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Computer Analysis Of Smoke Movement In Tall Buildings

Smoke and heat from fire in buildings has long been recognized as a potential hazard to occupants. With the increasing numbers of tall buildings in recent years, there is growing concern regarding the control of smoke movement as it relates to evacuation and fire-fighting.[1,2,3,4,5.]

Before methods of controlling smoke movement can be evaluated, it is necessary to understand the factors that determine its pattern and rate of flow. With a localized fire, smoke will probably follow the normal air flow pattern caused by wind, stack action and the air handling system.[1,2] To understand smoke movement, therefore, one must understand the nature of air movement. It is not practicable to measure the rates of air leakage through all of the components of an actual building. Calculations can be made, however, with a digital computer if it is possible to define the air leakage characteristics of all of the elements through which significant flow occurs.[6,7]

This paper presents the results of (1) computer calculations of air leakage rates resulting from stack and wind effects in a hypothetical 20-story building, using leakage characteristics based on field measurements; and (2) smoke concentration patterns from stack effect for both steady and transient conditions.

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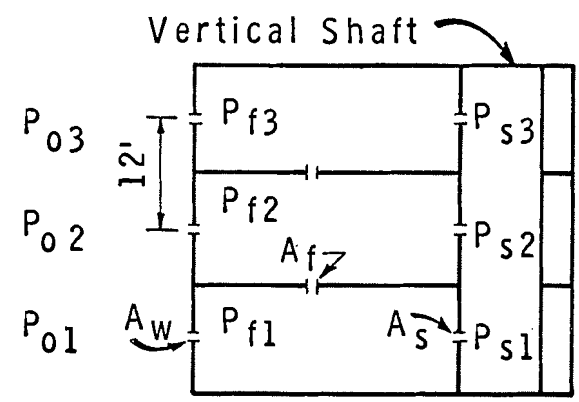
MATHEMATICAL MODEL

The mathematical model for this study has been described.[6] The basic components are illustrated in Fig. 1 for a 3-story building. Major separations are exterior walls, walls of vertical shafts, and floors. Leakage areas in the major separations are lumped and represented by orifice areas A_w, A_s, and A_f.



A_W = Exterior Wall Orifice Area
A_f = Floor Orifice Area
A_S = Vertical Shaft Orifice Area
P = Absolute Pressure

Fig. 1. Mathematical Model

The value of outside absolute pressure P_{o1} (Fig. 1) is taken as normal atmospheric pressure. Outside air pressures at other levels depend on the density of outside air and on wind pressure. Inside pressures in the floor, P_f, at various levels are interrelated by the weight of the column of inside air between levels and the pressure drop across the intervening floors. Inside pressures in the shaft, P_s, at various levels are interrelated only by the weight of the column of shaft air, assuming no friction pressure drop in the vertical shaft.

The problem entails determining the values of inside pressures with which a mass flow balance can be obtained for each floor and for the vertical shaft. A computer program was formulated using an iterative technique to solve for all unknown inside pressures. It was designed to permit variation in the number of floors, in the size of orifice areas and in the values of outside and inside air densities.

The plan dimension of the 20-story model building was taken as 120 by 120 ft. with a 12 ft height between stories. To establish realistic values of air tightness for major separations, leakage areas A_w, A_s and A_f were based on measurements in four buildings 9, 17, 34 and 44 stories in height. Description of the test buildings is given in Reference 8.

Air leakage characteristics of the exterior enclosures of three of the buildings varied from 0.5 to 0.8 cfm per sq ft of outside wall area at a pressure difference of 0.3 in. of water [8]. Based on 0.6 cfm per sq ft of outside wall area, a value of A_w for the model building of 2.5 sq ft per floor was assumed.

Measurements, on the four buildings, of pressure difference across the outside walls from stack action indicated that approximately 80 per cent of the total stack pressure difference is taken across the outside wall,[8] corresponding to a ratio of A_w to A_s of 1.0 to 2.0[6]. Using this ratio and the value of A_w, a total leakage area per floor for the vertical shafts, A_s, of 5.0 sq ft was assumed. Air leakage characteristics of elevator and stairwell shafts were measured in the 9- and 17-story buildings. Equivalent leakage areas per floor per car were approximately 0.5 sq ft for the elevator door and 0.5 sq ft for the elevator shaft wall. The wall is constructed of tile blocks and concrete for the 17-story building and of tile blocks for the 9-story building. Equivalent leakage areas per floor per stairwell door were 0.2 sq ft, for the stairwell door and 0.1 sq ft, for the stairwell shaft wall. For both buildings the walls of the stairwell are finished with plaster.

To determine the air tightness of the floor construction, the tenth floor of the 17-story building was pressurized with outside air, with test fans installed in the two stairwell door openings, and roof hatches and bottom doors in the stairwells opened to outside. The building air handling system was in operation so that it did not provide additional leakage openings. The leakage rate through the floor construction was obtained by taking the difference between the total air supplied by the test fans and the calculated leakage rates through the exterior walls and vertical shafts, based on their measured characteristics. The value thus obtained represents the leakage rate through cracks in the concrete floor construction formed by the various service pipes and by interstices formed by the exterior wall and the floor construction. The equivalent floor leakage area was 3.10 sq ft or 2.50×10^{-4} sq ft per sq ft of gross floor area. A value for A_f of 3.75 sq ft was assumed for the model building.

The tenth floor pressurization test was repeated with the air handling system off. The equivalent leakage area represented by branch air ducts serving the tenth floor was computed from the difference in the rate of air supply by the test fans with the system on and off. The leakage area was approximately 3.8 sq ft or 3.10×10^{-4} sq ft per sq ft of gross floor area. The value of 5.0 sq ft was assumed for the branch air ducts, giving a total of 10.0 sq ft for the value of A_s for the model building with the air handling system off.

The branch air ducts connected perimeter induction units and interior zone diffusers to high velocity main ducts, and return and exhaust grilles to low velocity mains. The second to sixteenth floors were served from the mechanical equipment located on the seventeenth floor.

Based on these measurements, the equivalent leakage areas for the 20-story model building are as follows:

$$A_w : A_s : A_f = 2.5 : 5.0 : 3.75 \text{ sq ft (air handling system on)},$$

$$A_w : A_s : A_f = 2.5 : 10.0 : 3.75 \text{ sq ft (air handling system off)}.$$

These leakage areas are for each floor and, for most of the calculations, are assumed to be the same for all floors. (The leakage areas of first floor and mechanical equipment floors usually differ from those of other floors, but for purposes of simplification, all are assumed to be the same.)

AIR FLOW PATTERNS

Air flow patterns in the 20-story model building were determined for the following conditions:

(1) stack action alone,
(2) wind action alone,
(3) combination of stack and wind action
(4) elevated temperature in a vertical shaft,
(5) elevated temperature in one floor.

Pressure difference and air flow pattern, and mass flow rate through each separation were determined for each condition. The pattern of smoke concentration throughout a building could then be determined for both transient and steady-state conditions for a given smoke concentration on a fire floor. For conditions (1), (2) and (3), a temperature of 85°F was assumed everywhere in the building. For conditions (4) and (5), a temperature of 75°F was assumed everywhere in the building except in the area of fire. These temperatures were assumed to remain constant with time.

Stack Action

Stack effect in a building is similar to stack effect in a chimney and is caused by a difference in temperature and, hence, a difference in the density of the inside and outside air. Table 1 gives values of pressure difference and air flow rate for each separation for an outside temperature of 0°F. Fig. 2 shows the air flow pattern resulting from stack action. Air flows into the building through the outside wall below the neutral pressure level (the level at which the pressure difference across the wall is zero), up through floors and vertical shaft and out through the outside wall above the neutral pressure level of the building. The total infiltration rate into the building is 1470 lb/min, with 1421 lb/min into the vertical shaft and the remainder through openings in the floor. Therefore, with a fire in a lower floor, smoke will migrate to upper floors with most of the upward flow taking place inside the vertical shafts.

Values of pressure difference and air flow rate in Table 1. are for the air handling system when it is on. When it is off, the total leakage area into the vertical shaft in each story is doubled, thus reducing the resistance to air flow within the building. Under these circumstances the total infiltration rate increases from 1470 lb/min to 1568 lb/min, with a corresponding increase in the flow rate in the vertical shafts. Because most of the total stack pressure difference is sustained by the outside walls, further decrease in the internal resistance to air flow (with the air handling system off) results in only a slight increase in the total infiltration rate and total flow rate in the vertical shafts. One half of the vertical flow is carried by the air ducts, and the flow rate in the vertical shafts is correspondingly reduced. The action of the air ducts as vertical shafts has important implications for smoke movement in buildings.

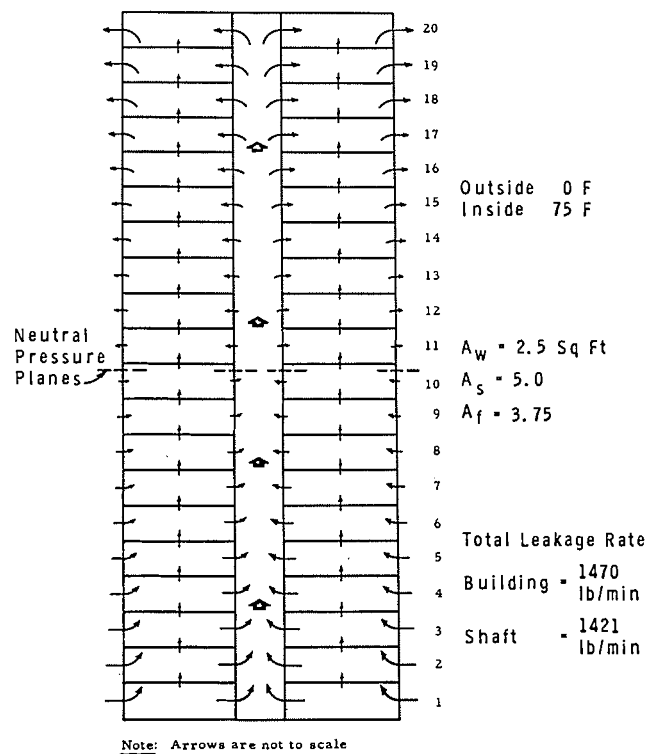


Fig. 2. Air Flow Pattern Caused by Stack Action

Fig. 2 represents the air flow pattern resulting from stack action when outside air temperature is below that inside. With an increase in the outside air temperature difference, there is a corresponding increase in the air leakage rates and an increase,

TABLE 1

PRESSURE DIFFERENCE AND AIR MASS FLOW CAUSED BY STACK ACTION

Outside – 0°F
Inside – 75°F

Leakage Areas per Story

A_w = 2.50 sq ft
A_s = 5.00 sq ft
A_f = 3.75 sq ft

	OUTSIDE WALL		VERTICAL SHAFT		BETWEEN FLOORS	
FLOOR NO.	ΔP IN. OF WATER	MASS FLOW LB/MIN	ΔP IN. OF WATER	MASS FLOW LB/MIN	ΔP IN. OF WATER	MASS FLOW LB/MIN
20	−0.227	−214	−0.045	−190		
19	−0.200	−201	−0.044	−188	0.0012	24
18	−0.176	−188	−0.041	−181	0.0030	37
17	−0.152	−175	−0.036	−172	0.0042	44
16	−0.129	−161	−0.031	−160	0.0049	47
15	−0.106	−146	−0.026	−146	0.0053	49
14	−0.083	−130	−0.021	−129	0.0055	50
13	−0.061	−111	−0.015	−110	0.0055	50
12	−0.039	−88	−0.009	−88	0.0056	50
11	−0.016	−57	−0.004	−56	0.0056	51
10	0.006	37	0.002	39	0.0058	51
9	0.028	80	0.008	81	0.0062	53
8	0.049	108	0.014	108	0.0063	53
7	0.072	129	0.021	129	0.0063	53
6	0.093	148	0.027	147	0.0062	53
5	0.115	164	0.033	163	0.0060	52
4	0.137	179	0.038	176	0.0056	50
2	0.185	208	0.047	194	0.0035	40
1	0.212	223	0.048	197	0.0014	25

NOTE: Outside Wall – + flow into building
– flow out of building

Vertical Shaft – + flow into shaft
– flow out of shaft

Floor – + upward flow
– downward flow

Total Infiltration Rate

Into building – 1470 lb/min
Into shaft – 1421 lb/min

TABLE 2

SMOKE CONCENTRATION VS TIME FOR 20-STORY BUILDING UNDER STACK ACTION WITH FIRE ON FIRST STORY

TIME	5 MINUTES			10 MINUTES			15 MINUTES			20 MINUTES			25 MINUTES		
FLOOR	FLOOR	ELEV.	STAIR	FLOOR	ELEV.	STAIR	FLOOR	ELEV.	STAIR	FLOOR	ELEV.	STAIR	FLOOR	ELEV.	STAIR
20					0.091		0.010	0.136		0.019	0.142		0.027	0.143	
19		0.011			0.119		0.013	0.140		0.021	0.142		0.029	0.143	
18		0.023			0.128		0.014	0.141		0.021	0.142		0.029	0.143	0.017
17		0.035			0.132		0.014	0.141		0.021	0.142		0.028	0.143	0.028
16		0.046			0.134		0.013	0.141		0.020	0.143	0.013	0.027	0.144	0.039
15		0.057			0.136		0.013	0.141		0.019	0.143	0.020	0.026	0.144	0.049
14		0.066			0.137		0.012	0.141		0.017	0.143	0.027	0.023	0.144	0.058
13		0.074			0.137		0.010	0.141		0.015	0.143	0.034	0.020	0.144	0.067
12		0.081			0.138			0.142	0.013	0.013	0.143	0.041	0.017	0.144	0.074
11		0.088			0.138			0.142	0.018		0.143	0.049	0.011	0.144	0.081
10		0.093			0.139			0.142	0.023		0.143	0.056		0.144	0.088
9		0.101			0.143			0.146	0.030		0.147	0.065		0.148	0.096
8		0.113			0.152	0.010		0.155	0.046		0.156	0.077		0.157	0.108
7		0.129			0.166	0.016		0.169	0.053		0.170	0.093		0.171	0.125
6		0.151			0.187	0.026		0.190	0.071		0.191	0.115		0.192	0.147
5		0.182			0.217	0.042		0.220	0.098		0.222	0.146		0.223	0.179
4		0.230	0.014		0.265	0.073		0.268	0.141		0.270	0.193		0.272	0.227
3		0.311	0.038		0.346	0.132		0.350	0.218		0.352	0.275		0.355	0.310
2	0.010	0.476	0.118	0.018	0.512	0.271	0.026	0.517	0.377	0.034	0.521	0.441	0.040	0.524	0.479
1	1.000	0.967	0.481	1.000	0.999	0.727	1.000	1.000	0.857	1.000	1.000	0.925	1.000	1.000	0.960

NOTE: Smoke concentration on first floor = 1.000; only those values greater than or equal to 0.010 are shown.

therefore, in the rate of smoke movement inside the building in the event of fire. During summer, with an outside air temperature above that inside, the air flow pattern is the reverse of that shown in Fig. 2; air flows into the building through the outside wall at upper levels and down through floors and vertical shafts and out of the building through the outside wall at lower levels. Because of the smaller inside-to-outside air temperature differences air leakage rates in summer are smaller than those in winter. For example, with an outside temperature of 90°F the total infiltration rate for the 20-story building is 583 lb/min, and for the vertical shaft 559 lb/min.

Wind Action

Wind effect on a building depends on wind speed and direction, on characteristics of the surrounding terrain, including shielding effect of adjacent buildings, and on building shape and height.[9,10,11] This is further complicated by the variable nature of wind, both spatially and with time.

The velocity profile shown in Fig. 3 is intended to represent a relatively flat terrain[9] (no shielding) and a mean wind velocity of 15 mph at 33 ft above ground, the usual reference height at meteorological stations. The wind pressure coefficients assumed for the 20-story building are 0.8 velocity head for the windward wall and −0.6 velocity head for the leeward and side walls. The leakage areas are assumed to be uniformly distributed in the perimeter of the building, so that for a square building the leakage area for the windward face is one quarter the total outside wall leakage area.

With these simplified conditions and equivalent leakage areas of A_w: A_s: A_f = 2.5: 5.0: 3.75 sq ft, the resultant air flow pattern from wind action is given in Fig. 3. As expected, air flows into the building through the windward wall and out through the leeward and side walls. The total outlet area in the outside wall being larger than the total inlet area, the pressures inside the building are closer to the negative leeward pressures. Wind velocity, however, increases with height, so that values of negative pressure inside the building in upper levels are greater than those at lower levels. This results in an upward flow of air inside the building, and outside air enters the building through the leeward and side walls at lower levels.

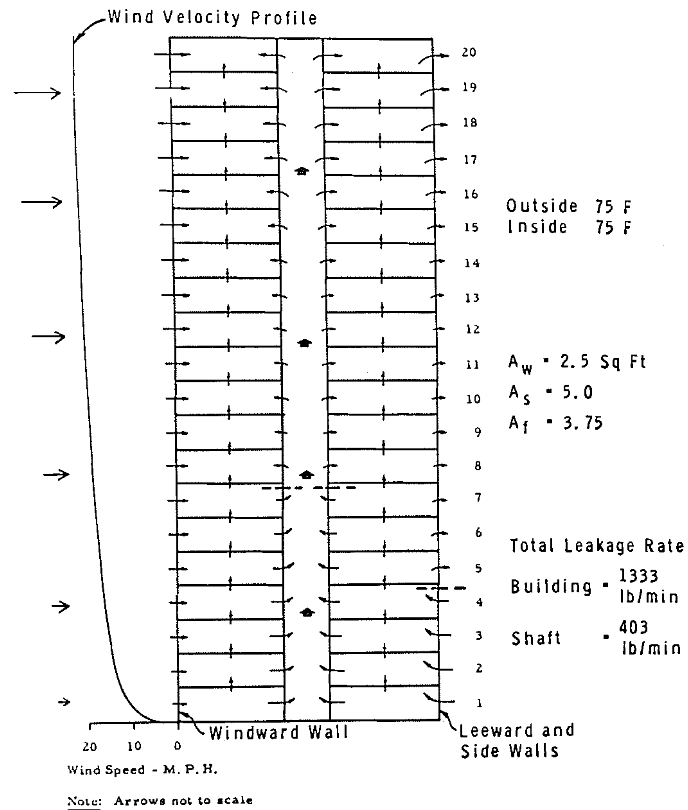


Fig. 3. Air Flow Pattern Caused by Wind Action

The total infiltration rate of the building is 1333 lb/min, which is approximately equal to the infiltration rate with the building under stack action. The corresponding vertical air flow rate is 403 lb/min, which is approximately equal to the vertical air flow rate due to stack action, with an inside-to-outside air temperature difference of only 10°F. If the inlet and outlet areas of the outside wall are equal, as with a quartering wind on a square-shaped building, the pressures inside the building are mid-way between the windward and leeward pressures and there is no vertical air movement. The air movement caused by wind is mainly from the windward to the leeward walls and in most cases contributes little to the spread of smoke from floor to floor.

Stack and Wind Action Combined

When the conditions of the two previous cases are combined, the resultant air flow pattern is different (Fig. 4). The air flow pattern caused by stack action is modified by the influence of wind action. For the conditions chosen, the total infiltration rate for the

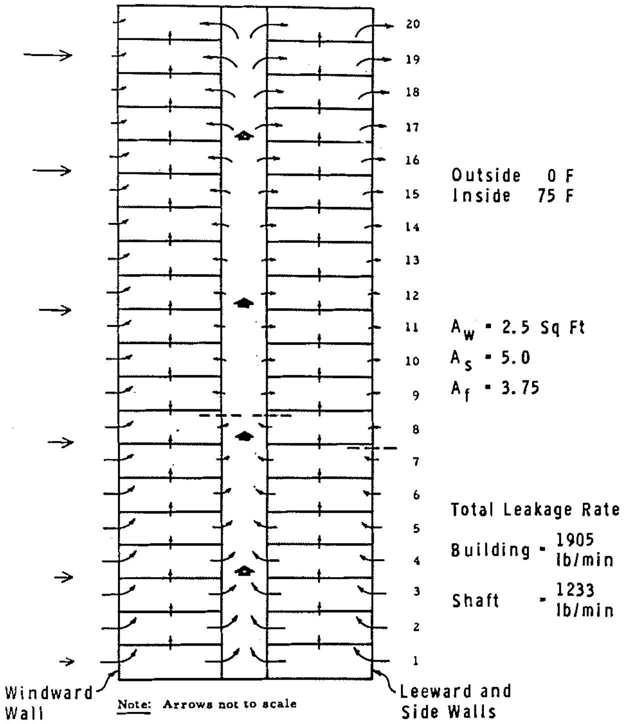


Fig. 4. Air Flow Pattern Caused by Wind and Stack Action

building is 1905 lb/min, which is 29 per cent greater than the infiltration rate due to stack action alone. The total infiltration rate into the vertical shaft is 1233 lb/min, which is less than the rate of 1421 lb/min obtained with the building under stack action alone.

Of the three cases considered, that of stack action alone results in the greatest vertical air flow rate and thus the greatest potential for smoke spread from floor to floor in the event of fire.

Fire in Vertical Shaft

To determine the influence on air flow patterns of a fire or high temperature gases in a vertical shaft the air inside the equivalent of a two-car elevator shaft was assumed to be at a uniform temperature of 500°F. Other air temperatures, both outside and inside the building, were assumed to remain at 75°F. Leakage area per floor was assumed to be 2.0 sq ft for the two-car elevator shaft, based on field measurements, and 3.0 sq ft for the remaining shafts, including those for the other elevators, giving a total vertical shaft leakage area A_s of 5.0 sq ft, as before.

The resultant air flow pattern is given in Fig. 5. The neutral pressure levels of the building and shafts are located between the ninth and tenth floors. Air flows into the elevator shaft below the tenth floor and out above it. A similar air flow pattern occurs across the outside walls. The reverse occurs, however, across the wall of the remaining shafts, together with a downward flow of air; and air flow is downward through all floors. Total infiltration rates are 1718 lb/min for the two-car elevator shaft, 904 lb/min for the remaining shafts, and 754 lb/min for the building. The rate of air recirculation within the building induced by high temperature in the elevator shaft is, therefore, 964 lb/min. Recirculation induced by a fire in a shaft would promote the spread of smoke throughout a building.

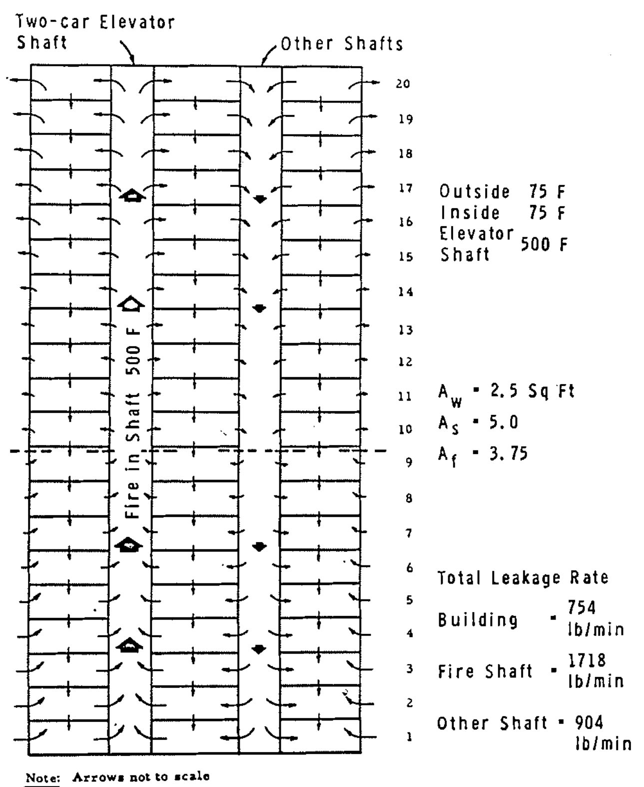


Fig. 5. Air Flow Pattern Caused by Fire in Elevator Shaft

Effect of Elevated Temperature on One Floor

In the absence of wind or stack action caused by inside-to-outside temperature differences, air circulation can be induced by elevated temperature on a floor containing a fire. For this case, the mathematical model was modified so that on each floor leakage areas in the vertical walls were divided and located at one-quarter and three-quarters of the floor height. Fig. 6 shows the air flow pattern and flow rates across the fire floor enclosure, in which the average air temperature is assumed to be 500°F; on other floors inside and outside temperatures are 75°F. Movement of air across the fire floor enclosure results in an induced air flow across the enclosures of the two floors above and below the fire floor.

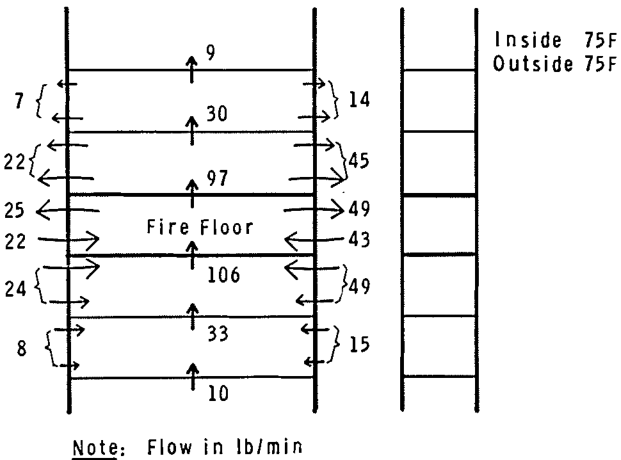


Fig. 6. Air Flow Pattern Caused by 500°F Temperature on Floor

Flow rates were also calculated for a fourth floor fire (air temperature of 500°F), assuming an outside air temperature of 0°F. The over-all air flow pattern is the same as that given in Fig. 2, with air inflow through the bottom and top openings in the outside walls of the fire floor and, similarly, air outflow from the fire floor through both openings in the walls of the vertical shafts. Increasing the temperature of the fourth floor from 75°R to 500°F caused a doubling in the rate of air outflow from the fire floor to the floor above and a decrease of 10 per cent in the flow rate into the vertical shaft.

Calculations were made for another case, similar to the above except for a large outside wall opening on the fire floor that represented a broken window. The resultant air flow pattern in shown in Fig. 7. Because of the large exterior opening the fourth floor pressure is close to outside pressure, so that there is a downward flow of air from the fourth to the first floors through the intervening floors. Otherwise the general air flow pattern is the same as before. If the fire floor were located above the neutral

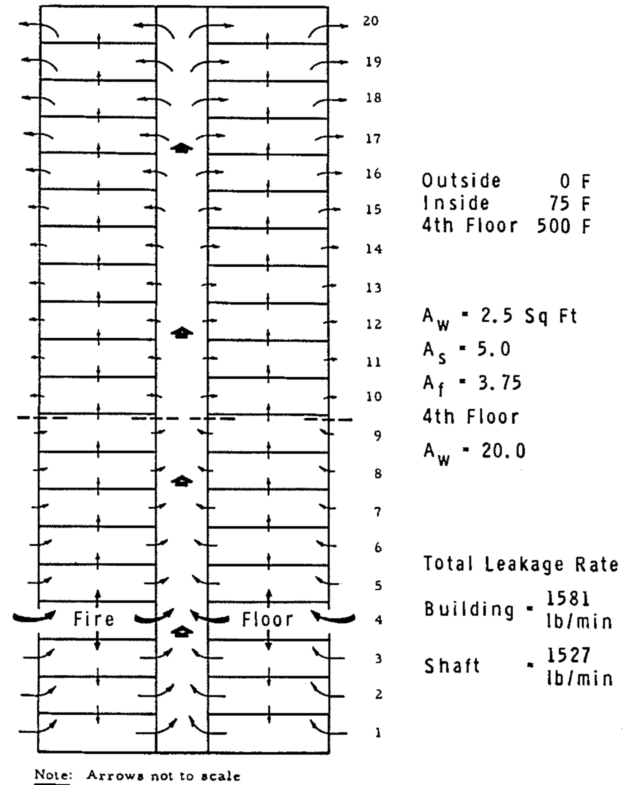


Fig. 7. Air Flow Pattern Caused by Fourth Floor Fire and Stack Action (Large Outside Wall Opening on Fourth Floor)

pressure level a similar reversal of flow would occur, with flow of air into the fire floor from the floor above. With a large exterior wall opening, the rates of air flow from the fire floor into the vertical shafts and into the floor above are increased by about 60 per cent. The rate of air flow from the fire floor into the floor below is 96 lb/min. It may be seen that smoke spread from the fire floor is increased significantly when there is a large opening in the outside walls (e.g. open doors or broken windows). It should be noted too that, with a building under wind action alone, a large opening in the windward wall of the fire floor would increase the pressure in the fire floor relative to adjacent floors and hence cause smoke to spread both upward and downward from the fire floor.

SMOKE CONCENTRATION PATTERN

Calculations were made of both steady and transient values of smoke concentration throughout the model building in relation to the concentration on the fire floor. It was assumed that the rate of smoke movement is a function of air flow rate, and that there is instantaneous mixing of smoke and air along all flow paths. The method of calculation is given in Appendix A.

Air temperature on the fire floor was assumed to be 75°F, as in the remainder of the building, so that air flow rates and patterns are constant with time. In an actual fire the leakage of heated air from the fire floor would result in increasing rates of air flow and smoke movement, but calculation of the rate of smoke spread for this condition is more complex.

Steady-State Case

The smoke concentration pattern was determined for the model building under stack action, using the air flow rates given in Table 1. and assuming that a fire on the first floor produced a constant smoke concentration of 1.0. The relative smoke concentration pattern for this condition is shown in Fig. 8. Dilution of smoke by infiltration of outside air gave a smoke concentration of less than one in vertical shafts and other floors. Concentration in the shaft is always equal to or greater than that on any floor because of the much higher air flow rates through openings in the floors. Floors four to ten were relatively smoke free. Smoke concentration in the shaft decreased with height to a constant value of 0.156 above the neutral pressure level of the shaft. Smoke concentration from the thirteenth to twentieth floors was essentially equal to this value.

The final steady values of smoke concentration depend on the ratios of flow rates into and out of each compartment. These ratios of flow rates are primarily dependent on the relative values of leakage areas, so that the values in Fig. 8 are approximately correct for other conditions where outside temperature is lower than inside temperature.

Transient Case

Table 2. gives the relative smoke concentration as a function of time for the model building under stack action, with air flow rates as given in Table 1. Initially, the smoke concentration was assumed to be 1.0 on the first floor and zero on all other floors. Air temperature was 75°F on all floors. The vertical shafts of the building were assumed to be made up of four elevator and two stairwell shafts, with total equivalent leakage areas of 4.5 sq ft and 0.5 sq ft per floor, and corresponding internal volumes of 3480 and 2400 ft ^{3} per floor, respectively.

Only smoke concentrations in excess of 0.01 (1 per cent of the smoke concentration on the fire floor) are shown. This concentration was selected as the critical value for the safety of occupants[5]. On this basis, smoke concentrations over the whole height of the elevator shaft, the lower levels of the stairwell shaft and the second floor are above the critical value at 5 minutes. At 10 minutes, floors 11 to 20 show signs of smoke contamination, and after 15 minutes floors 13 to 20 exceed the critical value. At 30 minutes the smoke concentration in all but floors 3 to 10 is above the critical level. The time taken to reach the steady-state values given in Fig. 8 is in excess of 3 hours.

Smoke concentration patterns were also obtained for fires on the second, sixth and eleventh floors. As expected, smoke contamination occurs in the shafts and floors above the fire floor. With fire on

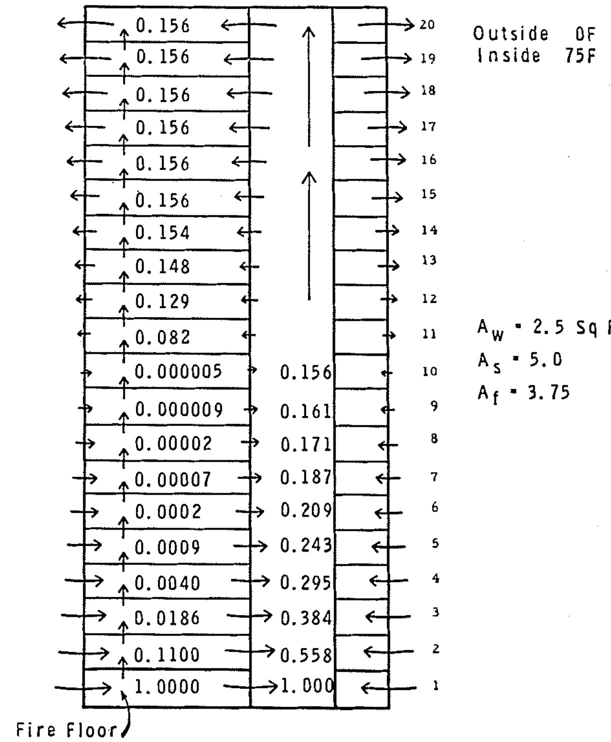


Fig. 8. Smoke Concentration Pattern Caused by Fire on First Floor and Stack Action - Steady State.

the second or sixth floors, the times to reach the critical smoke concentration level in the shafts and upper floors are similar to those for fire on the first floor. With fire on the eleventh floor (above the neutral pressure level of the building) only the floors above are affected, and vertical shafts remain smoke free. The time taken to reach the critical smoke concentration level in the twelfth and thirteenth floors is 5 and 25 minutes, respectively. The remaining floors are relatively smoke free.

Overall rate of air leakage in tall buildings depends primarily on the leakage areas in the outside walls and walls of the vertical shafts and not on the leakage areas of the floor.[6]

With the leakage area in the floor doubled, that is, A_w: A_s: (A_f) = 2.5: 5.0:(7.5), the total air leakage rate of the model building increases only slightly, from 1470 lb/min to 1483 lb/min. With a fire on the first floor, the change with time of the smoke concentrations throughout the building is not, in general, much affected and final steady values are similar to those given in Fig. 8.

With the leakage area in the outside wall reduced to one-half, that is, (A_w): A_s: A_f = (1.25): 5.0: 3.75, the total air leakage rate of the building decreases from 1470 lb/min to 799 lb/min and the rates of increase smoke concentration is approximately one-half those given in Table 2. Because the ratios of air inflow and outflow of each compartment is approximately the same as before, the values of smoke concentration at steady state are also similar to those given in Fig. 8.

For a building under stack action the worst situation with regard to smoke contamination and evacuation of occupants is with a fire in the lower floors. Escape routes such as elevator and stairwell shafts are quickly smoke logged and the upper floors are made untenable in a short time. In these calculations smoke concentration on the fire floor was assumed constant from time zero. In actual fire situations, the time available for evacuation also depends on the rate at which smoke develops from an incipient fire, the extent and nature of the fire, and the stage at which the fire is detected and an alarm issued.

SUMMARY

This paper describes a computer study of smoke movement utilizing a mathematical model of a 20-story building. The model was based on measured air leakage characteristics of four tall office buildings. The results indicate the relative influence of a number of factors on smoke movement in buildings.

Stack action is the principal mechanism by which smoke is transferred from a fire floor to other floors above. With fire on a lower floor during cold weather, smoke concentrations in elevators and stairwell shafts and on upper floors reach critical levels in a very short time. Smoke moves mainly vertically, in elevator shafts and air ducts, and, to a lesser extent, in stairwells. The vertical air movement, and hence the rate of smoke movement, caused by wind action alone is substantially less than that caused by stack action. A large opening in the outside wall of a fire floor at a lower level results in a greater rate of vertical smoke movement caused by stack action. With wind action alone, it is expected that a large opening in the windward wall of a fire floor would also cause an increase in the rate of vertical smoke movement.

If fire is present in a vertical shaft, the resulting high temperature causes an upward movement of air in the shaft and a downward movement in all other shafts. This can result in a recirculation of air through the heated shaft so that smoke will spread throughout the building.

These calculations of smoke movement were based on conditions of constant temperature throughout the building. Flow of heated air from an actual fire however, would cause a change in air flow rates and pattern with time, and make the calculation of smoke concentrations for this condition extremely complex. It is expected that rates of smoke movement for non-isothermal conditions are higher than those for the assumed constant temperature condition.

The present study emphasizes the need for measures to control smoke movement in order to provide for the safety of occupants and minimize smoke damage in the event of fire. Evaluation of various measures involving either changes in building design or the use of mechanical equipment can be facilitated by computer studies as described in this paper.

ACKNOWLEDGEMENT

The author is indebted to Mr. A. G. Wilson and to Mr. J. H. McGuire for discussions during the progress of the work; to Mr. H. A. Smith, who prepared the computer programs for the analysis of air movement; and to Mr. D. Templeton, who prepared the computer programs for the analysis of transient smoke movement.

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APPENDIX A
CALCULATION OF SMOKE CONCENTRATION

STEADY STATE CASE

For the steady state case, with a known smoke concentration in a fire floor, smoke flow balance is conducted in each compartment starting with the compartment adjacent to the fire floor and in the direction of the air flow pattern. In this way quantity of smoke entering each compartment is known and the smoke concentration in the compartment can be calculated. With reference to Fig. A-1, smoke balance equation for the n^{th} compartment is as follows:

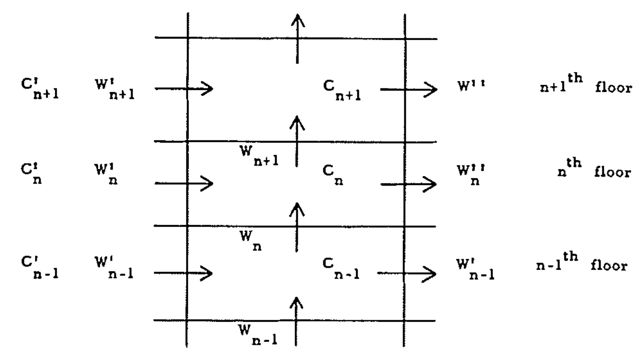

Fig. A-1

$$W_n C_{n-1} + W_n' C_n' = (W_{n+1} + W_n'') C_n \qquad (1)$$

where

W = air mass flow, lb/min

C = smoke concentration, lb of smoke/lb of air

then $$C_n = \frac{W_n C_{n-1} + W_n' C_n'}{W_{n+1} \quad W_n''} \qquad (2)$$

where C_n is the smoke concentration in the n^{th} compartment to be determined.

TRANSIENT CASE

For the transient case the equation for the n^{th} compartment is:

$$\rho V \frac{dC_n}{dt} + (W_{n+1} + W''_n) C_n = W_n C_{n-1} + W'_n C_n \qquad (3)$$

where

ρ = density of air, lb/ft^3

V = volume of compartment, ft^3

This equation assumes instantaneous mixing of smoke with air in the compartment. Each vertical shaft is divided into separate compartments of one floor height. For example, for a building with N floors and two vertical shafts, the total number of first-order linear differential equations required to describe transient smoke concentrations is 3N. This system of simultaneous equations is solved by a finite difference method to obtain the values of smoke concentration in each compartment at a given time.

DISCUSSION

C.J. ALLEN, (Albert Kahn Assocs., Detroit, Mich.): Can you explain why the neutral plane is not shifted in Fig. 7 with a large opening in the 4th (fire floor)?

MR. TAMURA: The location of neutral plane of the building depends mainly on the vertical distribution of openings in the outside wall. Assuming a uniform distribution of openings, the neutral plane of the building under the influence of stack action alone is located at the 10th floor as shown in Fig. 2. With a large opening in the outside wall at the 4th floor, the level of the neutral plane is shifted to the 9th floor as indicated in Fig. 7.

T. KUSUDA, (National Bureau of Standards, Washington, D.C.): How did you calculate the pressure distribution? What is the computer time for a steady state case? What is the computer time for a transient case?

MR. TAMURA: To determine the pressure distribution in a building, mass flow balance equation was set up for each floor and shaft compartment in the building. From these equations, inside pressures were calculated using an iterative method. The smoke concentration pattern for the steady state case as given in Fig. 8 was calculated with a desk calculator using Eq. (2) of Appendix A. The computer time required to calculate smoke concentration pattern for the transient case as given in Table 2 relative to real time was in the ratio of 1:8.

MR. KUSUDA: Can you give us the computer time as in Fig 7?

MR. TAMURA: The computer time required to determine the pressure distribution and, hence, the air flow pattern as shown in Fig. 7 was approximately 1½ hours. On the average, the computer time per case was approximately ½ hour. Computer calculations were conducted on IBM System 360.

R.E. BARRETT, (Columbus, Ohio): Mr. Tamura is to be complimented for another fine contribution to the understanding of this complex problem.

Although I realize that prediction of stack effect air flow is complicated, I was surprised to hear Mr. Tamura report that while stack effect produced an upward flow in the shafts of 1421 lb/min and wind produced a flow of 403 lb/min in the same direction, when stack effect and wind were considered together, the resultant flow was only 1233 lb/min, less than stack effect alone. Intuition suggests that when two mechanisms which produce similar effects are combined, the resultant effect should be greater than that produced by either mechanism alone. Would the author like to comment on this?

As evidenced by the references listed in Mr. Tamura's paper, there has been significant interest in the past few years in both the practical and analytical problems associated with stack effect and wind and the accompanying air and smoke movement. Further interest was evidenced at the Symposium on "The Control of Smoke Movement on Escape Routes in Buildings" held at Hertfordshire, England in April. Therefore, we might logically ask the question, where do we go from here insofar as application of analytical techniques to building design.

First we must answer the question, "Can these analytical studies be of value in improving the design of tall buildings?" It appears to me that we should *not* be satisfied with the current design practice for tall buildings from both the environmental and safety aspects. Considering environmental factors, air movement due to stack effect in tall buildings is accompanied by drafts and noise and difficulty is encountered in the operation of doors (leaf and elevator) due to pressure differences. Safety considerations include the uncertainty that fire-protection officers have concerning: (1) what design features need to be included in tall buildings to insure reasonable safety from smoke and fire, (2) can the ventilating system be utilized for control of smoke movement, (3) will safety features incorporated into building design actually perform as expected when a fire occurs, and (4) what action should the fire department take upon reaching buildings where fires are in progress, especially with regard to ventilating system operation. The value of analytical studies is that examination of these problems can be made during building design and alternative designs can be evaluated.

Once we have agreed that problems exist and techniques are available for analyzing the problem and evaluating proposed solutions, we might ask, "Can anything be done about controlling air and smoke flows in buildings?" Several years ago it would have been difficult to envision any practical means to significantly reduce stack effect. Alteration of building design (such as type and location of doors, wall tightness, ventilating fan pressure head, etc.) may have reduced specific problems, but that was about the practical limit.

We considered the use of design and selective control of the ventilation system to modify stack effect through pressurization and/or depressurization of sections of tall buildings. However, control costs appeared to be a problem. Recently, we have seen the announcements on several buildings that will utilize computers for operating the environmental control systems. This appears to offer an opportunity for reconsidering the use of the ventilating system for reduction of stack effect problems.

Therefore, I believe it is time to incorporate stack effect and smoke movement evaluations into the design of new tall buildings and to investigate utilizing ventilation systems for control of air and smoke movement.

MR. TAMURA: In reply to Mr. Barrett's first comment, the direction of air flow within a building caused by stack action is upward, whereas, the direction of air flow within a building caused by wind action is mainly from the windward to the leeward walls. The modification of the air flow pattern caused by wind action superimposed on stack action apparently results in a reduction in the upward flow rate.

Further to Mr. Barrett's comments on the control of smoke movement in the event of fire in tall buildings, because of the many factors which must be considered to ensure safety of occupants, the problem of smoke control is complex. We are at present investigating various methods of smoke control with the aid of computer technique similar to the one described in this paper.