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Fundamentals of Air System Design

Robert McDowall

SI

International System

A Course Book for
Self-Directed or Group Learning



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Robert McDowall is a professional engineer who has been involved in building services for over forty years and has taught courses on heating, ventilating, and air conditioning for thirty years. He has been responsible for the construction and maintenance of buildings for IBM and the University of Manitoba. An active member of ASHRAE, Robert served as a member of the board of directors from 1997–2000, as a member of the Standard 62 committee, and as author of the online courses *Fundamentals of HVAC Systems* (with course book) and *Fundamentals of HVAC Control Systems*.

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Preface

Fundamentals of Air System Design SI is an introductory guide to designing systems for the transfer of air in buildings and is intended for an audience of professional engineers or engineering students.

For this SI version, standards and guidelines have been updated, damper information has been revised based on research project information, and Chapter 10, "Sound and Vibrations in Air Systems," has been completely rewritten.

The course begins with a presentation of airflow fundamentals and then proceeds to an overview of various system components that may be included, such as fans, filters, and coils. Human comfort and the sizing and location of air supply outlets are addressed to enable the designer to develop a system for effective thermal, ventilation, and comfort control. Methods of duct sizing are discussed, and detailed design calculations are demonstrated using the constant-pressure-drop method. Design issues for sound and vibration control are introduced, followed by a discussion of the main industry standards governing air systems. Finally, a system design is presented in a step-by-step format that allows the reader to make design decisions and calculations and then check them against those provided in the text.

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Robert McDowall
Winnipeg, MB

December 6, 2010

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Fundamentals of Air System Design

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Fundamentals of Airflow

Study Objectives

After completing this chapter, you should be able to

- ❑ explain *static pressure*, *velocity pressure*, and *total pressure* and the relationship between them;
- ❑ calculate change in volume of air with change in temperature at constant pressure;
- ❑ calculate the approximate volume and temperature resulting from mixing airstreams;
- ❑ sketch and explain the psychrometric chart parameters of *temperature*, *moisture*, *relative humidity*, and *specific volume*; and
- ❑ explain duct frictional losses.

Instructions

Read the material in Chapter 1. Verify the examples presented in the chapter with your own calculations. At the end of the chapter, complete the skill development exercises without referring to the text. Review those sections of the chapter as needed to complete the exercises.

Static and Dynamic Compressible Fluid (Air) Laws

Because this course is designed to address the needs of people with varying backgrounds and experience, it is necessary to review the fundamental principles of fluid mechanics. Your understanding of these principles is essential to learning the applied system design concepts that follow in later chapters. The concepts are presented in the context of heating, ventilating, and air-conditioning (HVAC) applications, and terms are defined as they are used in that field.

This course makes use of three of the four basic principles of fluid mechanics:

- Fluid statics
- The Continuity Equation
- The Energy Equation

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Difference between Mass and Weight

A fundamental and often confused point must be addressed here: the difference between mass and weight. Mass is a property of matter that is invariant with location. For example, the mass of the astronauts remained essentially the same during their trip to and landing on the moon. However, their weight changed dramatically. The relationship of mass to weight is given by Newton's Law of Motion:

$$Force \propto Mass \times Acceleration$$

In the context of this course, the *force* is the weight required to hold up the matter (that is, to keep it from falling), and the *acceleration* is the acceleration due to gravity. This acceleration due to gravity, g, is virtually constant at sea level on Earth at 9.81 m/s^2. Note that the law is stated as a proportionality, so we must insert a *proportionality constant* to make it an operationally useful equation.

The symbol for the proportionality constant that has been in use for generations is $1/g_c$. This is unfortunate because of its similarity with the symbol for acceleration due to gravity, g. The proportionality constant g_c is actually used to convert the units of mass × acceleration to units of force. In the system currently used extensively in the HVAC industry, the value of g_c is 9.81 $kg_m \cdot m/kg_f \cdot s^2$. The reason for this choice is that the weight of a kilogram mass (kg_m) is numerically equal to a kilogram force (kg_f) at sea level. A kilogram force is equal to 9.81 newtons, the basic SI unit of force. A newton (N) is the force required to give a mass of one kilogram an acceleration of one metre per second squared.

Two important rules result from this:

- Mass and weight are inherently different but related, and kilogram-mass (kg_m) is completely different from kilogram-force (kg_f).
- The symbol g_c is a units conversion factor.

As a thermodynamic property, *density* is the ratio of mass to volume. It has the units of kg_m/m^3 and is denoted by the symbol ρ (lower case Greek letter *rho*). At times, it is convenient to express the density as weight density, γ, (the lower case Greek letter *gamma*), and by this we mean the force of gravity on a unit volume of mass. The conversion is accomplished by multiplying by g (the acceleration due to gravity) and by taking into account the need for units conversion with the constant g_c.

Thus, $\gamma = \rho g/g_c$. The units of γ are

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$$\frac{\rho\left(\frac{\mathrm{kg}_m}{\mathrm{m}^3}\right)g\left(\frac{\mathrm{m}}{\mathrm{s}^2}\right)}{g_c\left(\frac{\mathrm{kg}_m}{\mathrm{kg}_f}\right)\left(\frac{\mathrm{m}}{\mathrm{s}^2}\right)} = \frac{\mathrm{kg}_f}{\mathrm{m}^3}$$

Also, numerically $g/g_c = 1$, because both have the value 9.81.

Specific volume is the reciprocal of density and is defined as the volume of a unit mass of material. It is expressed in cubic meters per kilogram: $v = \mathrm{m}^3/\mathrm{kg}_m$.

Fluid Statics

Hydrostatic pressure is something we all experience in a swimming pool; recall how the pressure on your eardrums increases as you dive deeper in the pool. The pressure is due to two factors:

- Atmospheric air pressure on the surface of the water
- The weight of a column of water equal to the depth below the surface

Imagine a column of water as shown in Figure 1-1. The weight is equal to the volume times the weight density, $W = \gamma hA$. The force required to hold the column of fluid plus oppose the pressure of the atmosphere is $W + p_a$. The force, F, is also the pressure at the point of application of force, F, times the area. In equilibrium, we write

$$F = pA = p_aA + W = p_aA + \gamma hA$$

Therefore, $p = p_a + \gamma h$.

The pressure difference between A and B in Figure 1-1 is

$$\Delta p = \gamma \Delta h \qquad \textbf{(1-1)}$$

Note that the density is the *weight* density, $\gamma = (g/g_c)\rho$.

The Continuity Equation

The Continuity Equation expresses the idea that all mass is accounted for; none is lost or created. Mass that enters a space also leaves the space, provided no change in the stored amount occurs. Filling a tank, or releasing gas from a compressed gas bottle, obviously are cases where stored mass changes. However, when air flows through a duct, or into and out of a fan, the amount of air flowing per unit time is the same at the inlet as at the outlet. Figure 1-2 depicts such a situation.

The volume of air that passes through a cross section of the duct is given as VA, where V is the velocity and A is the area. Rationalize this by imagining that

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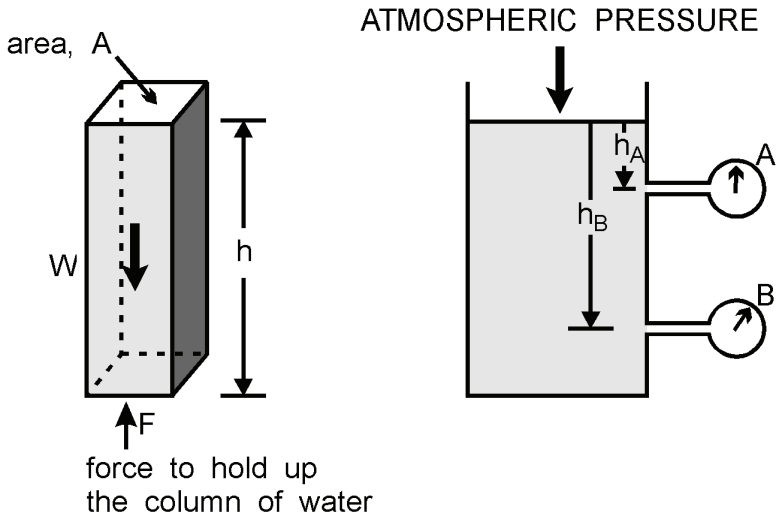


Figure 1-1 Fluid static system.

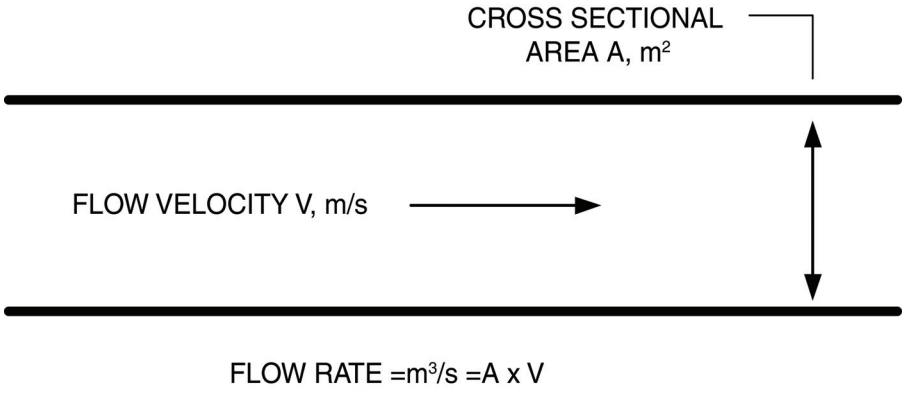


Figure 1-2 Continuity equation.

the flow rate would double if the area doubles or if the velocity doubles. The mass associated with a unit of volume is the density, ρ. Therefore, the mass flow rate is given by ρAV.

The conservation of mass idea states that no change in mass flow rate occurs under steady conditions when there is no storage change. Considering two locations, 1 and 2, on the same duct, we can write

$$(\rho AV)_1 = (\rho AV)_2$$

Under normal conditions in a short length of duct with no heating or cooling coils, the pressure and temperature changes are so small that the density is virtually constant. The Continuity Equation can then be written as

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$$(AV)_1 = (AV)_2 \quad \textbf{(1-2)}$$

In the HVAC industry, flow rate almost invariably means *volume flow rate*, not mass flow rate. The most common units are cubic meters per second, m^3/s, and liters per second, L/s.

Air behaves as a perfect gas, and the change in density is proportional to the absolute temperature. Absolute temperature in kelvins (K) is the temperature above absolute zero, which is –273°C. To convert from degrees Celsius to kelvins, add 273°. Thus if outdoor air is heated from 2°C to 22°C as it comes in through the air-conditioning system, the density, γ, changes from γ_2 to

$$\gamma_2 \times \frac{2 + 273}{22 + 273} = \gamma_2 \times 0.932$$

which is a 6.7% decrease in density.

Similarly, on a hot day, cooling 40°C outdoor air down to 13°C will increase the density by

$$\frac{40 + 273}{13 + 273} = 1.094 \text{ or } 9.4\%$$

The difference is even more significant in a cold climate. For example, suppose it is January and the outside temperature is –35°C. The outdoor air is brought in over a heating coil and supplied at 24°C. The drop in density as the air is heated is from γ_{-35} to

$$\gamma_{-35} \times \frac{-35 + 273}{24 + 273} = \gamma_{-35} \times 0.801$$

This means that the air will be approximately 20% less dense. Being 20% less dense, the air occupies 20% more space at our constant pressure. Thus 1000 L/s at –35°C when heated to 24°C becomes 1248 L/s at 24°C.

The mass of air stays the same. However, with rising temperature, the volume increases as density drops. Remember, this is in the normal commercial and institutional HVAC system with very small pressure changes.

A very common process in air conditioning is mixing airstreams. Suppose we have a situation where 11,000 L/s of air at 24°C from a space is being mixed with 3000 L/s of outdoor air at 5°C. We want to know what the resulting mixed-air temperature and volume will be. The industry practice, which works well for estimating and small temperature differences, is to assume that the volume, L/s, is equivalent to mass and use Equation 1-3:

$$(L_1/s \times T_1) + (L_2/s \times T_2) = [(L_1/s + L_2/s) \times T_m] \quad \textbf{(1-3)}$$

For example, based on Equation 1-3, the resulting volume is

$$11,000 + 3000 = 14,000 \text{ L/s}$$

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$$(11,000 \times 24) + (3000 \times 5) = [(11,000 + 3000) \times T_m]$$

T_m = 19.9°C, which is very close to the correct answer of 19.7°C.

For wide temperature differences, the inaccuracy can be almost eliminated by adjusting the incoming L/s values to be the L/s at the initially calculated mixed temperature and recalculating the mixed temperature using the adjusted flow values.

The Energy Equation (First Law of Thermodynamics)

The third principle we will use in this course is the Energy Equation, which is based on the idea that energy, like mass, is neither created nor destroyed. A major consequence of this idea is that the forms that energy takes are interchangeable; that one form can be converted into another. There is one caveat to this idea, based on the Second Law of Thermodynamics: heat cannot be completely converted into work in a cyclic process.

The units of the forms of energy are many and varied. Authors, industries, and nations all seem to have a unique set of preferences and biases. However, because most studies of energy begin with a definition of mechanical work (force × distance), it is appropriate to say that the fundamental unit of energy is force × distance, or newton-metre, also called a *joule* (J).

The joule is the energy equivalent of one amp flowing through one ohm for one second. One amp flowing through one ohm is a watt, so a watt per second is a joule. This unit is too small to be useful, so we normally talk about kilowatt hours. The kilowatt-hour (kWh) is the same energy as 1000 for 60 seconds × 60 minutes = 3,600,000 J, or 3.6 MJ.

It is common to write energy conversion in terms of a unit of mass flowing, for example, kWh/kg, MJ/kg. Whatever the units used, all values must be expressed in the same units when comparing or adding. Conversion factors are available in many texts and reference books, and you are expected to obtain and use conversion tables competently.

Following is a brief listing and discussion of the forms of energy:

- *Work* (*W)* results from a force applied through a distance in the direction of the force. It is also the result of a torque applied through an angular displacement. Work can be either internal or external. Machines such as pumps, fans, and compressors do mechanical work, W_m, on the fluid. Machines such as turbines produce mechanical work, W_m, performed by the fluid on an external machine, such as an electric generator. Fluid friction, W_f, can be considered to be work done by the fluid on the duct or obstruction in much the same way as aircraft engines do work to overcome air drag in a flying airplane. In the HVAC industry, frictional forces exist in ductwork as the air passes down a straight section, as it makes a turn, or as it passes through louvers or a heat exchanger. This work results in a loss of pressure that must always be compensated for by the fan.

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- *Flow work* (pv) is energy supplied to the system when fluid crosses the boundary entering the system. It is also done by the system as fluid leaves. Consider the situation where air discharges from a compressed air tank and makes room for itself in the atmosphere. The air pushes away the atmosphere. The air occupies space, and the atmosphere must make way for it by becoming a little bit higher, therefore increasing its own potential energy. Flow work is always present, even though the amount done on the system at the inlet may be very nearly equal to the amount done by the system at the outlet. Flow work is always given by the product of pressure and specific volume, pv, for one kilogram of fluid.
- *Heat* (Q) is the result of energy transfer due to a temperature difference. That heat can be transformed into work, and that work can be dissipated into internal energy and transferred as heat, constitute the main business of thermodynamics. Note that heat is not stored and it is not "contained" by a fluid. Heat is thermal energy in transit. It is defined only at the boundary of a system.
- *Internal energy* (u) is often confused with heat, but they are different concepts. Internal energy is associated with molecular motion, molecular bonding, and other forms of molecular activity, such as spinning or rotation of molecules. Internal energy can have units of kWh/kg or MJ/kg. In an ideal gas and a liquid, u is directly related to temperature. For example, a 1 kWh increase in internal energy is represented by a 86.1°C rise in temperature for 10 kg of water.
- *Potential energy* is energy that represents the work done on a mass in moving it in the Earth's gravitational field. For example, if a 1 kg_m book is elevated 1 m above a desk, work in the amount of 1 $m \cdot kg_f$ has been done on it. This work can be recovered by lowering the book and raising a mass someplace else through linkages or pulleys. Or the force of gravity will accelerate the book if it is allowed to drop, and the potential energy will be converted to kinetic energy associated with the velocity. Potential energy is always measured relative to some datum of zero elevation: $PE = (mg/g_c)z$, where z is measured relative to some assigned datum in the system.
- *Kinetic energy* results from motion. For example, an automobile traveling at 100 km/h has kinetic energy, as does a baseball thrown at 140 km/h. The kinetic energy is derived from a steady force applied through a distance required to accelerate the body from rest to a velocity V:

$$Kinetic\ Energy = mV^2/2\ J\ (m \text{ in kg}, V \text{ in m/s})$$

The Energy Equation is simply a balance of the forms of energy described above. It is assumed that the system is in steady state. If another form was found to be important (such as chemical energy in combustion), it could be added to the list. If one or more of the forms is not present or important, it can be dropped. If we include those discussed above, the Energy Equation is written as follows:

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$$W_m - W_f + Q + m\left[u + pv + \frac{g}{g_c}z + \frac{V^2}{2g_c}\right]_{in} = m\left[u + pv + \frac{g}{g_c}z + \frac{V^2}{2g_c}\right]_{out} \quad \textbf{(1-4)}$$

In air systems, the mass is that of flowing air; heat is added (or removed at a specified rate) and work is done at a certain rate, such as in 10 kW motor driving a fan. The Energy Equation can be turned into a Rate Equation by considering the following:

- Heat as a rate, kJ/h or kW; $\dot{Q}$
- Work as a rate, kW; $\dot{W}$
- Mass as a mass flow rate, kg/h; $\dot{m}$

A dot over the symbol commonly indicates a *rate*. In practice, always put the time in seconds, minutes, or hours to ensure consistent units. Although various units for the energy terms have been suggested above, the units for all terms in the equation must be the same:

$$\dot{W}_m - \dot{W}_f + \dot{Q} + \dot{m}\left[u + pv + \frac{g}{g_c}z + \frac{V^2}{2g_c}\right]_{in} = \dot{m}\left[u + pv + \frac{g}{g_c}z + \frac{V^2}{2g_c}\right]_{out} \quad \textbf{(1-5a)}$$

If this form of the Energy Equation is divided through by the mass flow rate, $\dot{m}$, the following form results, where heat and work are on a unit mass flowing basis:

$$W_m - W_f + q + \left[u + pv + \frac{g}{g_c}z + \frac{V^2}{2g_c}\right]_{in} = \left[u + pv + \frac{g}{g_c}z + \frac{V^2}{2g_c}\right]_{out} \quad \textbf{(1-5b)}$$

The terms of the Energy Equation are depicted in Figure 1-3.

Static Pressure, Velocity Pressure, and Total Pressure

Now let's discuss a run of ductwork with the following conditions:

- No machines exist, so all work terms are zero.
- No heat transfer exists, because the duct air is the same temperature as the surrounding air.
- There are no significant changes in elevation, so z is constant.
- The internal energy, u, is essentially constant.

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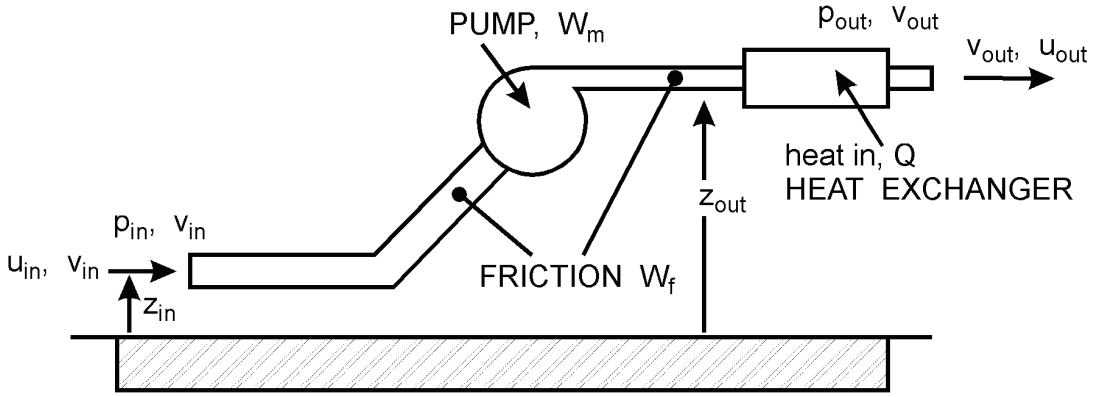


Figure 1-3 The energy equation applied to a flow system.

In this case, we have the simpler form of the Energy Equation:

$$\left[pv + \frac{V^2}{2g_c}\right]_{in} = \left[pv + \frac{V^2}{2g_c}\right]_{out} \tag{1-6a}$$

The above circumstances exist for a pitot tube, as shown in Figure 1-4, where the flow comes to zero velocity (where the arrow indicates *total pressure in direction of flow)*. The Energy Equation becomes

$$\left[pv + \frac{V^2}{2g_c}\right]_{duct\ or\ static} = [pv]_{total} \tag{1-6b}$$

Suppose further that the specific volume is constant because of the small pressure changes involved and that we change the specific volume to the mass density using $v = 1/\rho$, multiply through by g_c/g, and replace $(g/g_c)\rho$ by the weight density, γ. Equation 1-6b then becomes

$$\left[\frac{p}{\gamma} + \frac{V^2}{2_g}\right]_{duct} = \left[\frac{p}{\gamma}\right]_{total} \tag{1-6c}$$

The location duct could be anyplace, and we can say that the total duct pressure is constant in the absence of friction and significant heat transfer. The following is known as Bernoulli's Equation:

$$\left[\frac{p}{\gamma} + \frac{V^2}{2g}\right]_{duct} = constant \tag{1-6d}$$

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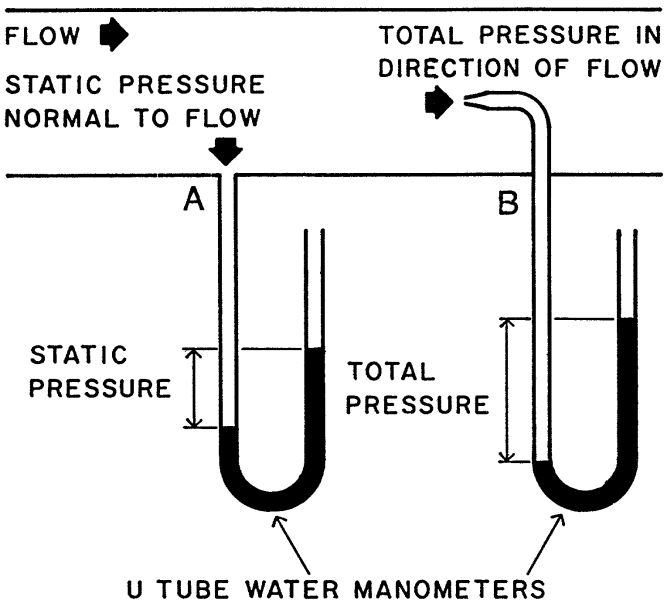


Figure 1-4 Static and total pressures.

Among other things, Bernoulli's Equation says that as the velocity goes up or down (perhaps due to area changes or takeoff air), the static pressure changes. Note that the units for Equation 1-6d as written are meters. These are pressure equivalents to the weight of a column of the fluid on a unit area. Thus the units are meters of air or meters of water, depending on the fluid actually flowing and not the instrument that is used for measuring.

Returning to Equation 1-6c and multiplying through by the weight density, g, we define the velocity pressure and obtain

$$\left[p + \gamma \frac{V^2}{2g} \right]_{duct} = p_{total}$$

or

$$p_{static} + p_{velocity} = p_{total} \qquad \textbf{(1-6e)}$$

Examining the units of the velocity pressure term, we find that

$$\gamma \frac{V^2}{2g} = \left[\frac{\mathrm{kg}_f}{\mathrm{m}^3} \right] \left[\frac{\mathrm{m}^2/\mathrm{sec}^2}{\mathrm{m}/\mathrm{sec}^2} \right] = \frac{\mathrm{kg}_f}{\mathrm{m}^2} = \mathrm{Pa}$$

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where Pa is the symbol for pascals, kilogram force per square metre. Here again, the density is for the fluid flowing.

Note that the relationship between velocity and velocity pressure can be used both ways, to find pressure or velocity. Two equations commonly used in practice are as follows:

$$V = 1.41\sqrt{\frac{p_v}{\rho_{air}}}\text{m/s} \quad \textbf{(1-7)}$$

$$P_v = 0.602V^2\text{Pa} \quad \textbf{(1-8)}$$

where the numbers 1.41 and 0.602 contain the conversion factors appropriate for p_v in pascals; density, ρ, in kg/m^3 (standard air density is 1.204 kg/m^3); and velocity, V, in m/s.

Standard air, for the HVAC industry, is dry air at 20°C and 101.325 kPa, with a mass density of 1.204 kg/m^3. Sea level pressure is 101.325 kPa, so standard air can be considered typical dry air at sea level. For this reason, most airflow tables and charts are based on standard air. Note that defining an airflow in terms of standard air also defines the weight and mass flow. Thus, 10 m^3/s of standard air is also 10 × 1.204 = 12.04 kg/s.

As elevation increases, air density decreases, and above 1000 meters, density corrections should be considered. Because most projects are located at altitudes from sea level to 1000 m, most designs can use standard air without correction. Air expands as it is heated and density drops. For many air-conditioning systems, this can be ignored, but be careful. As shown in the cold climate example, outdoor air at –35°C has a density about 20% lower than it does at 24°C.

Standard air is dry air with no moisture vapor, but the air we experience is never dry; atmospheric air always includes water in the form of moisture vapor. Also, the quantity of moisture vapor varies. It is typically under 2% by weight, and it influences the density and thermal properties of air. The addition and removal of moisture are common processes in air systems and can be conveniently shown on a chart called a *psychrometric chart*. The main axes on a psychrometric chart are temperature along the bottom *x*-axis and moisture weight compared to dry air weight, kg/kg or g/kg, on the *y*-axis.

There is a maximum proportion of moisture vapor with the air at any given temperature, so the chart has the characteristic form shown in Figure 1-5. Shown are

- vertical temperature lines, °C.
- horizontal moisture content (humidity ratio) lines, kg of moisture/kg of dry air.
- sloping down left to right specific-volume lines, m^3/kg. For example, air at 25°C and 25% relative humidity (RH) has a specific volume of 0.85 m^3/kg. At this specific volume, 1 kg of air occupies 0.85 m^3.

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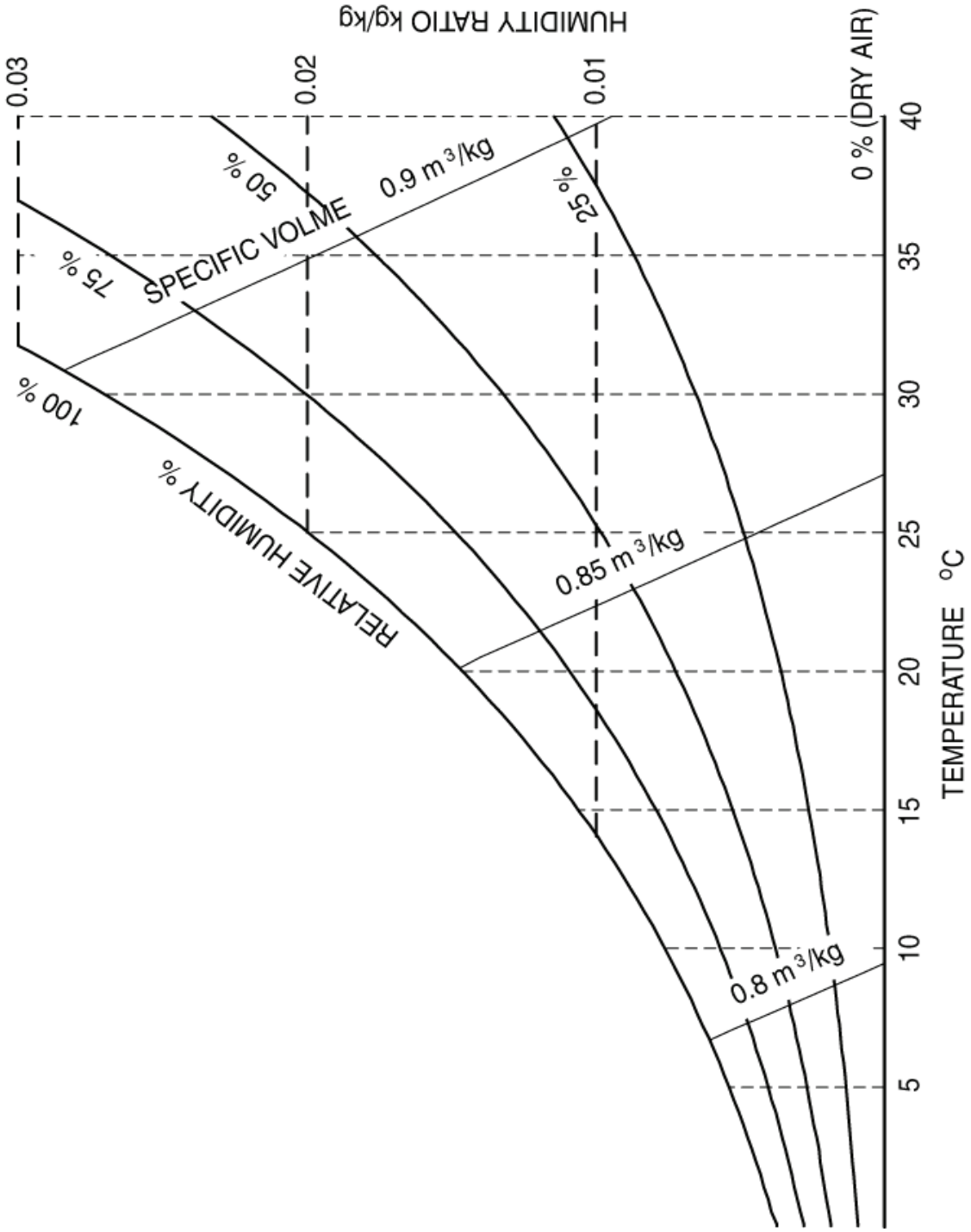


Figure 1-5 Psychrometric chart.

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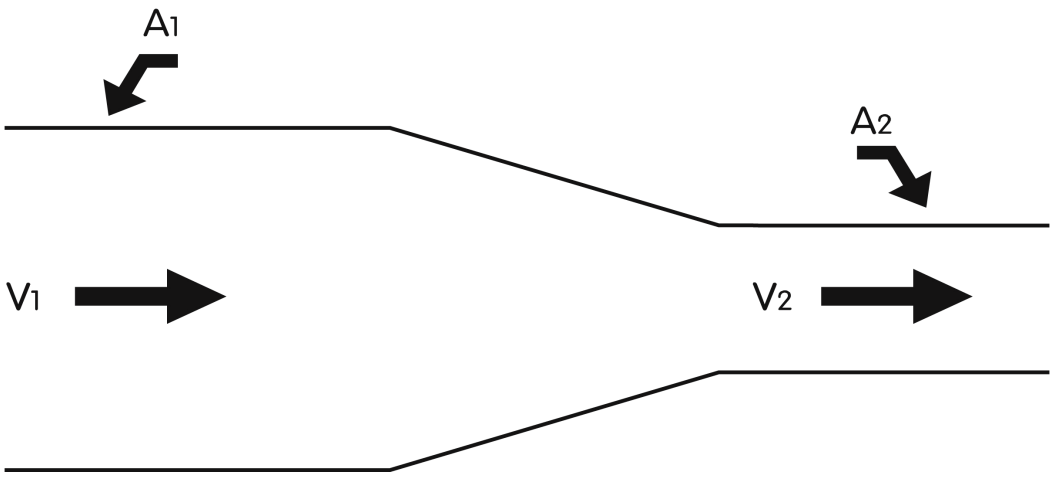


Figure 1-6 Conversion of static pressure to velocity pressure.

- curved RH lines, %. The highest of these lines, labeled 100% RH, is the maximum moisture that can be in gaseous form at that temperature.

When the air is saturated with moisture, we say the humidity is 100%. When the same volume of air holds only half the weight of water vapor that it has the capacity to hold at that temperature, we call it 50% RH. The chart shows the 25%, 50%, 75%, and 100% RH lines. The saturation line is 100% and the horizontal line along the *x*-axis is 0%. Note that on the chart, the RH lines are not linearly related. Thus, at a particular temperature, the 50% RH curve is not at half the height of the saturation (100% humidity) line.

Psychrometric charts are based on standard air, and humidity ratio may be labeled kg/kg or g/kg. The advantage of using grams is that the scale is in whole numbers; for example, 8 rather than 0.008. For most above-ground terrestrial systems, the kg_m and kg_w issue can be ignored; but be careful with units when dealing with substantial pressure changes as those that occur in mines, submarines, planes, and space vehicles. We will return to the psychrometric chart in future chapters.

Air Handling—A Practical Application

How these basic principles apply to air system design is illustrated in Figure 1-6, which shows a duct with the air coming in the left and going out the right. For this example, we assume this to be a frictionless process. Notice that the duct reduces in cross section, with area A_1 greater than A_2. There is one velocity at A_1 and another at A_2. This process can be analyzed using the Continuity Equation.

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The Continuity Equation says that for a given mass flow, and by the law of conservation of matter or mass, air entered on the left side must come exit the right side, because we can neither destroy nor create air in the duct between the two points. The Continuity Equation says that the cubic meters *in* is equal to the cubic meters *out*, ignoring any kind of compressibility or temperature change. In other words, the quantity of air in ($m^3{}_1$) is equal to the quantity of air out ($m^3{}_2$), giving $m^3{}_1 = m^3{}_2$. Because $m^3 = AV$, then $A_1V_1 = A_2V_2$. If we measure the duct, we know what A_1 and A_2 are. If we know V_1, we can solve for V_2, and we know that because A_1 is bigger than A_2, V_2 must be bigger than V_1.

This relationship can be explained by the Continuity Equation:

$$V_2 = V_1\left(\frac{A_1}{A_2}\right) \tag{1-9}$$

So as the cross-sectional area is reduced, the velocity is increased, as predicted by the Continuity Equation.

Let's return to the Energy Equation and the relationship in which the total pressure is equal to the velocity pressure plus the static pressure ($p_t = p_v + p_s$). If the velocity increases, the velocity pressure has to increase, because velocity pressure is $p_v = V^2/2g$. As the air flows from left to right in Figure 1-6, both velocity and kinetic energy increase.

The simple device shown in Figure 1-6 converts potential energy into kinetic energy. But how does this happen? In this example, there are two forms of energy: static pressure (the flow work) and velocity pressure (kinetic energy). If the kinetic energy increases, then the static pressure must decrease by the same amount.

If A_2 is one-half as big as A_1, then V_2 is twice as big as V_1. Because the velocity pressure is proportional to the square of the velocity ($V^2/2g$), pV_2 is four times pV_1, and static pressure p_s is smaller by an equal amount. This is not too difficult to understand because it is expected that the static pressure will be less at A_2 than at A_1.

Figure 1-6 shows an accelerator. Velocity is increased by making the duct area smaller. Suppose Figure 1-6 is reversed, as in Figure 1-7, which shows a decelerator. Because the air comes in at a higher velocity through the smaller section and goes out at a lower velocity through the larger section, the kinetic energy is reduced. If the velocity is reduced by a factor of two, the kinetic energy level (and the velocity pressure) is reduced by four. Consequently, the static pressure increases by an equal amount. Static-pressure probe manometers placed at A_1 and at A_2 in Figure 1-7 would show that the static pressure at A_2 is greater than at A_1.

This phenomenon is called *static pressure regain*, and it is a very important principle of air system design. One method of designing ducts is called the *static pressure regain method*, which is applied to a duct with a series of out-

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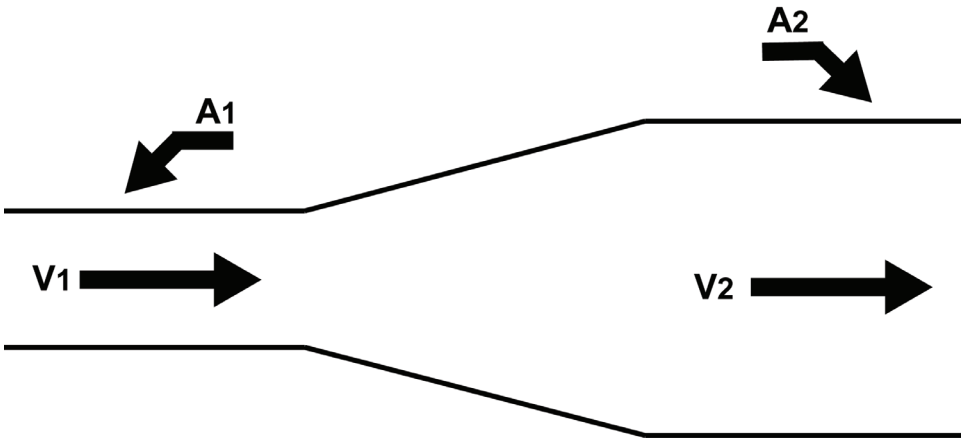


Figure 1-7 A decelerator.

lets. After each outlet, the velocity is reduced and the duct size is reduced so that the static pressure at the next outlet is approximately the same.

Friction Effects

Until now, we have considered frictionless systems. But in the real world of air system design, friction must be taken into account. Viscosity is the property responsible for dissipation of the fluid's kinetic energy into intrinsic internal energy. In air ducts, the amount of energy transferred is small, but the effect on pressure drop is major. The frictional pressure drop is commonly characterized by the Darcy-Weisbach equation:

$$\Delta p_f = f \frac{L}{D}\left[\gamma \frac{V^2}{2g}\right] \text{ Pa} \qquad \textbf{(1-10)}$$

In terms of *head* as meters of fluid flowing, the Darcy-Weisbach equation can be written

$$\frac{\Delta p_f}{\gamma} = f \frac{L}{D}\left[\frac{V^2}{2g}\right] \text{ m} \qquad \textbf{(1-11)}$$

For standard air, the Darcy-Weisbach equation can be written

$$\Delta p_f = \left[\frac{1000 f L}{D_h}\right]\left[\frac{\rho V^2}{2}\right] \text{ Pa} \qquad \textbf{(1-12)}$$

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where

f = dimensionless friction factor

L = duct length, m

D = diameter, mm

D_h = hydraulic diameter, mm. Actual diameter for round ducts but a calculated value for oval and rectangular ducts.

This is a purely empirical formula which states that the frictional pressure drop is proportional to length, L, inversely proportional to the effective diameter, D_h, and proportional to velocity pressure or velocity head. One would hope that the proportionality constant, f (dimensionless), would be truly constant, and that turns out to be partially true. When the flow is fast, f (called the *friction factor*) is fairly constant and depends only on the duct roughness. When the flow is slow, f is inversely proportional to velocity, but the wall roughness is unimportant. The terms *fast* and *slow* must be explained.

Consider all of the properties and characteristics involved in fluid friction: velocity, diameter, viscosity, and density. Consider also the variety of motions that we observe: slow, such as the streamline flow of water out of a hose, or fast, such as the turbulent flow of water out of the same hose when the faucet is fully open.

We are fortunate that these phenomena can all be related through a single parameter known as the Reynolds number, which is defined as

$$\mathrm{Re} = \frac{V\rho D}{\mu} \qquad \textbf{(1-13)}$$

where μ is the absolute viscosity in mPa·s, V is the velocity in m/s, D is the diameter in m, and ρ is the density in kg/m^3.

The Reynolds number is the ratio of the momentum of the flow, $V\rho$, to the viscosity, μ. If the viscosity is high relative to the momentum, the flow is laminar or streamline (like maple syrup). But if the viscosity is low (as for air), the flow will be turbulent for any realistic duct size. Laminar airflow occurs in laminar flow filters where the pore size, D, is very small.

So there are two distinct regimes of flow (laminar and turbulent) that depend on the Reynolds number. The effect of these distinctions is manifest in the behavior of the friction factor, as shown on the Moody chart (Figure 1-8) (Moody 1944). This chart shows the friction factor as a function of the Reynolds number. Note that both axes have logarithmic scales.

Several interesting features are present on the Moody chart:

- The laminar flow region is shown for Reynolds numbers smaller than about 2000. The dashed extension of the solid line indicates that under some circumstances, the relationship can be extended up to 4000. This part of the line is not to be trusted. In the laminar flow region, the friction factor is inversely proportional to the Reynolds number:

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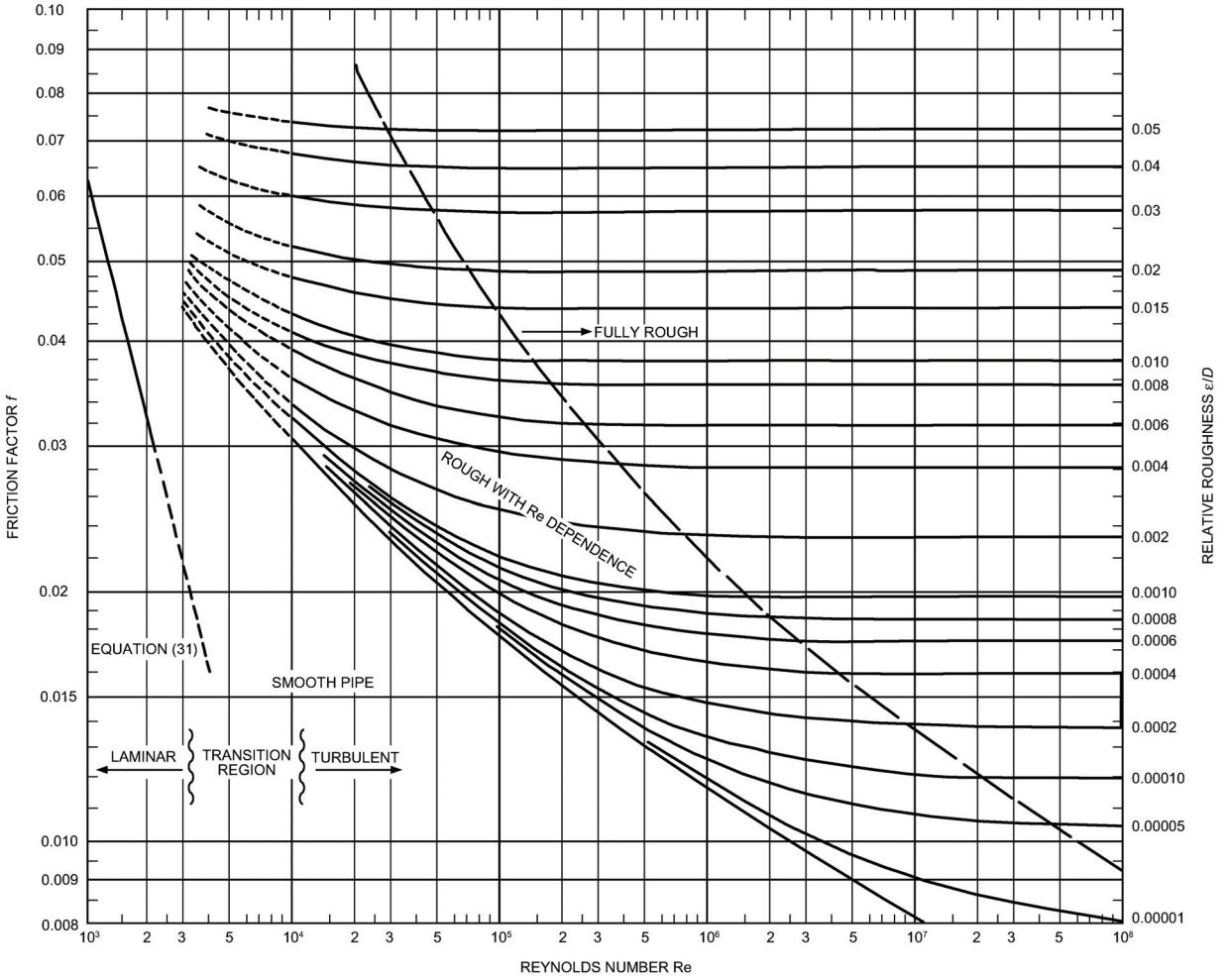


Figure 1-8 Moody chart (ASHRAE 2009).

$$f = 64/\mathrm{Re} \qquad \textbf{(1-14)}$$

- If this value is substituted into Equation 1-12, we get the following:

$$\Delta p_f = n\left[\frac{vLV}{D^2}\right] \mathrm{Pa} \qquad \textbf{(1-15)}$$

where n is a numeric constant and V, the kinematic viscosity, is μ/ρ with units of m^2/s. Note that the frictional pressure drop varies with the first power of velocity.

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- There is also a dashed line labeled "fully rough." To the right of this line, the friction factor is constant for a particular value of roughness, ε. The relative roughness values are shown. For example, the roughness of commercial steel pipe is 152 μm. Relative to a 100 mm pipe, ε/D is about 0.00152. In this fully rough region, a constant value of f can be used regardless of flow rate or velocity, and the frictional pressure drop varies with the second power of velocity.
- Between laminar and fully turbulent flow, the friction factor depends on the Reynolds number and the relative roughness, and an iterative solution to a problem may be necessary. In this region, pressure drop varies with a power of velocity between 1 and 2. Unfortunately, many air duct flows occur in this transition region and HVAC air velocities are neither known accurately nor constant.

Test work performed by ASHRAE and its predecessor organization ASHVE (American Society of Heating and Ventilating Engineers) indicated prior to Moody's work (Moody 1944) that ε for galvanized sheet metal ductwork was about 0.15 mm. This is based on transverse joints spaced at 750 mm intervals. When joints are spaced at 1150 mm intervals, the value is reduced to 0.09 mm.

The System Constant Form of the Darcy-Weisbach Equation

HVAC air and piping systems usually use a simplified form of the Darcy-Weisbach equation, where it is assumed that the friction factor is constant and that L and D do not change (although the system may be made up of various L and D and fittings). Grouping all of the constants together, we can rewrite Equation 1-15 in two forms. The first form includes the loss coefficient, K, and the second for includes the system constant, C_s. Note that C_{s2} equals the reciprocal of K, $C_{s2} = 1/K$.

$$\Delta p_f = K\left[\frac{\mathrm{m}^3}{\mathrm{s}}\right]^2 \tag{1-16}$$

or

$$\frac{\mathrm{m}^3}{\mathrm{s}} = C_s\sqrt{\Delta p_f} \tag{1-17}$$

Equation 1-16 is the system constant form of the Darcy-Weisbach equation. It is used extensively in HVAC systems work. A *system curve*, as shown in Figure 1-9, portrays the frictional pressure drop for a particular system. The curve is a parabola that can be generated with one known experimental or calculated value for a particular system. One pair of m^3/s and Δp_f is required to determine K or C_s.

Consider a complex air-handling system where we want to move 10 m^3/s through the system. The pressure drop in the system is calculated to be 1 kPa.

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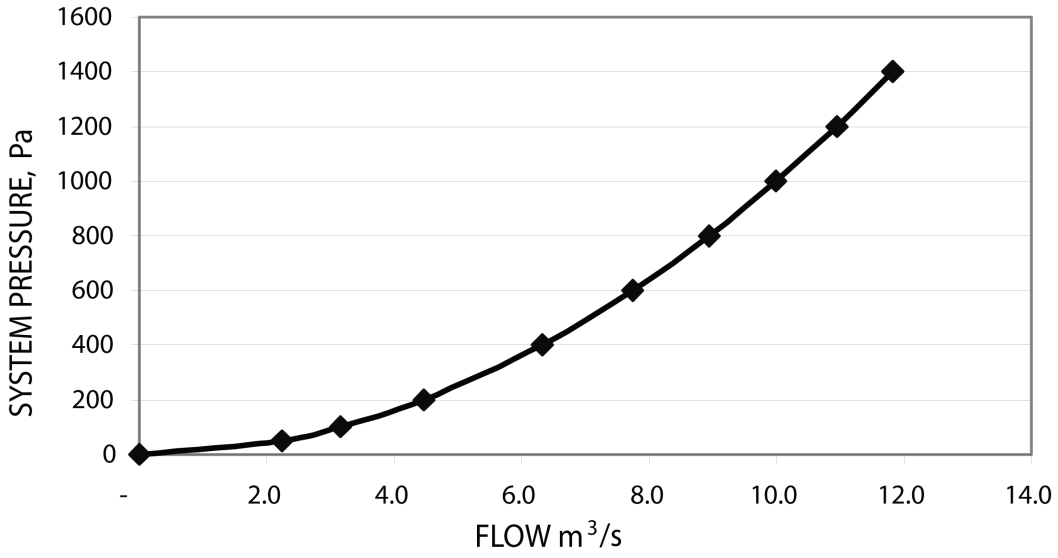


Figure 1-9 Typical system curve.

The system constant form of the Darcy-Weisbach equation can be used to find the system constant:

$$C_s = \frac{10}{\sqrt{1000}} = 0.316$$

Similarly, we find that $K = 10$. Values of Δp_f and m^3/s can be plotted on a graph. Other values can be determined by using

$$\Delta p_f = K(m^3/s)^2$$

As long as the system is unchanged, it will operate on this curve.

The Friction Chart

In 1945, D.K. Wright published a paper titled, "A new friction chart for round ductwork" in the ASHVE *Transactions* (1945). A graph from this article has become essentially the standard for HVAC work. This graph, often known as the Wright Friction Factor Chart, takes the Darcy-Weisbach relationship and the Moody chart (Moody 1944) and converts them into a graphical presentation that lets us determine frictional pressure drops at various diameters of round ductwork and at various velocities based on an ε value for galvanized sheet metal ductwork of 0.15 mm.

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Since that time, ASHRAE, assisted by the Sheet Metal and Air Conditioning National Contractors' Association (SMACNA), has conducted a series of tests and obtained slightly different numbers than those used by Wright. The new data have been included in the *ASHRAE Handbook—Fundamentals* since 1993 (ASHRAE 2009) The friction factor chart (see Figure 1-10) was revised based on standard galvanized sheet metal ductwork with an absolute ε roughness of 0.09 mm instead of 0.15 mm.

Other factors, including the shape of the duct, the roughness of the material of construction, and fittings used must be considered. These are discussed in Chapter 7, "Duct System Design."

Density and Altitude Effects

Standard psychrometric charts and performance data published by manufacturers generally assume equipment operation at sea level with standard air. However, when the project is located at a significantly higher altitude, allowances must be made for lower pressure. Factors by which the usual data must be multiplied when operating at higher altitudes are summarized in Table 1-1. For items not listed, consult appropriate sources, such as Carrier's *Altitude Effects* (1967).

The Next Step

This chapter introduced the fundamentals of airflow theory and included discussion of air flowing in ducts. Chapter 2 introduces the other common components of air systems that condition air and deliver it to the occupied space. Included are the systems' function and main operating characteristics. More detail on choosing components and their detailed operation are explained in later chapters.

Summary

The difference between mass and weight was explained. Mass is a property of matter that is invariant with location, but weight changes depending on the local gravitation. Conveniently for designers of most buildings, gravity is constant, with kg and kg_w being numerically the same.

Hydrostatic pressure, commonly referred to as static pressure, is the pressure at one place due to the column of fluid above. The pressure is the same in all directions at any point. In a duct with air flowing under pressure, the static pressure around the duct is the same on all sides.

The Continuity Equation states that mass is neither created nor destroyed. Thus, under steady conditions with no storage, the mass flow into a system must equal the mass flow out of the system. The volume of air at constant pressure is proportional to the absolute temperature. Thus, while the mass into a system equals the mass out, the volume in can be different from the volume out if the temperature is changed.

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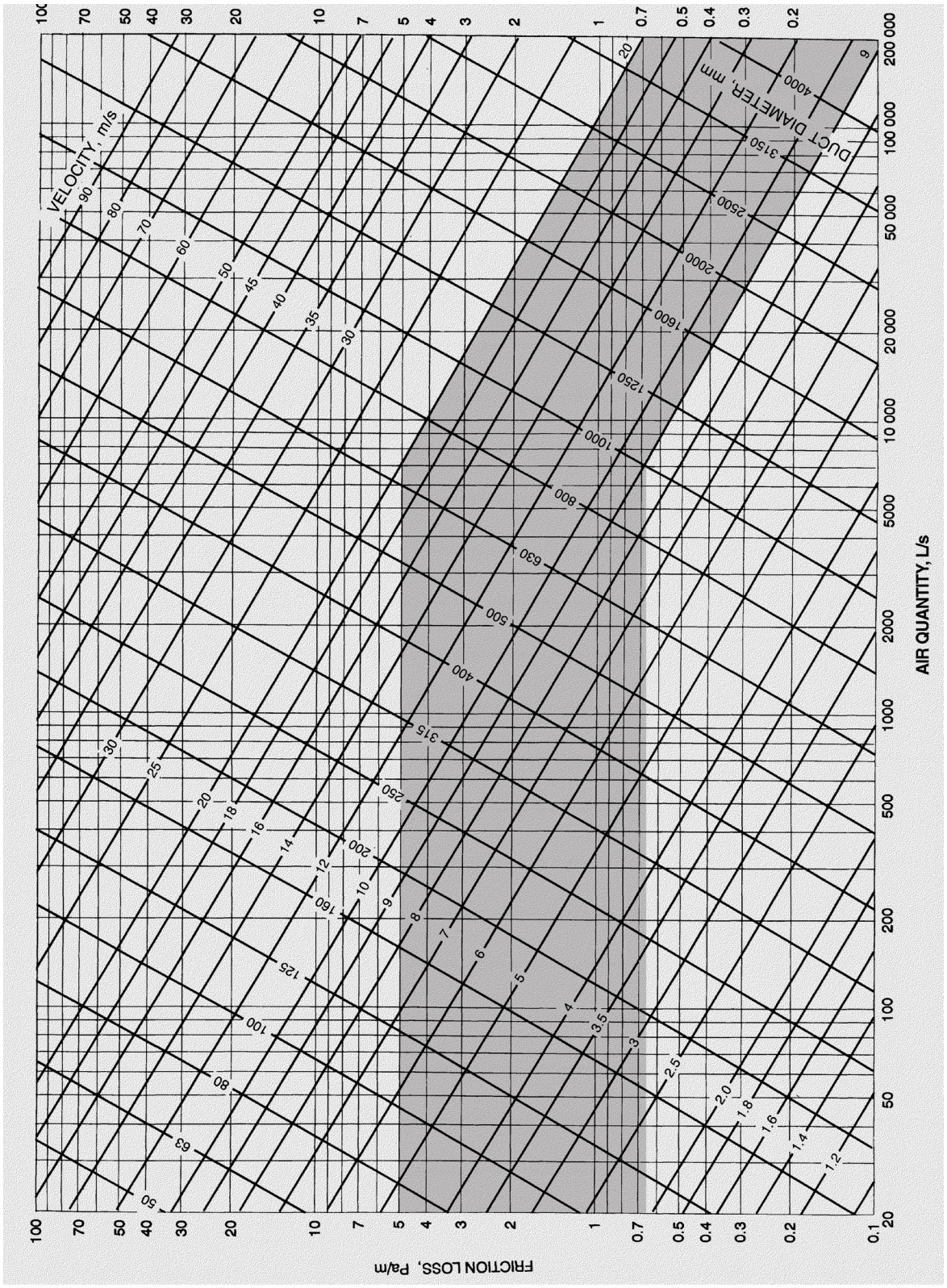


Figure 1-10 Friction chart (ASHRAE 2009).

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Table 1-1 Typical Altitude Correction Factors

Item	Altitude, m (above sea level)			
	750	1500	2000	3000
Compressors	1.00	1.00	1.00	1.00
Condensers, air-cooled	0.95	0.90	0.85	0.80
Condensers, evaporative	1.00	1.01	1.02	1.03
Chillers	1.00	1.00	1.00	1.00
Induction room terminals (chilled water)	0.93	0.86	0.80	0.74
Fan-coil units				
Total capacity (*SHF = 0.40 – 0.95)	0.97	0.95	0.93	0.91
Sensible capacity (SHF = 0.40 – 0.95)	0.92	0.85	0.78	0.71
Total capacity (SHF = 0.95 – 1.00)	0.93	0.86	0.79	0.73
Packaged air-conditioning units, air-cooled condenser				
Total capacity (*SHF = 0.40 – 0.95)	0.98	0.96	0.94	0.92
Sensible capacity (SHF = 0.40 – 0.95)	0.92	0.85	0.78	0.71
Total capacity (SHF = 0.95 – 1.00)	0.96	0.82	0.88	0.84

*SHF = Sensible Heat Factor

The useful but not absolutely correct formula for calculating the result of mixing airstreams was introduced: $(V_1 \times T_1) + (V_2 \times T_2) = [(V_1 + V_2) \times T_3]$. Remember to keep the volume units consistent, m^3/s or L/s.

Energy, like mass, is neither created nor destroyed. It can be converted from one form to another and measured in different units. However, in consistent units in any process

energy in = energy out – energy stored in the system

Energy can be in a number of forms: *work*, done by a force over distance or torque through an angle; *heat*, energy transfer due to a temperature difference; *internal energy*, due to thermal energy relative to some datum; *potential energy*, work done by movement in the Earth's gravitational field; and *kinetic energy* from motion.

Static pressure is the pressure exerted by a fluid at rest. Velocity pressure is the pressure exerted by a fluid by virtue of its motion. Typically, measuring the pressure at a tapping in the side of a duct provides the static pressure. The pressure on the open end of a tube facing the flow of air measures both the static and the velocity pressure, called *total pressure*. The difference between the static pressure and total pressure is the velocity pressure.

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Bernoulli's Equation states that in a system without energy losses or gains, the sum of static pressure and velocity pressure is constant:

$$\left[\frac{p}{\gamma} + \frac{V^2}{2g}\right]_{duct} = constant$$

The valuable concept in Bernoulli's Equation is that if the velocity is reduced due to a wider duct, the drop in velocity pressure (V^2 reduces) is exactly matched by an increase in static pressure with friction ignored. Velocity pressure in pascals for standard air = $0.602V^2$ Pa.

Standard air and the psychrometric chart were introduced to raise the issue of decreasing density with increasing temperature and the issue of moisture in the air.

Friction effects occur in ducts for several reasons, including surface roughness, duct joints, fittings, equipment, and outlets. The theory behind duct friction was discussed, including Reynolds number, the Moody chart (Moody 1944), and the Darcy-Weisbach equation. The critical point to remember is that in a fixed system, the pressure drop through the system is about proportional to the square of the flow: $\Delta p = K(\text{m}^3/\text{s})^2$. Thus, doubling the flow creates four times the pressure drop.

The pressure drops through ducts can be calculated, but the simplest method is to use a friction chart, such as that shown in Figure 1-10 for standard air.

Standard psychrometric charts and performance data generally assume equipment operation with standard air. The lower air density at high altitudes significantly affects some equipment but not all. Reference tables can be used and manufacturers contacted for assistance in these cases.

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Skill Development Exercises for Chapter 1

Complete these questions by writing your answers on the worksheets at the back of this book.

1-1 In Figure 1-6, area $A_1 = 2$ m^2, area $A_2 = 1.25$ m^2, and velocity $V_1 = 10$ m/s. Calculate V_2 (m/s).

a) 16 m/s b) 25.6 m/s c) 7.5 m/s d) 12.6 m/s

1-2 The total pressure at a certain point in a system is determined to be 1.25 kPa, and the static pressure at that point is determined to be 500 Pa. What is the velocity pressure (Pa) at that point?

a) 1.75 b) 1 c) 750 d) 250

1-3 Which of the following is the most correct definition of *static pressure regain*?

a) as the velocity of an airstream decreases, the static pressure increases.

b) as the velocity of an enclosed airstream decreases due to friction, the static pressure increases.

c) friction reduces static pressure, while velocity pressure increases with reduction in duct size.

1-4 An air-handling system is determined to have a 1500 Pa pressure drop through the system at a flow of 4000 L/s. What is the system constant?

a) 2.7 b) 6000 c) 77.4 d) 103

1-5 The product of fluid pressure and specific volume is _____?

a) internal energy b) Reynolds number (Re)
c) kinetic energy d) flow work
e) viscosity

1-6 A water manometer measures _____.

a) velocity b) pressure c) temperature d) all of the above

1-7 Fan pressures are typically indicated in what units?

a) Pa b) kg/m^2 c) N/m d) none of the above

1-8 If the cross-sectional area of a duct decreases in size, the velocity of an airstream passing through the duct increases.

a) True b) False

1-9 Air passes through a length of inaccessible duct with a constant cross-sectional area. You suspect that there is a serious leak in the duct. The velocity pressure drops from 200 to 160 Pa along the suspect section of duct. Approximately what percentage of air is being lost through the leak?

a) 5% b) 10% c) 20% d) 41%

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I-I0 2000 L/s of outdoor air at 2°C is drawn in over a heater and delivered into the building at 24°C. What volume of air is delivered?

a) 1851 L/s b) 2000 L/s c) 2079 L/s d) 2160 L/s

I-II In an air-conditioning system, 15 m^3/s of return air at 25°C is mixing with 2.3 m^3/s of outdoor air at 35°C. What is the approximate resulting volume and temperature?

a) 17.3 m^3/s, 22.7°C b) 17.3 m^3/s, 29.9°C

c) 17.3 m^3/s, 26.3°C d) 17.3 m^3/s, 33.7°C