V_2 = velocity of standard air in the outlet duct, feet per minute.
A_1 = area of the inlet duct, square feet.
A_2 = area of the outlet duct, square feet.
C_1 = loss coefficient based on area A_1.
C_2 = loss coefficient based on area A_2.

For a gradual symmetrical enlargement, Equation 8 changes to

$$H_{ge} = C_r\left(\frac{V_2 - V_1}{4005}\right)^2 = C_1C_1\left(\frac{V_1}{4005}\right)^2 = C_2C_2\left(\frac{V_2}{4005}\right)^2 \quad (9)$$

where

H_{ge} = pressure loss due to gradual enlargement, inches of water.
C_r = coefficient of loss, as ratio of loss to loss for abrupt expansion, dependent upon the total angle included between the sides of the duct.

The loss for a sudden symmetrical contraction can be expressed as

$$H_c = C_2\left(\frac{V_2}{4005}\right)^2 = C_1\left(\frac{V_1}{4005}\right)^2 = C_c\left(\frac{V_c}{4005}\right)^2 \quad (10)$$

where

H_c = pressure loss due to sudden contraction (Fig. 10b).
C_c = loss coefficient based or orifice area A_c.
V_c = velocity of air through orifice, feet per minute.

The loss for a gradual symmetrical contraction can be similarly expressed as

$$H_{gc} = C_2\left(\frac{V_2}{4005}\right)^2 \quad (11)$$

where the coefficient of loss C_2 depends on the included angle of the sides of the duct and the sharpness of the edges at the junction of taper to following duct section.

DUCT DESIGN

The following discussion refers to ducts for commercial and industrial heating, ventilating, and air-conditioning systems of the central station type. The design procedures given yield the static pressure required to overcome the resistance of the ductwork, including the supply outlets and return intakes. The fan selected for the duct system must not only produce this pressure but also the additional pressure required by the central equipment such as washers or spray chambers, heating or cooling coils, and filters. Pressure losses of these components should be obtained from the manufacturers' catalogs.

Special duct design procedures for heating ducts used in residences can be found in Chapter 18 Warm Air Heating Systems. The design of ducts in industrial exhaust systems is discussed in Chapter 52.

General rules which should be followed in the design of ducts are:

1. The air should be conveyed as directly as possible at the permissible velocities to obtain the desired results with minimum noise and greatest economy of power, material, and space.

2. Sudden changes in the direction or velocity of the air should be avoided. When sudden changes are necessary at bends, turning vanes should be used to minimize the pressure loss.

3. Diverging transition pieces should be made as gradual as practicable. As shown in the section on area changes, losses in abrupt enlargements are high and therefore such transitions should be avoided. The included angle of divergence for enlargement should not exceed 20 deg. Losses in contractions are low but the included angle of convergence should not be greater than 60 deg.

4. Where the greatest air carrying capacity per square foot of sheet metal is desired, rectangular ducts should be made as nearly square as possible. Aspect ratios (ratio of width to depth) greater than 8 to 1 should be avoided. Where possible, a ratio of 4 to 1 or less should be maintained.

5. Ducts should be constructed of smooth material, such as steel or aluminum sheet metal. For ducts made from other materials, proper allowance for the change in roughness should be made.[8]

6. Through the design procedures which follow, a reasonably precise estimate of the flow resistances offered by the system can be obtained. However, it should be recognized that in actual installations, resistances may vary considerably from the calculated values because of variation in the smoothness of materials, types of joints used, and the ability of workmen to fabricate the system in accordance with the design. Fans and motors should therefore be selected to provide at least a slight factor of safety, and dampers should be installed in each branch outlet for balancing the system.

Procedure for Duct Design

The general procedure is as follows:

1. Study the plan of the building and arrange the positions of the supply outlets to provide proper distribution of air within each space. Select outlet sizes from manufacturers' catalog data.

2. Draw a sketch of the most convenient system of ductwork, connecting the supply outlets and return intakes with the central station apparatus, taking cognizance of the building construction, avoiding all obstructions in steel work and equipment, and at the same time maintaining a simple design.

3. Calculate the sizes of all main and branch ducts by one of the procedures given in the following section.

4. Determine the total pressure requirement of the supply and return duct systems. Although the loss in total pressure of each duct run connecting the fan and each supply outlet (or return intake) should be calculated and made the same for all runs, ordinarily only the pressure loss of the duct run apparently having the greatest resistance is referred to as the pressure loss of the duct system. Dampers are relied upon for balancing the system.

Design Velocities

It is not possible to give specific rules for selecting duct velocities, but the velocities given in Table 6 have been found to give satisfactory results in designing conventional systems. Since the fan horsepower increases approximately as the square of the velocity, and noise generation increases with static pressure, velocities should be kept low for quiet and economical operation. On the other hand, as evident from Equation 3, at a given flow rate the duct size increases with decreasing velocity. For multistory buildings, it is sometimes possible to reduce the height between floors by using very small ducts, thereby effecting a considerable reduction in building investment cost. The various space-saving systems which are becoming increasingly numerous are discussed in the section High-Velocity Systems in Chapter 19 Central Systems for Air Conditioning. The design of high-velocity ducts is discussed briefly in a later section, Design of High-Velocity Ducts, in this chapter.

DESIGN METHODS

In the design of air duct systems, three methods are employed: (1) *velocity-reduction*, (2) *equal-friction*, and (3) *static-regain*. The three methods and their refinements represent different design levels of accuracy and complexity, and they should be selected, therefore, to suit the application. Simple duct systems may be designed as quickly and easily as possible, but for large installations the system static-

Table 6 .... Recommended and Maximum Duct Velocities for Conventional Systems

Designation	Recommended Velocities, Fpm: Residences	Schools, Theaters, Public Buildings	Industrial Buildings
Outdoor Air Intakes[a]	500	500	500
Filters[a]	250	300	350
Heating Coils[a]	450	500	600
Air Washers	500	500	500
Suction Connections	700	800	1000
Fan Outlets	1000–1600	1300–2000	1600–2400
Main Ducts	700–900	1000–1300	1200–1800
Branch Ducts	600	600–900	800–1000
Branch Risers	500	600–700	800
	Maximum Velocities, Fpm		
Outdoor Air Intakes[a]	800	900	1200
Filters[a]	300	350	350
Heating Coils[a]	500	600	700
Air Washers	500	500	500
Suction Connections	900	1000	1400
Fan Outlets	1700	1500–2200	1700–2800
Main Ducts	800–1200	1100–1600	1300–2200
Branch Ducts	700–1000	800–1300	1000–1800
Branch Risers	650–800	800–1200	1000–1600

[a] These velocities are for total face area, not the net free area; other velocities in table are for net free area.

pressure requirement must be determined as precisely as possible, the most accurate method being recommended.

Velocity-Reduction Method

This method consists of selecting the velocity at the fan discharge and designing for progressively lower velocities in the main at each branch duct. With the selected velocities and known air-flow rates, the various duct diameters are read directly from Figs. 2 or 3, and the equivalent rectangular sizes are obtained from Table 2. The pressure loss of the run having apparently the highest resistance is determined by adding the straight pipe, elbow, and transition losses; this total value represents the fan static pressure required for the supply-duct system. The return-air system is sized similarly, starting with the lowest velocities at the return intakes and increasing them progressively in the direction of the fan inlet. Dampers are relied upon for balancing the system.

A refinement of this method is to size the several branch ducts to dissipate the pressure available at the entrance to each. The pressure loss of the ductwork between the fan and first branch take-off is subtracted from the now known fan static pressure to obtain the available pressure at each junction. By trial, a branch velocity is found that results in the branch pressure loss being equal to, or somewhat less than, that available. The procedure is repeated for each branch.

If the fan is specified so that the static pressure available for the ductwork is known, the method consists of finding, by trial, the velocities in the main duct that will result in a pressure loss equal to the pressure available. The branch ducts are then sized as previously explained if such a refinement is deemed necessary.

The merits of the *velocity-reduction* method are that (1) duct sizes are determined very easily, and (2) velocities can be limited to those known to be safe from causing noise problems. Its weaknesses are: (1) proper choice of velocities requires experience and judgment, and (2) the designer cannot always determine by inspection which run probably has the highest resistance.

Equal-Friction Method

The principle of this method is to make the pressure loss per foot of length the same for the entire system. With this method little balancing is required for symmetrical layouts in which all runs have about the same resistance. For layouts having both short and long runs, the shortest run will require considerable dampering.

Usual practice is to select the velocity in the main duct near the fan from the standpoint of noise for the particular application. Since the flow rate (cfm) is known, this establishes a value of friction loss per 100 ft of duct in Figs. 2 or 3. This same friction loss value is maintained throughout the design. For example, the flow rate in the main after the first branch take-off is reduced by that handled by the branch. Therefore, proceed vertically downward in Figs. 2 or 3 to the new flow rate value, and read the velocity and diameter. Note that the velocity is reduced by this procedure. An advantage of this method is that it *automatically* reduces the duct velocities in the direction of flow, thereby insuring that noise will not be a problem. The equivalent rectangular size of any diameter is obtained from Table 2. By continuing the procedure, all sections, including branch ducts, are sized from Figs. 2 and 3 at the same friction loss per foot of actual length.

After sizing the system the pressure loss of the run having apparently the highest resistance is calculated. In so doing, the pressure losses of all elbows and transitions are included, and are expressed in terms of *equivalent length* of straight pipe.

The principal limitation of the *equal-friction* method is that it does not differentiate between runs having several transitions, elbows, etc., and runs having none. Only the *actual length* of duct is considered; this and the flow rate fix the duct size. Moreover, when computing the system resistance, care must be exercised that the pressure losses of transitions, elbows, etc., are included and added to the straight pipe losses.

If the pressure available for the ductwork is known, as it is for packaged equipment, this pressure can be divided by the total equivalent length of the run apparently having the highest resistance to obtain a design friction loss value per foot, for use with Fig. 2 or Fig. 3. Hence, for these applications, it is not necessary to select an initial velocity. However, the method then has the weakness that the resistances of fittings must be expressed in terms of *equivalent length*. Since transitions, elbows, etc., have predominantly dynamic losses, the equivalent length of a particular fitting varies considerably with its actual size. Note, for example, the values for elbows in Fig. 7 of Chapter 18 are related to duct size, and note also, that the elbow losses in Fig. 9 of this chapter are given in terms of the number of *diameters*. Hence, when the available pressure is known, the method requires that the duct size be estimated in advance. The calculated duct size should therefore be compared with the initial estimate, and if considerably different, a recalculation should be made using the calculated size.

Less dampering is required if the method is modified so that only the main duct is sized by the equal-friction method. The fan is selected for this total duct resistance and the pressure available at each branch take-off is found in the