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Building Pressures Caused by Chimney Action and Mechanical Ventilation

Air pressure differences and resulting air leakage patterns in buildings affect building performance[1] in a number of ways. The pattern of pressure differences depends upon the forces in operation. Air flow due to chimney action, resulting from differences in the density of inside and outside air, is particularly important in multi-story buildings and colder climates. When not affected by other forces, air flows in at low levels and out at high levels. The total pressure difference causing flow is the difference in weight of the inside and outside air columns for the height of the building involved. The distribution of this total pressure difference, or theoretical draft, depends upon the relative resistance to flow at the exterior enclosure and internal separations. With no internal separations, the full theoretical draft acts across the enclosure; with increasing pressure losses across internal separations, the pressure differences across the enclosure are correspondingly reduced.

Pressure distributions and flow patterns in buildings can be influenced by the design and operation of ventilation and exhaust systems. A net supply of air is sometimes provided to control air infiltration at entrances caused by chimney action in multi-story buildings. The effect of net supply or exhaust also depends upon the distribution of leakage openings within the buildings.

Little is known about air leakage in large multi-story buildings. In particular, information is lacking on the resistance to air flow within such buildings. Direct measurement in the field is usually not feasible, because it is not practicable to isolate the flow paths and measure the air quantities. The net effects can be measured, however, in terms of the distribution of pressure differentials under known conditions. It would be helpful in interpreting the results of such pressure measurements to know how these pressures and the resulting air flow are affected by the distribution of resistances in the exterior enclosure and internal separations. Such information would also be helpful in establishing the requirements for control of air leakage caused by chimney action.

This paper gives the results of an analytical study of the distribution of pressure differences caused by chimney action in buildings. Results are also given of the way in which these pressure differences are affected by various arrangements of excess supply and exhaust air.

DESCRIPTION OF THE MATHEMATICAL MODEL

The components in the mathematical model for the study are illustrated in Fig. 1 for a three-story building. The major separations are the exterior walls, walls of vertical service shafts, elevator shafts and stairwells, and the floor construction. To simplify the model, separations formed by partitions for various rooms on each floor were omitted. These partitions are generally interconnected in office buildings where partitions are movable and there are leaky suspended ceilings. Mechanical air supply and exhaust ducts are important in terms of their effect on the mass balance at each

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floor, and if not operating may represent interconnections between floors in addition to those provided by the internal separations. Provision was made in the model for net air supply or exhaust at each floor to determine its effect on pressure differences across the separations.

Air leakages in the exterior walls occur through interstices formed by windows and walls, cracks of openable windows, joints of curtain walls, and in some instances through the wall construction. Air leakages through the wall of the vertical shaft occur through cracks formed by elevator and stairwell doors and, in service shafts, through the space between pipes and ducts and the wall. Air leakages through the floor construction occur through cracks formed by the various service pipes and interstices formed by the exterior wall and the floor construction. In the model building, these leakage areas in major separations were lumped and represented by orifice areas. The following equation* was used to represent the mass flow through an orifice.

$$w = CA\rho^n(\Delta P)^n$$

where

w = mass flow
C = proportionality constant
A = orifice area
ρ = air density
ΔP = pressure difference across orifice
n = flow exponent

For most calculations a flow exponent of 1/2 (turbulent flow) was assumed; in some cases it was taken as 1 (laminar flow). Because of the combination of turbulent and laminar flows the value for leakage paths, as they occur in buildings, will vary between 1/2 and 1; for example, that for cracks in openable windows and doors is generally about 2/3.[2] Because the distribution of the available pressure difference due to chimney effect depends only on the relative resistances to air flow of the various separations, the orifice areas in the exterior wall, A_w, were used as a reference (i.e., taken as unity); and orifice areas in the floor construction and in the wall of the vertical shaft, A_f and A_s, were taken as multiples of the exterior wall orifice area for each story. For simplification, the area of the orifice representing the mechanical air supply or exhaust opening at each floor was the same as that representing the outside wall. The floor height of the model building was assumed to be 12 ft.

The value of the outside absolute pressures P_{O1} of Fig. 1 was taken as normal atmospheric pressure. With no wind, outside air pressures at other levels depend only on the specific weight of the air, which is a function of outside temperature. Inside pressures at various levels are inter-related by the weight of the column of inside air between levels and the pressure drop across the intervening floors. The problem entails determining the inside pressures in such a way that a mass flow balance is obtained for each floor and for the vertical shaft. The number of simultaneous equations equal the number of floors plus one. As the equations for an exponent of 1/2 are nonlinear, iterative calculations are required to solve for the unknown inside pressures.

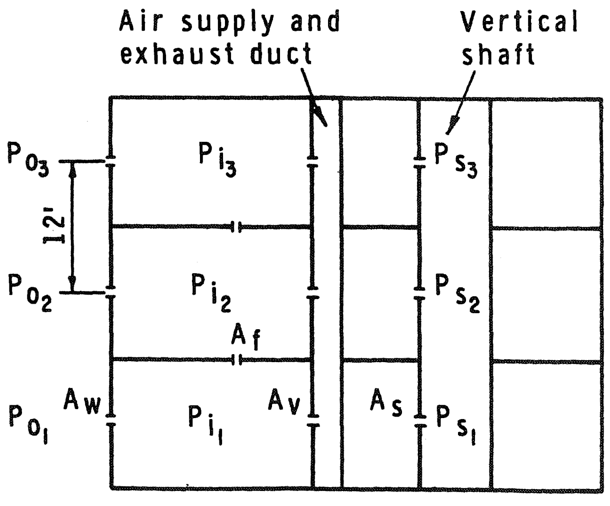
A computer program was formulated to solve all unknown absolute pressures inside the building and the resultant pressure differences across all major separations. The solutions were obtained with the aid of a digital computer. The computer program was designed to permit variation in the number of floors and in orifice areas from floor to floor. The amount of pressurization due to the operation of the mechanical ventilation system was defined in terms of the pressure difference across the ventilation orifice at each floor, ΔP_v. This could be varied from floor to floor.

RESULTS

Effect of Interior Openings and Height

A typical set of results is given in Fig. 2, for a ten-story building with a uniform distribution of openings in the vertical direction. For this distribution the neutral zone level, where inside and outside pressures are equal, is located at mid-height. With no internal resistance to flow (A_f/A_w and $A_s/$

Fig. 1 Mathematical model building



A_W = Exterior wall orifice area
A_f = Floor orifice area
A_S = Vertical shaft orifice area
A_V = Ventilation duct orifice area
P = Absolute pressure

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* See Appendix A.

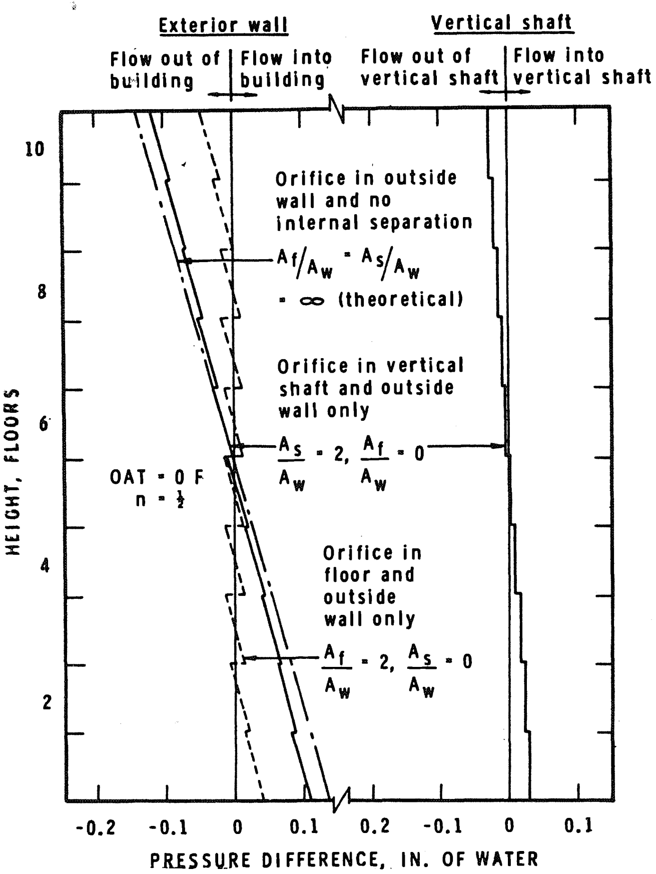


Fig. 2 Pressure differences due to chimney effect

$A_w = \infty$) there is no pressure drop across the floors; the sum of the pressure differences across the exterior wall at the bottom and top of the building is equal to the total theoretical draft for the building. With openings in the shaft only, there is an equal pressure drop across each floor; with openings in the floor only, this pressure drop increases toward the neutral zone level because of increasing flow rates in that direction through the floor openings. With resistance to flow imposed by the interior separations, the sum of the pressure differences across the exterior wall at any two levels is less than the theoretical draft by the sum of the pressure drops between intervening floors. With openings in the shaft only the difference between the pressure drops across the wall of the shaft at any two levels is equal to the pressure drop across intervening floors. The ratio of actual to theoretical draft is greater with openings in the shaft only than with openings in the floor only.

The pattern of air flow is evident from the pattern and magnitude of the pressure differences. Air flows into the building below the neutral zone and flows out above it. Similarly, air flows from the lower floors into the vertical shaft; and from the shaft into the upper floors. There is also an upward flow through openings in the floors.

The results illustrated in Fig. 2 are for an outside temperature of 0 F. For practical purposes the ratio of actual to theoretical draft, however, is independent of temperature when the pressures are due to chimney effect alone; any variations in the ratio occur because of the dependence of the flow relation on temperature.

The effect of variations in leakage areas and number of floors on the ratio of actual to theoretical draft is shown in Fig. 3. Calculations were made for an outside temperature of 0 F and an inside temperature of 75 F. With interior leakage openings only in the floors, all internal flow paths are in series; the actual draft decreases rapidly as the number of stories increase and is asymptotic to zero. The draft increases as the ratio of A_f/A_w increases, that is, as the resistance to flow within the building decreases. With interior leakage openings only in the vertical shaft and no pressure loss within the shaft, the resistance of the flow path from bottom to top of the building is independent of height, so that the ratio of actual to theoretical draft is constant for any value of A_s/A_w, regardless of the number of stories. In an actual building some pressure loss within the vertical shafts would occur so that some increase in the resistance of the flow path through the vertical shafts would occur with increasing height. For a building with three floors, the resistance to flow through openings only in the shaft is the same as

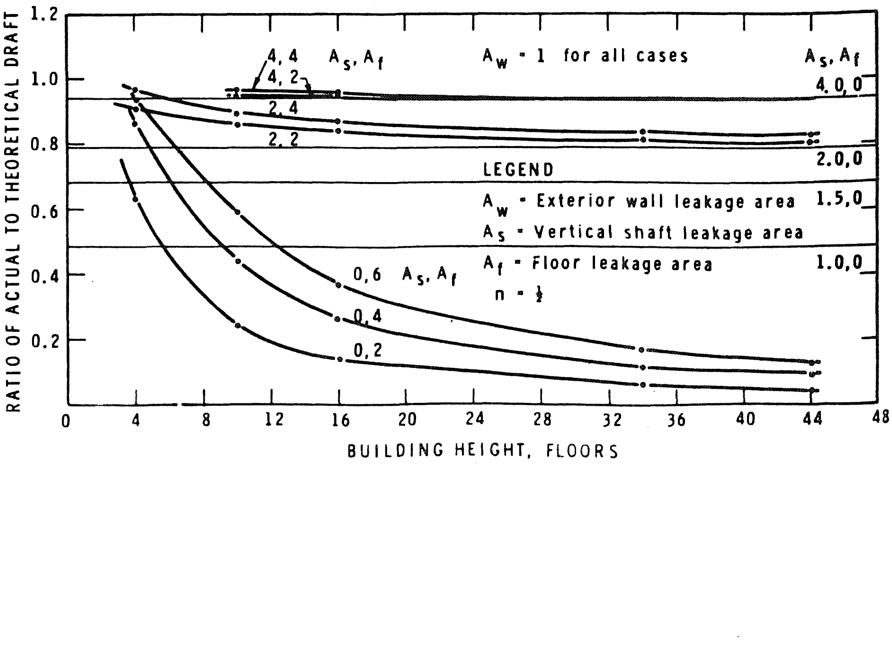


Fig. 3 Effect of building height and separation openings

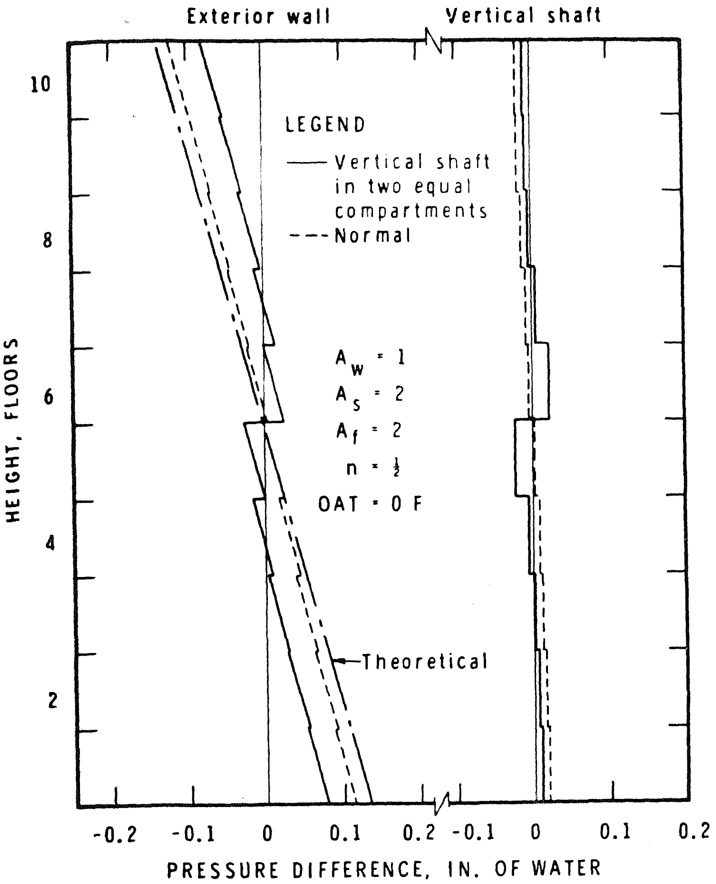


Fig. 4 Effect of dividing vertical shaft in two equal compartments

that through similar openings only in the floor, so that the ratio of actual to theoretical draft is the same.

The effects of combinations of leakage areas in the vertical shaft and between floors are also shown in Fig. 3. As the building height increases the resistance to series flow through floor openings increases; for high buildings the ratio of actual to theoretical draft depends mainly on the resistance of the flow paths through the vertical shafts. The values for a flow exponent of unity for most combinations of leakage areas are different from those shown in Fig. 3, but the trends are similar. With A_f and/or A_s larger than A_W the ratio of actual to theoretical draft is less with n = 1 than with n = 1/2.

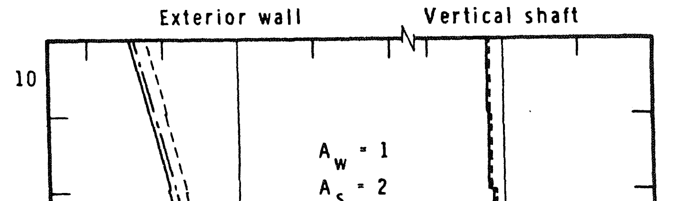
Fig. 3 indicates that for tall buildings the resistance of openings in the vertical shafts in relation to those on the exterior is the dominant factor in determining the distribution of the pressure differences due to chimney action. To reduce pressure difference across exterior walls the resistance of the flow path through the shaft must increase. In an actual building this requires tighter elevator and stairwell doors and more effective sealing of ducts and pipes passing through the wall of the ventilation shaft. The net effect is a greater pressure drop across these components.

The resistance to upward flow through the building will be increased if the vertical shafts are not continuous. An example of this is given in Fig. 4 for the ten-story model in which there is complete separation of the vertical shaft at mid-height. Thus, all air flowing from the lower half of the building to the upper must pass through the floor opening at mid-height, and there is an increase in pressure drop across the floors and shaft in this region.

The relative resistances to flow used for this and succeeding examples ($A_W = 1$, $A_s = 2$, $A_f = 2$) appear to be within the range anticipated in actual buildings.[3] For the conditions of Fig. 4 the ratio of actual to theoretical draft across the top and bottom of the building is reduced from 0.86 to 0.58. The total air leakage into the building is also reduced by approximately 34% for the conditions illustrated.

With complete separation of the vertical shaft at mid-height, the building acts somewhat as two separate buildings, one above the other, with a neutral zone level associated with each. If there were complete separation of the two halves, including elimination of the openings in the intervening floor, they would act independently and there would be maximum pressure differences across the intervening floor. In an actual building, however, it would be difficult to separate the upper and

Fig. 5 Effect of opening main entrance doors



lower halves of the various vertical shafts completely, and the effects on the various pressure differences would be correspondingly less.

The examples given so far have been for model buildings with a uniform vertical distribution of openings in the enclosure. In an actual building one level may have larger openings than the others; for example, because of doors the area of the ground floor openings may be larger than those at other levels. Fig. 5 shows the pressure distributions for the ten-story model with A_w for the ground floor of 1 and 8, and A_w for the other floors constant at 1.

With increasing A_w at the ground floor, the pressure difference across the entrance decreases; correspondingly, there is a significant increase in the pressure difference across the vertical shaft and floors at the lower levels. The effects of increasing A_w at the ground floor diminish with height; there is some lowering of the neutral zone level and some increase in the pressure difference across the exterior walls and vertical shaft at the top of the building.

For the example illustrated by Fig. 5, the over-all increase in air leakage resulting from an increase in A_w at the ground floor level from 1 to 8 is 35%; the increase in leakage into the 1st floor amounts to 194%. Infiltration through outside walls of the second and succeeding floors is decreased.

It is sometimes proposed that ground floor entrances to high buildings be opened to facilitate traffic flow to shops. Fig. 5 indicates the effect of this on pressure patterns due to chimney action. As noted, there is a large increase in ground floor infiltration and pressure differences across vertical shafts. The use of air curtain entrances is sometimes suggested to control these pressure differences and air leakage; it should be recognized that, for a given entrance infiltration, the air curtain entrance will operate with the same pressure difference across it as that at any other entrance. For example, to revert to the leakage condition represented by an entrance having A_w = 1, as in Fig. 5, the entrance must sustain a pressure difference of about 0.1 in. of water.

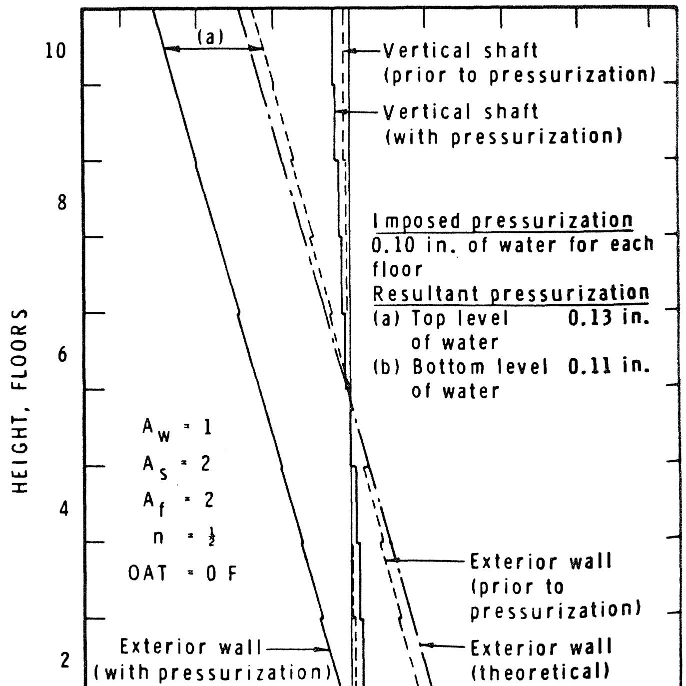
Curves in Fig. 5 are for an arbitrary ratio of A_s/A_w and A_f/A_w of 2. With larger values of A_s and A_f the pressure drop across the entrance for a given value of A_w at the entrance, would be greater. At the same time the pressure loss within the building would be less and there would be a greater pressure drop across the outer walls at the top of the building. The converse would occur with smaller values of A_s and A_f.

Effects of Pressurization

The effects of an imbalance of supply and exhaust air were investigated with the 10-story model. The imbalance on any floor, referred to as "imposed pressurization," was defined in terms of the pressure difference across the air supply or exhaust openings. As these openings were assigned unit area the same as the openings in the exterior wall, A_w, the imposed pressurization can be readily converted to an equivalent air flow through the exterior. The effect of this imposed pressurization on both the pressure differences across the exterior walls, referred to as resultant pressurization, and on the pressure differences across the interior separations, will depend on the distribution of excess supply or exhaust from floor to floor; the effect will also depend on the pressure distribution prior to pressurization. If there is no initial pressure difference across the enclosure and the pressurization is imposed uniformly at all floors, the resultant pressure difference across the enclosure will be the same at all levels and equal to that imposed.

Fig. 6 illustrates the effects of combined pressurization and chimney action, with equal excess air supply at all levels equivalent to an imposed pressurization of 0.10 in. of water, which neutralizes the pressure difference across the ground floor entrance. The resultant pressurization is somewhat greater than that imposed and increases from bottom to top because a non-linear flow relation is assumed. For a flow exponent of one, the resultant pressurization would equal that

Fig. 6 Effect of uniform imposed pressurization on stack pressure differences



imposed. It will also be noted that the pressure difference across the floors is less when the building is pressurized uniformly. Because the flow relation is non-linear there is less upward flow through the building; for high values of imposed pressurization the ratio of actual to theoretical chimney draft approaches one. For linear flow conditions this ratio is constant.

An equal excess of supply air on all floors, as illustrated in Fig. 6, can be effective in reducing the pressure difference across exterior walls at lower levels, but there is a penalty in increased pressure differences which cause exfiltration at higher levels. The total excess air supply, which must be provided by outside air, is equivalent to 290% of the air infiltration with no pressurization for the conditions illustrated.

Pressure differences across ground floor entrances can be neutralized by providing an excess air supply only on that floor. In the 10-story model this requires an imposed pressurization on the ground floor of 1.2 in. of water (Fig. 7). The pressure distribution across the exterior wall, floors and vertical shaft is essentially the same as that illustrated in Fig. 5, in which pressure differences across the entrance were neutralized by increasing the area of the entrance opening, A_w, to about 8.

The excess air supply required in Fig. 7 is approximately equivalent to the air infiltration through the enlarged entrance opening in Fig. 5. It must be supplied by the introduction of outside air through the ventilation system; the amount required is about equal to the total air infiltration without pressurization. Infiltration on other floors below the neutral zone level is about 37% of the original total infiltration. This infiltration, together with the excess supply air required to neutralize the pressure difference across the entrance in Fig. 7, is substantially less than the total excess supply air required with uniform pressurization at all levels. Consequently, the increase in pressure difference across upper levels of the building is much less than that in Fig. 6. With a greater resistance to flow within the building the increase in pressure difference at upper levels would be still less; with a lower resistance there would be a greater effect at upper levels and a greater excess air supply required to neutralize the pressure difference at the entrance.

To counteract pressure differences from chimney action across exterior walls in the upper floors requires an excess of exhaust air over supply. One approach, involving net supply below the neutral zone and net exhaust above, is illustrated in Fig. 8, where the imposed pressurization is 0.1 in. of water for all floors - positive below the neutral zone and negative above it. The resultant pressurization is less than that when excess air supply at all levels is uniform (Fig. 6), but is equal and of opposite sign at the top and bottom. Pressure differences across the floors and vertical shafts are greater than with no pressurization. This arrangement has the advantage that pressure differences across both top and bottom of the enclosure are reduced.

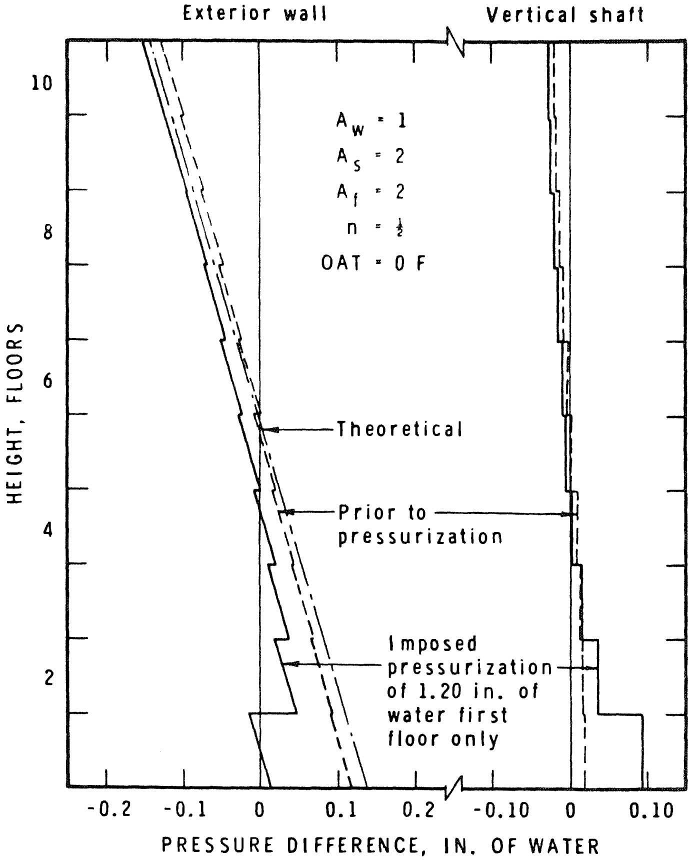


Fig. 7 Effect of first floor pressurization to neutralize entrance pressure difference

The second example in Fig. 8 is for the 10-story model with vertical shafts split at the mid-height, as in Fig. 4. With the same excess supply and exhaust in lower and upper halves of the building, as in the example above, a much greater pressure difference occurs across the floor at mid-height. The result is that pressure differences across the enclosure are essentially balanced at top and bottom of the building, while there are substantial pressure differences causing exfiltration immediately below mid-height and infiltration immediately above. The greater the increase in resistance to flow inside the building in relation to that of the exterior, the greater will be the pressure difference across the floors and vertical shafts and the resultant pressurization for a given excess of supply or exhaust air.

In theory it would be possible to neutralize the pressure difference across outside walls due to chimney action over the full height of the building by controlling excess supply or exhaust in each story. This is illustrated in Fig. 9 for the 10-story model. To maintain an average pressure difference of zero across the walls of each story, the pressure difference across each floor separation must equal the theoretical draft from floor to floor. With uniform floor spacing the total theoretical draft for the building is thus distributed uniformly between the floors.

Similarly, with no pressure difference across openings in the exterior wall the total theoretical draft is divided between the top and bottom openings into the vertical shaft in proportion to the resistance of these openings. The pressure difference across openings into the vertical shaft at any other floor is then the pressure difference across the ground floor opening less the sum of the pressure differences across intervening floors. The pressure difference pattern for the vertical shaft is independent of the resistance to flow of openings in the exterior wall and floors and can be readily established for any assumed distribution of openings in the shaft. The excess supply or exhaust air required on any floor to neutralize pressure differences across the exterior wall is independent of the leakage characteristics of the wall; it depends upon the distribution of openings in the floor and vertical shaft and can be readily calculated for any assumed distribution once the pressure difference pattern is established.

In Fig. 9, the excess supply and exhaust air required is again defined in terms of imposed pressurization, that is, the pressure difference across unit area to provide the necessary flow. Fig. 9 is based on a flow exponent of 1/2; excess supply and exhaust air requirements are thus in proportion to the square root of the imposed pressurization. As an example, assume that leakage through the exterior wall is equivalent to one air change per hour at a pressure difference of 0.104 in. of water. This is the pressure difference due to chimney action across the ground floor walls in Fig. 9 prior to pressurization and is equivalent to the velocity head of a 15 mph wind. Taking A_w and A_f equal to 2 and A_w equal to unity, the imposed pressurization required to neutralize chimney action on the ground floor is 1.07 in. of water as in Fig. 9. The excess supply air required on the ground floor then amounts to $1 \times (1.07/0.104)^{\frac{1}{2}} = 3.35$ air changes per hour. By a similar calculation the excess supply required on the second floor is 1.9 air changes. For buildings with several stories, the excess supply or exhaust air required depends primarily on the effective area of openings into the vertical shaft. Pressurization, as illustrated in Fig. 8 and 9, could be provided by a separate interior air handling system, exhausting air from floors above the neutral zone level and discharging it in floors below.

CONCLUSIONS

1. With no other forces in operation, the total or theoretical pressure difference caused by chimney action is distributed across the exterior enclosure and internal separations in proportion to the relative resistances to flow of these components. With a high resistance to upward flow in the building (in relation to the resistance of the building enclosure) the pressure differences across the enclosure are

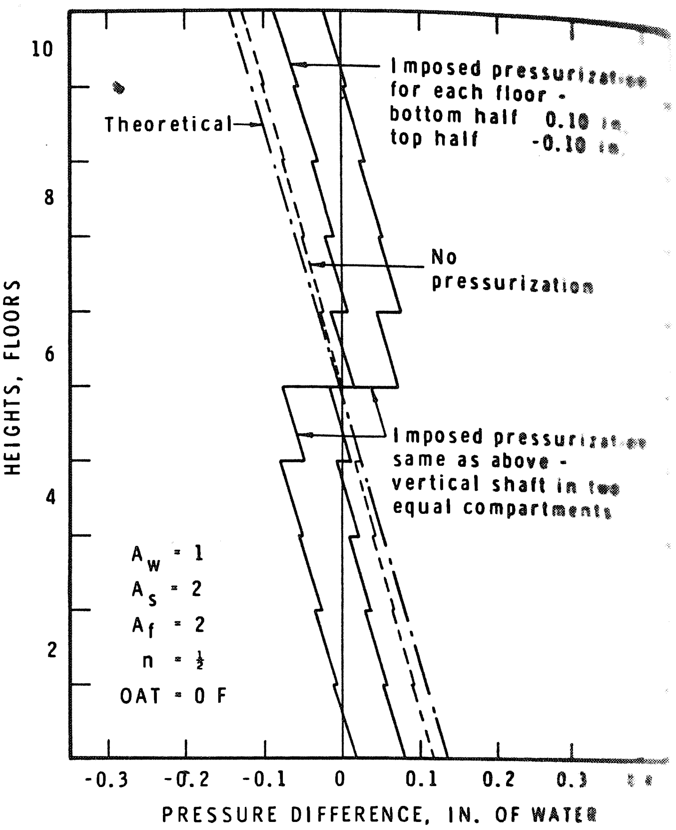
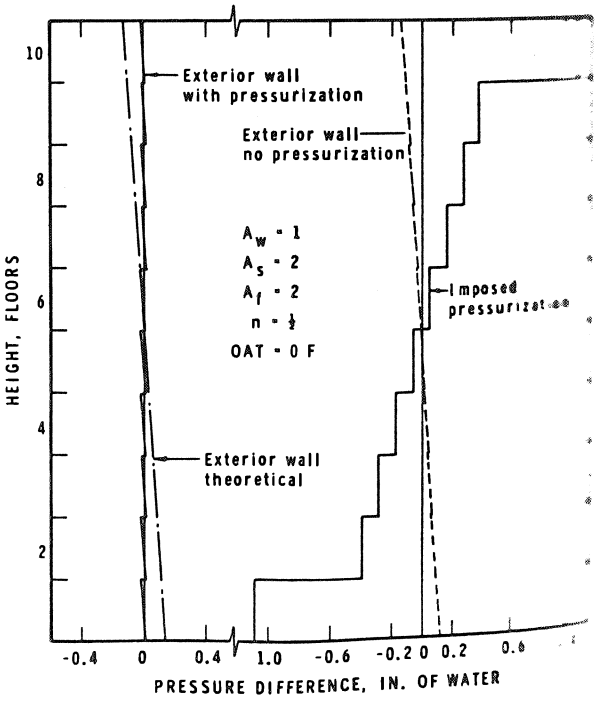


Fig. 8 Effect of non-uniform imposed pressuriza

Fig. 9 Imposed pressurization to neutralize exterior wall pressure differences.



reduced and those across internal separations increased. For buildings with many floors (e.g., more than ten) the resistance to air flow through floor openings tends to become high, and the resistance of openings into vertical shafts becomes the dominant factor in determining the ratio of actual to theoretical pressure differences from chimney effect. Construction and design features that increase the resistance of the flow path through the vertical shafts will have the most effect in reducing pressure differences across the building enclosure.

2. The effect on pressure differences of increasing the entrance area at the ground floor depends on the resistance to flow within the building in relation to that of the building enclosure. In general, there is a reduction in the pressure difference across the entrance and a corresponding increase in the pressure difference across separations above; with a significant resistance to upward flow, most of this increase in pressure difference occurs across the ground floor entrance to vertical shafts and across the floor construction above.

3. Pressurization (providing an excess of supply or exhaust air) offers possibilities for the control of pressure differences from chimney effect by altering the distribution of the theoretical pressure difference across the various separations. Excess supply air introduced uniformly at all levels can be effective in neutralizing the pressure difference across ground floor entrances, but there will be a corresponding increase in the pressure differences causing exfiltration at upper levels. The total amount of excess outside air required depends upon the tightness of the building enclosure.

4. If pressurization is to minimize pressure differences at the entrance, there is a potential advantage in pressurizing only the ground floor. If there is a significant resistance to upward flow within the building, the resulting pressurization at other levels will be significantly less than that at the ground floor, and the total excess air required will be much less than with uniform pressurization imposed on all floors.

5. If the building provides a significant resistance to upward air flow, it is possible to minimize chimney pressure differences across the building enclosure by providing an excess of supply air at lower levels and an excess of exhaust air at upper levels. The ultimate arrangement would neutralize these pressure differences on each floor. The amount of excess supply or exhaust required depends upon the resistance to flow within the building and is independent of the leakage characteristics of the enclosure. For multi-story buildings the resistance to flow depends primarily on the resistance imposed by the vertical shafts.

6. The distribution of pressure difference due to chimney action and excess supply or exhaust air, and the air flows that result can be determined analytically if leakage characteristics are known. Appropriate values for the leakage characteristics, particularly those for openings between floors and into vertical shafts, can only be determined by measurements on actual buildings. Interpretation of such measurements can be assisted by the results of mathematical studies such as those presented in this paper.

ACKNOWLEDGEMENT

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APPENDIX A

DERIVATION OF MASS FLOW EQUATION FOR A FLOW SYSTEM

For the flow problem considered in this paper it can be expected that

$$E = f(R_e)$$

where

E = Euler's number

R_e = Reynold's number

For small ranges of ΔP and V

$$\frac{\Delta P}{\rho V^2} = K\left(\frac{VD\rho}{\mu}\right)^m$$

$$V = K'\,\Delta P^{\frac{1}{2+m}}\,\mu^{\frac{m}{2+m}}\,\rho^{-\left(\frac{1+m}{2+m}\right)}$$

$$w = AV_{\rho}$$

$$= K'A\,\rho^{\frac{1}{2+m}}\,\Delta P^{\frac{1}{2+m}}\,\mu^{\frac{m}{2+m}}$$

Let $$n = \frac{1}{2+m}$$

$$w = K'A\rho^n\,\Delta P^n\,\mu^{1-2n}$$

Let $$C = K'\,\mu^{1-2n}$$

$$w = CA\rho^n\,\Delta P^n$$

DISCUSSION

NEIL B. HUTCHEON (Ottawa, Ontario): It will be evident that this kind of study is important, but it is also very demanding and a difficult kind of study to carry out. Not only is the situation you are trying to analyze quite complex, but, in addition, you must have available a building in which to make the measurements. It will be quite evident, I think, that it requires a very understanding and cooperative owner to allow you to enter a building at odd hours, punch holes in his walls, and clutter up his equipment room. We have been extremely fortunate in getting such cooperation from the owners of these buildings.

I have one comment that adds a bit of reinforcement to the point stressed by Mr. Locklin and Mr. Wilson. I think it is quite clear that architects often design buildings without regard for some of the technical problems. The mechanical engineer must then do the best he can with the situations presented to him. Problems arising from chimney effect must be faced in the initial stages of planning of buildings. It may even be necessary to change our whole approach to the design of walls and floors to provide the necessary control over air movements in tall buildings.

I have one other comment. We have talked here about the heating season, primarily. Under a cooling season the chimney effect is reversed. The tendency is greatly reduced, however, because you get only a few degrees temperature difference in the summer conditions compared with very large temperature differences in the winter.

RICHARD E. BARRETT AND DAVID W. LOCKLI (Columbus, Ohio): This paper (Trans. No. 2046 makes a significant contribution to the design o tall buildings by providing a detailed look at thre actual buildings. The concept of theoretical draf has been known and used for many years but, until now, there has been a noticeable void in relating theoretical models to actual buildings. The lack of data in this area has been partly due to the complexities of the problem, with air leakage, pressure differentials, air-conditioning fans and controls, and environmental aspects all interrelated. The authors are to be complimented for tackling such a problem and producing meaningful results.

We at Battelle Memorial Institute have used detailed computer models to evaluate air flows and pressure differentials for important leakage paths in several tall buildings, and find that the measurements presented in this paper generally verify the results we predicted for similar situations.

The difference between the measured air leakage rates through exterior walls and the National Association of Metal Manufacturers' standard points up the real problem of discrepancy between design and construction. Tests of building sections may show that a building wall design is adequate to provide a relatively tight wall; but it is another question as to whether the same leakage values can be maintained in the construction of a complete building. The problems of working in more taxing environments of temperature, wind, and elevation undoubtedly reduce the degree of care used in actual construction. Tests of the type performed by the authors are definitely important in providing the engineer with data on actual buildings and will enable better prediction of leakage values when designing new buildings.

The large pressure differentials measured across shaft doors to mechanical equipment rooms point to a possible problem area. The authors measured a pressure differential of 0.30 in. of water with a 40 F outdoor temperature and an indoor temperature probably near 70 F. For an outdoor temperature of -10 F, the pressure differential would increase to about 0.8 in. of water or 4.2 psf. This would be a force of 84 lb on a 20 sq ft door. Some rather simple measurements we made using a spring scale and several subjects indicated that (1) the force needed to open a door is about 10 lb greater than one-half the total pressure force on the door, and (2) the maximum pulling force a typical subject can exert is about 40 to 45 lb. For the door given above, and for a -10 F outdoor temperature, the opening forces would be 52 lb, which indicates a problem in opening the door under these conditions. The opening force grows proportionally greater for taller buildings, although using a two-door vestibule reduces opening forces. This condition could be eliminated by increasing the pressure in the mechanical equipment rooms by providing a positive means of bringing supply air into these rooms rather than using a spill damper from return air ducts or similar arrangements typically employed in present design practice.

The authors pointed out a difference in the ratio of actual to theoretical draft with the air-conditioning systems on and off. The ratio is affected by changes in exterior wall leakage as well as by changes in interior leakage. Therefore, a more plausible explanation of the lower ratios of actual to theoretical draft obtained with the air-conditioning systems operating may be that the resistance to leakage through the exterior wall by way of open intake and exhaust dampers was reduced rather than that resistance to flow through the internal flow paths was increased.

The second paper (Trans. No. 2047) provides an interesting analysis of a problem which is sufficiently complex that it is difficult to visualize intuitively. By investigating a simplified model, the authors have presented a generalized picture of the effect of changes in air leakage and pressurization and have avoided the complicating details associated with specific buildings. The results of this paper can guide engineers in the selection of allowable leakage ratios to achieve the particular mode of building operation that is desired.

The authors were concerned primarily with pressure differentials in this paper. But, as they mentioned, there is an air flow of significant quantity associated with these pressure differentials. In fact, some buildings have had heating equipment removed from upper floors because the stack effect flow of air from the lower parts of the building warms the upper floors. Some of the approaches discussed by the authors for reducing pressure differentials, per se, would result in a significant increase in stack effect air flow and, therefore, would probably be undesirable. These include pressurization of the first floor only and pressurizing the lower half while depressurizing the upper half of the building.

One point that the authors mentioned should be emphasized; a total pressure differential equal in value to the theoretical draft will occur in the building. This total pressure differential will be equal to the sum of (1) the pressure differential across the entrance doors, (2) the pressure differential across the exterior wall at the top floor, and (3) the pressure differentials encountered in going from the first floor to the top floor by any path. It is not possible to eliminate completely all of these pressure differentials.

The task of the building designer is to force the greatest portion of the total pressure differential or theoretical draft to occur at locations in the building which will cause the fewest problems for building operation and building tenants. For some buildings, a possible location for a large pressure differential to occur with a minimum of problems is across the exterior wall in the upper part of the building. This can be achieved by pressurizing the building. But, for pressurization to be practical, the exterior wall must be relatively tight to keep net supply air to a minimum. The authors have shown in the companion paper (Trans. No. 2046) that pressurization may not be practical without significant improvements in tightness of exterior wall construction.

AUTHOR WILSON: We appreciate the constructive comments of Messrs. Barrett and Locklin; in particular their emphasis on the dilemma of the designer, who must consider how best to distribute the pressure difference due to chimney action, as it cannot be eliminated.

We should make it clear that the intent of the first paper was not to promote any particular approach for controlling or altering the distribution of pressure differences resulting from chimney action. Our intent was to illustrate by example the manner in which the distribution of pressure differences would be affected by the relative resistances to flow of the building enclosure and interior separations, and the operation of the mechanical air distribution system.

The best approach in altering or controlling these pressure differences will, of course, depend on the particular circumstances; but for Canadian conditions with extended periods of sub-freezing outdoor temperatures in winter, I would be very hesitant to recommend to designers that they pressurize buildings in such a way as to increase significantly pressure differences leading to exfiltration through the enclosure in the upper parts of the building. Warm, moist air exfiltrating through joints and porous materials which occur in building enclosures as commonly designed and constructed, carries with it moisture which under wintertime conditions, will condense in the flow path. This mechanism leads to the deposition of very large quantities of water in the form of frost or ice, which can cause early and severe degradation of the structure.

A number of serious examples of this type of problem have come to our attention in recent years. We believe this is one of the more serious implications of air leakage, particularly in humidified buildings.

AUTHOR TAMURA: First of all, I would like to thank Mr. Barrett and Mr. Locklin for their helpful comments.

With reference to the second paper, perhaps it would be appropriate to make some additional comments on our estimate of the leakage characteristics of the exterior walls. In our tests there were several sources of error, most of which would tend to over-estimate the leakage rate. First, there is the estimate of the flow through the fan. Prior to the test the static pressure drop across each fan and fan speed were measured and recorded. Only those fans whose readings agreed approximately with the contractor's figures were used in the pressurization test. These readings were taken prior to the pressurization test. The flow rates of the fans would be affected to some extent, however, by changes in the air flow resistance of the system during the pressurization tests from its characteristics under normal operation.

Secondly, although the return air dampers were in a closed position to obtain 100% outside air, it is probable that some leakage flow occurred through the return air dampers, even though they were in the closed position to obtain 100% outside air, thus over-estimating the quantity of outside air.

Thirdly, although the outside dampers of fans not in operation were in the closed position, leakage openings through their dampers would represent additional openings in the exterior wall. Even with these possible sources of error, however, the air leakage rates of the exterior wall obtained would appear to be considerably higher than we would estimate from air leakage data on wall components.

In general, pressure differences across the interior separations were small and did not give rise to any problems. Relatively large pressure differences occurred across the stairwell doors leading to the top mechanical floor of the tallest of the three buildings. These doors were difficult to open. As pointed out by Messrs. Barrett and Locklin, the pressure difference across the door was 0.30 in. of water. In this same building noise due to air flow was very noticeable at the door of the elevator serving the forty-first to the forty-fifth observation floor. The pressure difference across these doors was approximately 0.20 in. of water. Opening of these elevator doors was accompanied by a noticeable gust of air, especially at the forty-fifth floor. Noise arising from airflow through crack openings around the doors depend on the configuration of the cracks and on the pressure difference across them. In an isolated case a loud air noise occurred across a door with a pressure difference of as low as 0.08 in. of water. Tests conducted by Mr. Barrett and Mr. Locklin on door openings are helpful in stating a maximum allowable pressure difference across interior separations.

As to their final comments relative to the lower values of the ratio of actual to theoretical draft with the ventilation system on, as compared to the values with it off, I find that I do not understand their explanation. As pointed out in the paper, with the system off, duct openings into the various floors would act as interconnections anc reduce the resistance to vertical flow within the building, thus tending to increase the ratio o actual to theoretical draft as defined; intake an exhaust dampers, if open, would act as opening in the exterior wall and would have the opposit effect. With the system on, however, we do nc think that it is a useful concept to regard the sup ply and exhaust openings as simple, passive open ings in the enclosure. Instead we regard them a sources of excess supply or exhaust air, their ef fect depending upon the final distribution of thi net supply or exhaust throughout the building

P. R. ACHENBACH (Washington, D.C.): Th authors ought to be complimented for these usef papers. However, I would like to ask a questi or two about Fig. 13 in the second paper (Tran No. 2047). The authors say, in applying the data, that they used the average pressure diffe ences across the enclosure from top to bottom. am wondering whether this is an arithmetic algebraic average and whether, in fact, this Fig.

is useful in evaluating what was happening in the way of airflow. In Fig. 11 they deny that there was a neutral zone in part of the building and an outward flow in the remainder. Even so, it would seem that Fig. 13 might have been useful in comparison with Fig. 11 when the building was pressurized virtually throughout its whole height with the ventilation system operating. In this case there was an average pressure difference of about 2/10, and in Fig. 13 I find there was a wall leakage of 4/10 to 6/10 cfm per sq ft of water, or total leakage somewhere between 100,000 and 150,000 cfm in building B. I would like a little clarification of the basis on which Fig. 13 was plotted, and whether it is, in fact, applicable to the other graphs.

Then, referring to the first paper (Trans. No. 2046), it seems to me that one of the most significant statements was in the last sentence before the conclusions, where the authors are talking about pressurization to reduce the effects. In their presentation they seemed to mention doing this by appropriate selection of supply and exhaust air, but in this last sentence they suggest doing it with an interior air handling system. It seems to me this is the right way to do it; by providing a stack indoors, especially for equalization, putting a cut-off in the neutral zone and using a blower at that level to draw air from the upper floors to supply it to the lower floors, you could exactly neutralize the indoor-outdoor pressure level at every level and neutralize the pressure differences across your stairway doors, not only alleviating the problem of door opening, but minimizing the total air exchange with the out-of-doors -- and you could do this using air that has already been conditioned by your heating or air-conditioning system.

AUTHOR WILSON: In reply to Mr. Achenbach's first comment, regarding Fig. 13, we would say that his application of it to the conditions of Fig. 11 is appropriate, within the limitations of the air flow data as outlined in Mr. Tamura's response to the comments of Messrs. Barrett and Locklin. In constructing Fig. 13, the average pressurization corresponding to a given net excess air was obtained by determining values of the difference between exterior wall pressure difference with and without pressurization at the permanent pressure top locations described in the paper, along with that across the ground floor entrance, and by determining the arithmetic average of these values. This amounted to averaging the pressurization effects at three levels in buildings A and B, and at five levels in building C. The amount of pressurization measured in this way naturally varied with the outside air temperature, that is, with the amount of pressure difference due to chimney action, because of the non-linear flow characteristics of the building enclosure. This is evident in Fig. 13 when comparing the two curves for building B. Thus, in utilizing Fig. 13 with reference to conditions in Fig. 11, the building leakage characteristic for an outside air temperature of 32 F would be applicable.

In connection with Mr. Achenbach's comments on the internal air handling system, I might reiterate that it was not our intention in this paper to promote any particular way of achieving a balanced air pressure across the enclosure at any or all levels. Zero pressure difference across the walls from top to bottom could be achieved by excess supply or exhaust of air obtained either from inside or outside the building. When obtained inside the building there is potential saving in heating costs but there is the added cost of the interior air handling system.

We were talking about this with our Chairman, D. S. Cooper. He mentioned that in some buildings there is a separate mechanical equipment room and air handling system for each floor. In this case it would be a relatively simple matter to control net supply and exhaust of outside air to balance exterior wall pressure differences. The outside air quantities required and therefore the increased heating costs would depend on the tightness of the floor separations.

If the pressure differences across the exterior walls are neutralized at each floor level, utilizing either inside or outside air, the pressure differences due to chimney action are then distributed uniformly across each floor. This does not overcome, however, the problem of excessive pressure differences across entrances to vertical shafts. Disregarding pressure losses within the shaft, the sum of the pressure differences across the doors of the vertical shafts at top and bottom of the building is equal to the total theoretical draft. The pressure difference across the doors of the shafts decreases uniformly toward the neutral zone of the shafts where it becomes zero.