flow range is sufficiently small, it is often expressed in SI units, although the remainder of the data will probably be in the English system. A hybrid but commonly used system of units is used throughout this text so that a clear picture of the subject matter can be maintained in the discussions that ensue.

Temperature

For the purpose of describing flow measurement, it is sufficient to state that temperature is a measure of relative hotness or coldness. In the SI system, temperature is expressed in degrees Celsius (°C) with 0°C and 100°C corresponding to the freezing and boiling points of water, respectively. At times, the absolute temperature, that is, the temperature referenced to lowest theoretical temperature, is required. Absolute temperature is measured in kelvins (K) and can be calculated by adding 273.15 to the temperature in degrees Celsius. The English equivalents are degrees Fahrenheit (°F), where 32°F and 212°F represent the freezing and boiling points of water, respectively, and degrees Rankine (°R) for expressing absolute temperature.

The following equations may be useful in converting units of temperature.

$$°C = \frac{5(°F - 32)}{9}$$

$$K = °C + 273.15$$

$$°R = °F + 460$$

EXAMPLE 2-1

Problem: Convert 320°F to kelvins.

Solution: Convert to degrees Celsius and then to kelvins as follows:

°C = 5 (320 – 32) / 9 = 160°C

K = 160 + 273

= 433 K

EXAMPLE 2-2

Problem: Convert 233°K to degrees Fahrenheit.

Solution: Convert to degrees Celsius and then to degrees Fahrenheit as follows:

°C = 233 – 273 = –40°C

°F = (9 x –40 / 5) + 32

= –40°F

Pressure

Pressure is defined as the ratio of a force divided by the area over which it is exerted.

$$P = \frac{F}{A}$$

The commonly used English units to express pressure are pounds per square inch (psi). If pressure is referenced to atmospheric pressure, it is termed gage pressure. If it is referenced to a perfect vacuum, it is termed absolute pressure. To convert from gage to absolute units, atmospheric pressure is simply added to the gage pressure (see Figure 2-1).

The following conversions may be useful to convert units of pressure.

- 1 "standard" atmosphere (atm) = 14.696 psi = 1013.25 mbar
- 1 inch of mercury (in. Hg) = 0.491154 psi
- 1 inch of water (in. WC) = 0.03609 psi
- 1 kilogram per square centimeter (kg/cm^2) = 14.2233 psi
- 1 bar = 14.5038 psi
- 1 kilopascal (kPa) = 0.145038 psi

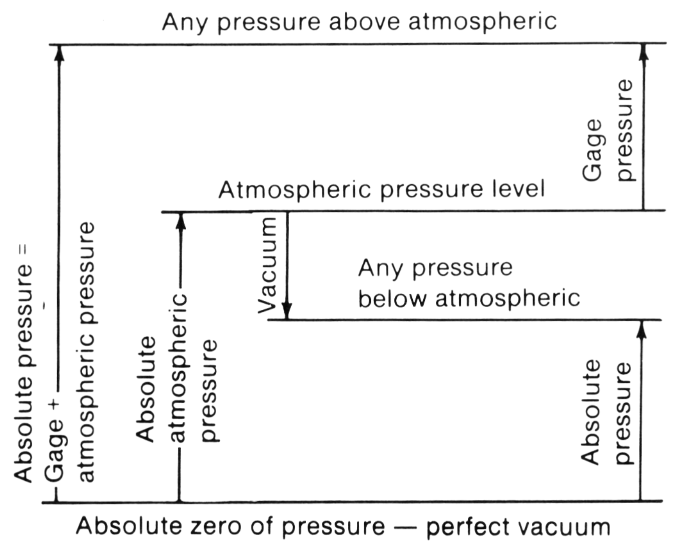

Figure 2-1. Relationships between gage and absolute pressures.

EXAMPLE 2-3

Problem: Determine the pressure exerted under a 2-inch cube weighing 5 pounds placed on a table.

Solution:

$$P = \frac{F}{A} = \frac{5 \text{ lb}}{4 \text{ in.}^2} = 1.25 \text{ psi}$$

If a 0.1-inch diamter metal rod were pushed into the table with a force of 5 pounds, the pressure exerted under the rod would be considerably higher than the above, as follows:

$$P = \frac{F}{A} = \frac{5 \text{ lb}}{\pi \times 0.01 \text{ in.}^2/4} = 636 \text{ psi}$$

EXAMPLE 2-4

Problem: Convert 3 kg/cm^2 to psia.

Solution: Convert the pressure to psig and then to psia as follows:

3 kg/cm^2 × (14.2233 psig / kg / cm^2) = 42.67 psig

42.67 + 14.696 = 57.366 psia

EXAMPLE 2-5

Problem: Convert 100 feet of water column (WC) to psig.

Solution:

100 feet WC × (12 inches/foot) = 1200 inches WC

1200 inches WC × (0.03609 psi/inch WC) = 43.308 psig

The result of dividing 100 feet of water column by 43.308 psig is a useful conversion factor of 2.31 feet of water column, which is equivalent to 1 psi. As a rule of thumb, 2 feet of water per psi can be used for rough calculations.

EXAMPLE 2-6

Problem: Calculate the dynamic head produced by a fan with 7-inch WC vacuum and 1-inch WC pressure on the inlet and outlet of the fan, respectively.

Solution: (+1 in. WC) – (–7 in. WC) = +8 in. WC

Density

The density of a fluid at given operating conditions is its mass per unit volume.

$$\rho = \frac{m}{V}$$

In the English system, density is expressed in pound mass per cubic foot (lb/ft^3), while common SI units are grams per cubic centimeter (g/cm^3).

The following conversion may be useful to convert units of density at 60°F.

$$1\ lb/ft^3 = 0.0160262\ g/cm^3$$

EXAMPLE 2-7

Problem: What is the density of a liquid in g/cm^3, 100 pounds of which at 60°F occupies 1.53 cubic feet of a 2.04 cubic foot container?

Solution:

$$\rho = m\ /\ V = 100\ lb/1.53\ ft^3 = 65.359\ lb/ft^3$$
$$= 65.359\ lb/ft^3 \times 0.0160262\ g/cm^3\ /\ 1\ lb/ft^3$$
$$= 1.0475\ g/cm^3$$

EXAMPLE 2-8

Problem: A 3.2 cubic foot air cylinder at 68°F is measured to be 28.2 pounds completely empty and 32.4 pounds after filling. Determine the density of the air before and after filling.

Solution: When the cylinder is empty and open to atmosphere, the density of air is 0.07528 lb/ft^3. The mass of air in the cylinder before filling is

$$3.2 \text{ ft}^3 \times 0.07528 \text{ lb/ft}^3 = 0.24 \text{ lb}$$

And the amount added during filling is

$$32.4 - 28.2 = 4.2 \text{ lb}$$

The total mass in the cylinder after filling is the sum of the mass of the air in the cylinder before filling and the air added to the cylinder, such that

$$\rho = m / V = (0.24 \text{ lb} + 4.2 \text{ lb})/3.2 \text{ ft}^3$$

$$= 1.39 \text{ lb/ft}^3$$

Expansion of Liquids

The density of a liquid will vary with both operating pressure and operating temperature. Since most liquids are nearly incompressible, the effects of pressure are often negligible and can be readily ignored. The effects of temperature on density are small compared to gases and except when the operating temperature is significantly different from the temperature at which density measurements are available or when a high degree of accuracy is desired. Volumetric expansion, which affects the density of the liquid, can be expressed as

$$V = V_0(1 + \beta[\Delta t])$$

where β is the cubical coefficient of expansion of the liquid that is consistent with the temperature units used.

Expansion of Solids

Expansion in solids is described by the same equation as for liquids using the following relation:

$$\beta = 3 \times \alpha$$

where α is the coefficient of linear expansion of the solid.

EXAMPLE 2-9

Problem: What will be the change in the density of a liquid due to a 10°C temperature rise if the liquid has a cubical expansion factor of 0.9×10^{-3} per degree Celsius?

Solution:

$$V = V_0(1 + [0.9 \times 10^{-3}/°C] \times [10°C])$$

$$= 1.009\ V_0$$

As the mass is the same before and after the temperature rise, the change in density is inversely proportional to the change in volume and can be expressed as

$$\rho/\rho_0 = V_0/V$$

$$= (1.009)^{-1}$$

$$= 0.991$$

Therefore, the net decrease in density is 0.9 percent.

Most flowmeters are affected by changes in the area of the flowmeter through which the fluid passes. Due to the cubical coefficient of expansion, materials from which a flowmeter is constructed will expand and contract with varying temperature. Therefore, the effective area through which the fluid passes can vary with temperature, although usually in a predictable manner.

The flowmeter can be scaled to correct the measurement for the nominal operating temperature in order to reduce error. This is usually sufficient to correct the majority of applications, but when the operating temperature varies significantly from the nominal temperature, compensation may be required.

EXAMPLE 2-10

Problem: Calculate the correction required when operating a flowmeter with a temperature coefficient of 0.3%/100°F, at a nominal temperature of 165°F.

Solution: Assuming a 75°F reference temperature, the correction is:

$$\text{Correction} = (165°F - 75°F) \times 0.3\%/100°F$$

$$= 0.27\%$$

Expansion of Gases

Boyle's Law

The density of a gas will vary significantly with *absolute* pressure, and variations of more than a few percent typically cannot be ignored. Increasing the pressure of a gas at constant temperature causes the gas to be compressed. This decreases the volume the gas occupies, thereby increasing the density of the gas, as the same mass occupies a smaller volume. Boyle's Law states that for any ideal gas or mixture of ideal gases at constant temperature, the volume is inversely proportional to the absolute pressure.

$$V = \frac{\text{constant}}{P}$$

Boyle's Law can be stated in the following form, which is more useful in comparing the volumes of an ideal gas at constant temperature and at different pressures:

$$\frac{V}{V_0} = \frac{P_0}{P}$$

EXAMPLE 2-11

Problem: How is the volume of an ideal gas at constant temperature and a pressure of 28 psig affected by a 5-psig increase in pressure?

Solution:

$$\frac{V}{V_0} = \frac{P_0}{P} = \frac{(28 + 14.7)}{(28 + 5 + 14.7)} = 0.895$$

Therefore, there is a 10.5 percent decrease in volume.

Charles' Law

The density of a gas will vary significantly with *absolute* temperature, and variations of more than a few percent typically cannot be ignored. Increasing the temperature of a gas at constant pressure causes the gas molecules to increase their activity and motion in relation to each other. This increased activity requires a larger volume in which to move, thereby decreasing the density of the gas, as the same mass now occupies a larger volume. Charles' Law states that for any ideal gas or mixture of ideal gases at constant pressure, the volume is proportional to the absolute temperature.