jets are the effects at various Reynolds numbers fully known.

3. The quantitative treatment of the forces that govern room air distribution problems has been limited, and non-isothermal conditions involving buoyant forces have not yet been fully explored.

4. Most investigations have been concerned with *free* jets, whereas air streams in practical room air distribution are not free streams but are influenced by walls, ceilings, floors, and obstructions.

Angle of Divergence

The angle of divergence is very definite close to the outlet face, but the boundary contours are somewhat billowy and are easily affected by external influences. Here, as in air distribution generally, room air movement is replete with local eddies, vortices, and surges, which are manifestations of unbalance in the forces acting within the air stream. These internal forces govern the air motion, yet they are extremely delicate.[8]

Measured angles of divergence (spread) for discharge into large open spaces have usually ranged from 20 to 24 deg with an average of 22 deg. Coalescing jets for closely spaced multiple outlets expand at somewhat smaller angles, averaging 18 deg, and jets discharging into relatively small spaces show even smaller angles of expansion.[9] Tests indicate that in cases where the outlet area itself is small compared to the dimensions of the space normal to the jet, the jet may be considered free as long as:

$$X \leq 1.5\sqrt{A_R}$$

where

X = distance from face of outlet, feet.

A_R = cross-sectional area of the confined space, square feet.

Four Zones in Jet Expansion

In analyzing the performance of jets, four major zones can be distinguished. They may be roughly defined in terms of the maximum or centerline velocity existing at the cross-section being considered:

Zone 1: A short zone, extending about 4 diameters or widths from the outlet face (or vena contracta for orifice discharge), in which the maximum velocity of the air stream remains practically unchanged.

Zone 2: A transition zone, extending to about 8 diameters for round outlets, or for rectangular outlets of small aspect ratio, over most of which maximum velocities vary inversely as the square root of the distance from the outlet. For rectangular outlets of large aspect ratio, this zone is elongated and extends from about 4 widths to a distance approximately equal to the width multiplied by four times the aspect ratio.

Zone 3: A long zone, of major engineering importance, in which the maximum velocity varies inversely as the distance from the outlet. This zone is often called the zone of fully *established turbulent flow* and may be 25 to 100 diameters long (or equivalent diameters of equal areas), depending on the shape and area of the outlet, the initial velocity, and the dimensions of the space into which the outlet discharges.

Zone 4: A terminal zone in which, in the case of confined spaces, the maximum velocity decreases at an increasing rate, or, in the case of large spaces free from wall effects, the maximum velocity decreases rapidly in a few diameters to the velocity range below 50 fpm which is usually regarded as *still air*.

Centerline Velocities in Zones 1 and 2

Experimental evidence indicates that in Zone 2

$$\frac{V_x}{V_0} = \sqrt{\frac{K'H_0}{X}} \tag{2}$$

where H_0 = width of jet at outlet or at vena contracta.

Approximately the same values of K' apply as for Zone 3 expansion from axial outlets.

In Zone 1, the ratio V_x/V_0 is constant and equal to the ratio of the center velocity of the jet at start of expansion to the average velocity, ranging from approximately 1.0 for rounded-entrance nozzles to about 1.2 for straight pipe discharge, but with much higher values for diverging-discharge outlets.

Since aspect ratio[7] and turbulence[8] primarily affect the center line velocities in Zones 1 and 2, the importance of H_0 is obvious. In commercial testing it has been shown, that aspect ratio has little effect on the terminal zone of the jet when H_0 is greater than 4 in. This is particularly true in the case of non-isothermal jets. When H_0 is very small, it is possible for the induced air to penetrate the core of the jet, and thus effectively to reduce center line velocities. The difference in performance between the radial type outlet with a small H_0 and the axial type outlet with a large H_0 shows the importance of the thickness of the jets.

When air is discharged from perforated panels of relatively large sizes the constant velocity core formed by the coalescence of the individual jets extends a considerable distance from the panel face. In this Zone 1 region, when the ratio Distance from panel/$\sqrt{\text{Panel area}}$ is less than 5, the equation

$$V_x = V_0 \cdot 1.2\sqrt{C_d \times R_{fa}} \tag{3}$$

should be used for estimating centerline velocities.[10]

Centerline Velocity in Zone 3

Research has shown that maximum or centerline velocities in Zone 3 of straight flow isothermal jets can be determined with good engineering accuracy from

$$\frac{V_x}{V_0} = \frac{KD_0}{X} = \frac{K'\sqrt{A_0}}{X} \tag{4}$$

$$V_x = \frac{K'V_0\sqrt{A_0}}{X} = \frac{K'Q}{X\sqrt{A_0}} \tag{5}$$

$$= \frac{K'Q}{X\sqrt{A_c \times C_d \times R_{fa}}} \tag{6}$$

where

V_x = centerline velocity, feet per minute.

$V_0 = \frac{V_c}{C_d \times R_{fa}}$ = average initial velocity at discharge from open-end duct or across contracted stream at vena contracta of orifice or multiple-opening outlet, feet per minute.

V_c = nominal velocity of discharge based on the core area, feet per minute.

C_d = coefficient of discharge (usually between 0.65 and 0.90).

R_{fa} = ratio of free area to gross (core) area.

X = distance from face of outlet, feet.

K and K' = proportionality constants, with $K' = 1.13\ K$.

D_0 = effective or equivalent diameter of stream at discharge from open-end duct or at a contracted section, feet.

$A_0 = A_c \times C_d \times R_{fa}$ = effective area of stream at discharge from an open-end duct or at a contracted section, square feet.

A_c = measured gross (core) area of outlet, square feet.

Q = discharge from outlet, cubic feet per minute.

Since A_0 equals the effective area of the stream, the flow area for commercial registers and diffusers according to the Equipment Test Code[11] of the Air Diffusion Council, may be used in Equation 4 with the appropriate value of K and K'.

Equation 4 is nondimensional and requires only that consistent units be used, as in the above nomenclature. Values of K and K' are listed in Table 2.[7,13]

In the case of multiple-opening outlets and annular-ring outlets, the streams coalesce into a solid jet before actual jet expansion takes place. This coalescence affects the experimentally determined proportionality constants K or K' and accounts for some of the divergence in reported values for similar outlets.

For perforated panels of relatively large size, the values of K and K' given in Table 2 apply only when the ratio Distance from Panel/$\sqrt{\text{Panel area}}$ is larger than 5. (See Centerline Velocities in Zones 1 and 2.)

Low velocity test results, in the range $V_x < 150$ fpm, indicate that the normal values of K and K' should be reduced about 20 percent for V_x = 50 fpm, as used in later Equation 9 for throw. Fig. 7 gives the effective diameter D_0 in inches for single openings and includes the coefficient of discharge.[12]

Table 2 .... Recommended Values of the Centerline Velocity Constant K or K'

(See Equation 4)

Type of Outlet	K: V_0 = 500 to 1000	K: V_0 = 2000 to 10,000	K': V_0 = 500 to 1000	K': V_0 = 2000 to 10,000
Free Openings				
Round or Square	5.0	6.2	5.7	7.0
Rectangular, large aspect ratio (<40)	4.3	5.3	4.9	6.0
Annular slots axial or radial*	—	—	3.9	4.8
Grilles and Grids				
Free area 40% or more	4.1	5.0	4.7	5.7
Perforated Panels				
Free area 3 to 5%	2.7	3.3	3.0	3.7
Free area 10 to 20%	3.5	4.3	4.0	4.9

* For radial slots use X/H instead of $X/(A)^{1/2}$. H is the height or width of the slot.

Note: K and K' are indexes of loss in axial kinetic energy. Interpolate as required. Departures from maximum value indicate losses in first and second zones when compared with the jet from a rounded-entrance, circular nozzle.

Determining Centerline Velocities

To permit correlation of data from all four zones, centerline velocity ratios are plotted against distance from outlet in Fig. 8 in accordance with the basic relation of Equation 2, and a nomogram for calculating the parameters

$$\frac{X}{A_0} \text{ and } \frac{V_x}{V_c} \text{ from } \frac{X}{\sqrt{A}} \text{ and } \frac{V_x}{V_0}$$

through R_{fa} and C_d is given in the same illustration.

The variation of the centerline velocity ratio with distance from outlet or, more properly, from start of jet expansion, is also shown on Fig. 8 for Zones 1 and 2. V_x/V_0 is plotted against X/H_0 and, for a range of aspect ratios, against $X/\sqrt{A}$ for the single value of $K' = 7.0$. Values of V_x/V_0 for other values of K' may be obtained by direct proportioning of $\sqrt{K'}$ to $\sqrt{7.0}$.

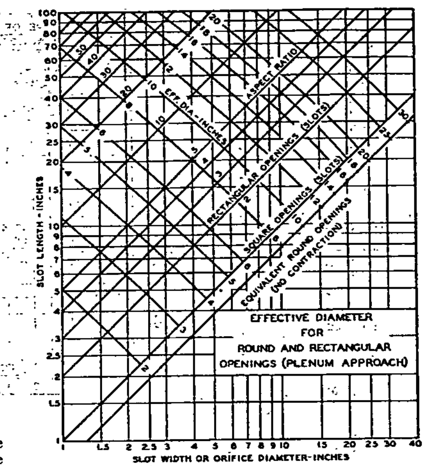

Fig. 7 .... Effective Diameters for Round and Rectangular Openings (Plenum Approach)

The following *Example 1* which is solved on Fig. 8 will illustrate the use of the chart.

Example 1: A grille has a core area 12 in. x 18.75 in., R_{fa} = 0.90, C_d = 0.80, and K' = 5.0. Find V_c (velocity through core area) when V_x is 50 fpm for throw of 50 feet (X = 50).

Solution:

$$A_c = \frac{12 \times 18.75}{144} = 1.56 \text{ sq ft}$$

$$\frac{X}{\sqrt{A_c}} = \frac{50}{1.25} = 40$$

$$A_0 = 1.56 \times 0.80 \times 0.90 = 1.123$$

$$\frac{X}{\sqrt{A_0}} = \frac{50}{1.06} = 47.2$$

$$\frac{V_x}{V_0} = \frac{K'\sqrt{A_0}}{X} = \frac{5\sqrt{1.123}}{50} = 0.106$$

$$\frac{V_x}{V_c} = \frac{V_x}{V_0(C_dR_{fa})} = \frac{0.106}{0.80 \times 0.90} = 0.147$$

For V_x = 50,

$$V_c = \frac{50}{0.147} = 340 \text{ fpm.}$$

The quantity of air discharged is then,

$$Q = V_cA_c = 340 \times 1.56 = 530 \text{ cfm.}$$

Throw

Equation 6 can be used to determine the *throw* X of an