Mitigation of Wind Effects on the Performance of Pressurization Systems in High-Rise Buildings

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ABSTRACT

Stairwell pressurization systems should ensure a sufficiently high velocity at open doors between the stairwell and the fire floor without exerting large forces on closed doors in the stairwell. It appears, however, that strong winds may make it difficult, and many times impossible, to fulfill simultaneously these two requirements in tall buildings. A simple model is used for evaluating the possible use of different design parameters, such as the shape and size of the stairwell, the flow resistance of the exit path, the orientation of the exit door, relative to the direction of prevailing strong winds, additional lobbies, pressurization of the elevator shaft, and the type and location of the injection system, for mitigating the effect of winds on the performance of pressurization systems. Several examples are presented and compared. One novel finding is that the use of a helical stairwell configuration, which has a relatively low flow resistance, may drastically reduce adverse wind effects. Results of a 1:10 scale model study of flow in a helical stairwell are presented, which show that its resistance to flow resistance is approximately one quarter of that of convectional type stairwells.

KEY WORDS: pressurization, wind effects, high-rise buildings

INTRODUCTION

The purpose of stairwell pressurization is to prevent penetration of smoke from the fire floor into stairwells that serve as egress and/or firefighting routes. See Klote and Milke[1] and Tamura[2] for comprehensive analysis of pressurization systems. This goal is achieved by creating a sufficiently high mean velocity, $U_d > U_{min}$, through the open door between the stairwell and the fire floor or other smoke filled spaces. The required value of U_{min} (usually in the range of 1.0-2.5 m/s) depends on the expected fire floor temperature and door height. Recommended values are suggested in some codes as a function of the building type [3, 4]. Another requirement from the pressurization system is that the force acting on doors in the stairwell would not be too large, so that people will be able to open them[3, 4].For many common doors in residential buildings, this requirement is satisfied when ΔP, the pressure difference across the doors, is smaller than 85 pa. As shown by Poreh and Trebukov[5], simultaneous fulfillment of the above two requirements in high-rise buildings during high wind speeds is not always possible. However, it is clear from their analysis that various design parameters can modify the magnitude of the wind effect on the performance of pressurization system. The purpose of this paper is to briefly examine how different design parameters can be used to mitigate this effect.

A SIMPLIFIED ANALYSIS OF THE WIND EFFECT

For simplicity, the following assumptions will be made in this analysis: The stairwell (SW) is pressurized by a blower injecting air at the top of the stairwell, as described schematically in Fig. 1. The airflow through cracks and open doors in the stairwell, other than the fire floor door and the exit door, is negligible. The maximum pressure difference across the doors in the stairwell is approximately equal to the pressure at its top, P_T. The fire is on the first floor.

The required flow through the open stairwell door (d) on the fire floor must be generated by a difference between the pressure at the stairwell at that level (P_d) and the ambient pressure at the location of the air release vent (P_R) from the fire floor. The vent could be an open window or a smoke shaft. In addition to the air release discharge, (Q_R), air will leave the stairwell though the exit path, (E), namely the lobby and the building exit doors. The value of Q_E may be expressed by the equation

$$Q_E = C_E(P_d - P_E)^{1/2}, \quad (1)$$

where P_E is the ambient pressure near the exit door, and C_E, is a dimensional coefficient, that is determined, primarily, by the number of doors along the exit path and their areas.

It is easy to see that, for the above mentioned conditions, the discharge of the blower will be $Q_B = Q_R + Q_E$ and the pressure P_T at the top of the stairwell will be:

$$P_T = P_d + \zeta\, \rho\, [(Q_B/A_{sw})^2/2]\, (n-1), = P_d + \zeta\, \rho\, [((Q_R+Q_E)/A_{sw})^2/2]\, (n-1), \quad (2)$$

where ζ is the *resistance coefficient of the stairwell* (per one floor), ρ is the density of the air, A_{sw} is the area of the stairwell, and n is the number of floors in the building.

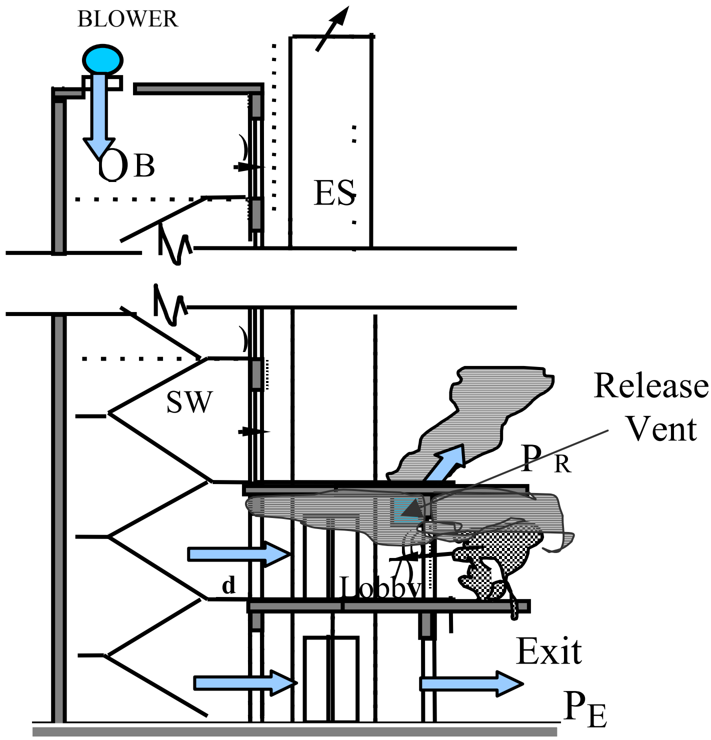


Fig. 1 - Schematic description of a simple pressurization system

As noted earlier, the basic requirements from the designer are: (1) to ensure that $U_d>U_{min}$ and (2) to ensure that P_T is not too high (<85 pa).

Wind generates a non-uniform pressure on the surface of buildings. The additional wind pressure at any point $\underline{x}$ may be expressed as

$$P_w(\underline{x})= C_p(\underline{x})\ \rho U_w^2/2, \qquad (3)$$

where $C_p(\underline{x})$, the *local wind pressure coefficient*, is a function of the geometry of the building and its environment and the relative wind direction, and U_w is the wind speed. The value of this coefficient is usually in the range $-0.6< C_p <0.8$. When large values of U_w are expected together with a positive pressure coefficient at the location of the release opening, ($C_p(R)>0$), the designer has to increase P_d above its value at no wind, $P_{d,0}$ by $P_w(R)$ to ensure that U_d will not decrease. In addition, since $Q_E=C_E[(P_{d,0}+C_p(R)\rho U_w^2/2)-P_E]^{1/2}$, it is easy to see that by doing so he will also increase the discharge Q_E and consequently Q_B, which will increase the pressure gradient above the fire floor.

In a similar manner, negative values of $C_p(E)$ will also increase Q_R and, thus,

$$Q_E=C_E[(P_{d,0}+ \Delta C_p\rho U_w^2/2)]^{1/2}, \qquad (4)$$

and

$$P_T=[P_{d,0}+C_p(E)\rho U_w^2/2)]+\{\zeta\ \rho((C_E[(P_{d,0}+\Delta C_p\rho U_w^2/2)]^{1/2}+Q_R)\}/A_{sw})^2/2\}(n-1), \quad (5)$$

where,

$$\Delta C_p=C_p(R)-C_p(E), \quad (6)$$

is the *differential wind pressure coefficient.*

Since the ambient pressures near the release vent and near the exit are not necessarily the same, in general, $\Delta C_p>0$. Theoretically, it's value can be in the range $-1.4<\Delta C_p<1.4$. It follows from this simplified model that when $\Delta C_p>$zero, P_T will increase with U_w and it is difficult to fulfill simultaneously the above requirements for high wind speeds.

THE EFFECT OF DESIGN PARAMETERS

The qualitative effect of various design parameters will now be discussed. Then, we'll compare the wind effects for different designs according to the maximum number of floors for which the pressure in the SW satisfies the above requirements: $\Delta P<85$ pa, at $U_w=5$ m/s and $\Delta C_p=0.5$ and $U_d=1.0$ m/s.

The Stairwell and the Injection System

It is clear from Eq. (5) that a low resistance of the stairwell to flow can mitigate the wind effect. Namely, reduce the value of P_T and enable a given pressurization system to perform properly in taller buildings. The total resistance of the stairwell is proportional to the number of floors in the building, n. The designer of the pressurization system can't change n, however. Theoretically, a division of the stairwell into two independent sections pressurized by two blowers is possible. The shortcoming of this option is that during evacuation, the doors between the upper and lower staircases will be open, due to movement of people. The pressures in the two sections will, thus, be determined by the location of the injection point in each stairwell and by the area of the door between them.

A simpler and quite common solution is to build a *multiple injection system* that distributes air to the stairwell through a vertical conduit with openings at (almost) every floor[1, 2]. The resistance coefficient of the stairwell will be reduced in this case by a factor of almost 3. Two different, multiple injection schemes may be used: A constant area conduit and a variable area conduit. The latter will secure a more even distribution of the air supply, but the first one would give a slightly lower resistance coefficient.

One may also locate the injection point at the ground floor. The maximum pressure would be near the injection point for a fire on the top floor. Its value relatively small, as Q_E does not contribute to Q_B. One must provide, however, a small vent at the ceiling of the stairwell, to remove smoke that might accumulate in the stairwell. One disadvantage of this option is that considerable air will leave the stairwell through the exit door, which makes it necessary to increase the capacity of the blower.

The area of the stairwell, A_{sw}, might also be increased to reduce P_T. At first, this options looks rather expensive. However, it appears to the authors that, following the terrorist attack on the WTC, simultaneous evacuations of high-rise buildings might be necessary, which will justify the use of larger stairwells.

Finally, one may reduce the value of the resistance coefficient ζ, which depends on the shape of the stairwell and balustrade.

Poreh and Trebukov[5] have estimated, using hydraulic analogies, that the value of ζ for *helical stairwells*, see Fig. 2, should be, approximately, times smaller than that of conventional stairwells, but did not prove it. In Appendix A, results from a physical model study of a helical, which confirm these estimates, are presented.

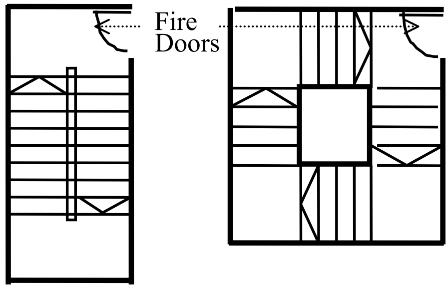


Fig. 2 - A conventional stairwell A helical stairwell

The resistance of the exit path

The resistance to the flow of air from the open door of the stairwell to the exit of the building, which is inversely proportional to the square of the coefficient C_E in Eq. 1, determines the discharge of air from the stairwell, Q_E, which does not contribute to the goal of the pressurization. As shown earlier, an increase in Q_E, increases the discharge through the stairwell as well as the pressure at its top P_T. It also increases the size and power of the blower. One should, therefore, try to decrease it, as much as possible. Revolving doors appear to be an ideal solution for the hydraulic problem. However, unless they are very large, they might slow the flight of people from the building. They are also quite expensive. When regular doors are installed in the exit path, their number and areas determine the resistance of the exit path. The larger their number, the better,

Additional lobbies

Lobbies are the backbone of passive smoke control. They provide improved and reliable smoke control performance, through compartmentation. When present in buildings with smoke pressurization, they reduce the probability of open doors between the stairwell and the fire apartment and thus the discharge of the blower. One should distinguish between various types of secondary lobbies: a) A secondary lobby between the stairwell and the main lobby, b) a secondary lobby between the elevator shaft and the main lobby and c) a secondary *common lobby* that separates both the stairwell and elevator shaft from the main lobby, that was found to perform better than the previous types, and d) lobbies with natural vents. Their performance depends to a large extent, however, on the location of the pressurized zones. In general, our calculations suggested that common lobbies (c) and naturally vented lobbies performs better than the other types.

The pressurized zones

One may pressurize the different parts of the building:

- The stairwell (SW),
- The elevator shaft (ES),
- The lobbies (L).

Pressurization of both the SW and the ES is particularly useful in mitigating wind effects. When the lobby is pressurized (to a lower pressure than the stairwell), the force acting on the stairwell doors may be reduced by up to 50%. A larger reduction of this force is possible, but it will result in an increased force on the doors between the main lobby and the secondary lobbies. In addition, pressurization of the ES produces additional flow of air into the exit lobby, particularly, if the elevator is programmed to automatically descent to the ground and open its doors during a fire. This flow will increase the pressure loss across the main building exit door, and, thus, tends to increase the exit discharge from that door and the pressure in the exit lobby, which will further decrease the discharge from the stairwell and the pressure P_T.

Reduction of the pressure difference coefficient ΔC_w.

The wind effect on the pressurization system depends primarily on the value of this coefficient $\Delta C_p = C_p(R) - C_p(E)$, and of course on the design wind speed. The product $\Delta C_p \rho U_w^2/2$ varies considerably in time and it is necessary to choose an appropriate design values based on the joint probability distribution of the wind speed and direction, relative to the shape and orientation of the building, and the locations of the main exit and the release vents. When there is a clear direction from which most of the high speed winds blow, it is desired to orient the exit to face that direction, to increase the probability of getting positive ambient wind pressure at the exit. When the air release from the lobbies is through a smoke shaft, P_R will be usually negative and the wind effect will be drastically reduced. When the air release is through a single open window in the main lobby, the designer should try to locate the window in a region of the envelope where the probability of a negative wind pressure coefficient during high wind speeds is high. When air release is through vents in the individual apartments that face different directions, it is impossible to reduce their values by design.

Clearly, determination of the design wind speed and pressure coefficients must be based on an analysis of the local wind statistics, a task that is beyond the capacity of the individual Fire Protection Engineer.

COMPARISON OF DIFFERENT DESIGNS

Using a zone model, which is described in Poreh and Tebukov[5], we have calculated for different designs the maximum number of floors, n_{max}, for which $\Delta P<85$ pa at the following ambient conditions: $U_w=5$ m/s, $\Delta C_p=0.5$ and $P_{d,0}=12$ pa. Such a pressure is usually sufficient for maintaining a door velocity U_d = 1 m/s. The area of the stairwell in all this designs was 12 m^2. The results are summarized in Table I. The design parameters that varied in this study were:

Pressurized zones (SW, ES and Lobbies), Injection type [Single (S), Multiple Uniform Injection(MUI), Multiple Non-Uniform (MNUI)], Location of injection or Blower [Top (T) or Bottom (B)], Vestibules (None or Common), number of doors in the exit path (2 or 3), ζ the Resistance of the SW (75 for a regular SW or 15 for a helical SW) and, on the last column on the right, the maximum number of floors (n_{max}) for the above specified conditions can be met. Missing cells indicate zero values or an irrelevant parameters. The results, it should be stressed, do not represent appropriate values for design, because of the large variance in the ambient conditions and the characteristics of buildings. They make it possible, however, to judge the relative merit of the various design parameters.

CONCLUSIONS

The following conclusions may be drawn from the above analysis and the results presented in Table I

- The wind effect on the performance of pressurization systems could be very large. Our calculations show that pressurization by a single blower that injects air at the top of a conventional stairwell would function properly, for the conditions specified above, only for buildings with 6 or less floors.
- The wind effect can be largely mitigated using an Helical Stairwell, Multiple Injection and Pressurization of the Elevator Shaft:
    - Using Multiple Uniform Injection (MUI) in a conventional stairwell increases n_{max} to 16.
    - Pressurization of the Elevator Shaft (ES) (with a conventional SW) increases n_{max} to 22.
    - By building a Helical Stairwell, the maximum building height increases n_{max} to 23.
    - Combining a Helical Stairwell and MUI increases n_{max} to 68.
    - Combining a Helical Stairwell, MUI and pressurization of the ES increases n_{max} to 120.
    - The use of common vestibules would also increase the maximum building height. See Options 10 and 10L. In addition, it reduces the probability of open doors between the stairwell and any other lobbies.
- Authorities should recommend design wind speeds for different climatic regions as well as appropriate minimum values of the design differential pressure coefficients for different building shapes. Such recommendations must be based on the joint probability distribution of the wind speed and direction in each area.
- The use of smoke shafts for air release, which ensures a negative wind pressure coefficient at their exit, is highly recommended for windy regions.

TABLE I: THE MAXIMUM BUILDING HEIGHT FOR DIFFERENT DESIGNS
(See text for symbols and assumptions)

Option Number	Pressurize d Zones	Injection Type	Injection Location	Vestibules	No. of doors in exit path	Elevator Door	ζ	n_{max}
1	SW	S	T	-	2	-	75	6
1H	SW	S	T	-	2	-	15	23
2	SW	MUI	T	-	2	-	75	16
2H	SW	MUI	T	-	2	-	15	68
3	SW	MNUI	-	-	2	-	75	18
3H	SW	MNUI	-	-	2	-	15	78
4	SW	S	B	-	2	-	75	20
4H	SW	S	B	-	2	-	15	53
5	SW	MUI	-	-	3	-	75	20
5H	SW	MUI	-	-	3	-	15	85
6	SW+ES	MUI	-	-	2	Closed	75	22
6H	SW+ES	S	T	-	2	Closed	15	30
7	SW+ES	S	T	-	2	Open	75	14
7H	SW+ES	S	T		2	Open	15	61
8	SW+ES	MUI	-	-	2	Open	75	50
8H	SW+ES	MUI	-	-	2	Open	15	120
10	SW	MUI	-	Common	2	-	75	18
10H	SW	MUI	-	Common	2	-	15	70
11	SW+ES	MUI	-	Common	2	Closed	75	30
11H	SW+ES	MUI	-	Common	2	Closed	15	90
12	SW+ES	MUI	-	Common	2	Open	75	**55**
12H	SW+ES	MUI	-	Common	2	Open	15	**130**

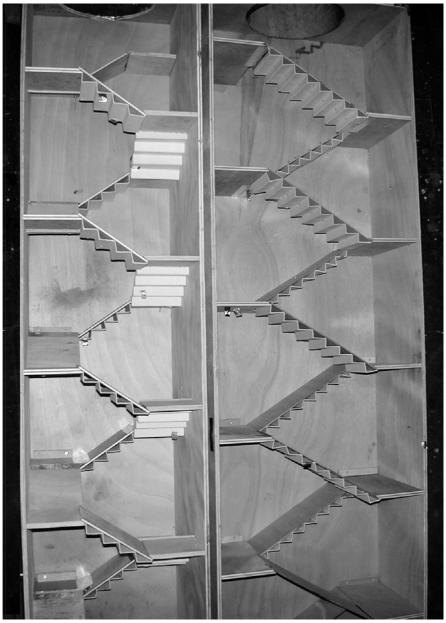
APPENDIX A

MEASUREMENTS OF THE RESISTANCE OF HELICAL STAIRWELLS IN A SCALE MODEL

INTRODUCTION

The values of the stairwell resistance coefficients ζ used in this paper were ζ= 75 and 15 for conventional and helical stairwells, respectively, as suggested, intuitively, by Poreh and Trebukov[5]. Within the framework of the M. Sc. thesis of the last author, measurements were made in a 1:10 scale model of such stairwell, from which these coefficients could be estimated. The results of this model study are briefly reported in this appendix.

EXPERIMENTAL CONFIGURATION



A photograph of the middle section of the models, placed vertically, side by side, with the front wall of the staircases open, is shown on the right hand side. The helical stairwell is on the left and the conventional stairwell is on the right.

The internal prototype dimensions of the stairwell (in m) were 3.50 x 3.50 and 2.50 x 5.00, respectively. The widths of the walkways were 1.13m and 1.25m, respectively.

Air was sucked from the lower part of the model stairwell, which is not seen in the photograph, by a blower. The discharge was measured at the top entrance to the models and the pressure losses in the stairwells were measured across 3 and 4 floors, located 3 floors below the ceiling, using a linear electronic pressure transducer.

Measurements were made in an empty stairwell and in stairwells with 1 and 2 people per m^2 (12 and 24 people on each floor). Vertical cylinders (prototype diameter and height 0.3 and 1.8 m, respectively) were used for modeling the people. The average measured resistance coefficients, ζ, are shown in the following table.

Number of people per m^2	Measured ζ		Ratio
	Conventional SW	Helical SW	
0	57	12	4.8
1	65	17	3.8
2	74	20	3.7

It appears from the results that the values of ζ used in calculating the maximum building height (Table I) were close to the measured value for the conventional stairwell with 2 people/m^2, but the estimated values for the helical stairwell, with the same number of people, were too low. We also noted that the effect of number of people on the resistance in this model is not the same as in the measurements of Tamura, which suggest a larger effect of people. It should be realized, however, that the value of ζ is quite sensitive to the dimensions of the stairwell and the balustrade. Moreover, the Reynolds number of the flow in the stairwells was close to 22,000, which is sufficiently large for securing model-prototype similarity. However, the Reynolds number of the flow around the cylinders was much lower.

Nevertheless, in view of the expected large dependency of ζ on the shape of the stairwell, our previous general conclusion regarding the merit of the helical stairwell is confirmed.

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