Numerical Study of Elevator and Stairwell Pressurization Systems Using Detailed Building Models

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Abstract

Numerical simulations are conducted for stairwell and elevator shaft pressurization smoke control systems aimed at strict adherence to the International Building Code (IBC) 2009 Sections 909.20.5 and 708.14.2.1, respectively. Detailed numerical CONTAM models for two Korean residential high-rise buildings are created based on floor plans and experimentally measured stack effect pressure differences reported in Ref. [1]. The first is a 40 story, two tower, high-rise having two elevator shafts and two stairwells per tower. The second is a 69 story, single tower, building with six elevator shafts and three stairwells. The simulation results confirm prior observations of Ref. [2] based on simplified building models. Strict adherence to IBC 2009 is essentially impossible to meet for elevator shaft pressurization systems. In particular, very large across door pressure differences are observed if the elevator pressurization system is required to operate with the exterior building doors in the closed position. Effects of the ambient temperature, the building configuration, and interactions with the stairwell system are examined. Potential improvements to the IBC code language and alternative system design approaches are also discussed.

INTRODUCTION

The following document presents a numerical investigation of elevator shaft and stairwell pressurization systems for the control of smoke distribution in realistic tall buildings. Smoke migration in such tall buildings is influenced by many factors, including the buoyancy of hot gases and the stack effect resulting when the interior building temperature differs from that of the surroundings. Stack effect pressures are predicted by [3]:

\[ \Delta P_{SO} = -\frac{g}{R} \frac{P_{atm}}{T_O - T_S} \left( \frac{1}{T_O} - \frac{1}{T_S} \right) z, \]  

(1)

where the subscripts refer to the shaft (S) and outside (O) ambient and the corresponding temperatures (T_O and T_S) are in absolute units. Furthermore, z is the distance above or below the neutral plane, g is the gravitational acceleration, P_{atm} is atmospheric pressure, and R is the specific gas constant for air. This total pressure difference is comprised of the sum of the pressure differences across the elevator (or stairwell) doors plus that across any interior pressure barriers between the shafts and the exterior, plus that across the building exterior. Together, stack effect pressure differences and hot gas buoyancy provide means by which smoke from fires can be distributed throughout tall buildings via stairwell and elevator shafts with potentially catastrophic consequences.
Pressurization systems aim to prevent the flow of smoke through shafts by creating positive pressure differences across all doorways; thereby preventing smoke from ever entering the shaft. While stairwell pressurization has a relatively long history of use, the International Building Code (IBC) has only recently allowed the use of elevator shaft pressurization systems. The IBC 2009 Section 708.14.2.1 states in part “Elevator hoistways shall be pressurized to maintain a minimum positive pressure of 25Pa and a maximum positive pressure of 67Pa with respect to adjacent spaces on all floors. ...with all elevator cars at the floor of recall and all hoistway doors on the floor of recall open...” (ie. the Phase 1 position). Minimum pressure differences are required to prevent smoke entry to the hoistway, whereas maximums are meant to maintain proper door functioning. Similarly, Section 909.20.5 governs stairwell pressurization systems and mandates across stairwell door pressure differences between 25Pa and 87Pa.

Very little research exists pertaining to elevator pressurization systems. Miller and Beasley [2] examined elevator and stairwell pressurization systems numerically using simplified building models lacking interior features, mechanical floors, basements or garage levels, HVAC systems, etc. They showed that stairwell only pressurization is feasible under the IBC code language. However, elevator shaft pressurization was found to be incapable of strict adherence to the IBC 2009 under all possible operating conditions. Very large pressure differences were observed in particular for systems operating with the exterior building doors in the closed position. Strong interactions with the stairwell pressurization system were also observed. The present paper extends the results of Ref. [2] to substantially more realistic building models. An improved thermal model for the average shaft temperatures is also presented and suggestions for code language changes and alternative system designs are discussed.

MODELING APPROACH

Numerical simulation results presented below are based on the CONTAM software developed by the Indoor Air Quality and Ventilation Group at the National Institute of Standards and Technologies. The software is a zonal model in which a building geometry is composed of a number of zones (rooms, shafts, floors, etc.). Each zone is treated as a lumped parameter with only hydrostatic pressure variations within the zone. Only the “long time” equilibrium pressure distributions are predicted.

Two Korean high-rise buildings described in Ref. [1] have been modeled in CONTAM. Ref. [1] documents experimental measurements of across door pressure differences for both buildings under (non-pressurized) stack effect conditions. Schematics of typical floor plans for each of the building models are provided in Fig. 1. Building “Model 1” [Fig. 1(a)] is a two tower, 40 story residential high-rise having two main elevator shafts (three cars each), two stairwells per tower, and five basement floors. One elevator shaft runs the entire height of the building and services the basement levels, the ground floor, and the tower floors down to and including the 8th floor (one per tower). A secondary shaft services the first 8 floors of each tower as well as the first basement level. A central market area separates two towers on the first 8 above ground floors. Building “Model 2” [Fig. 1(b)] is a 69 story building with six elevator shafts and one basement floor. Two “high-rise” (HR) shafts span floors 1-15. Two “mid-rise” (MR) shafts span floors 1-54 servicing floors 1,2, and 16-54. Two “high-rise” (HR) shafts span floors 1-69 servicing floors B1-2, and 54-69. All elevator shafts contain two cars each. Detailed CONTAM models have been developed for each building, including the presence of internal doorways, rooms, HVAC systems, mechanical floors, etc. Parameters for all simulations conducted for this study are provided in Tables 1 and 2 for Model 1 and Model 2, respectively (described below).
Pressurization is accomplished using fans blowing outside air into each individual shaft. The ambient air is in general at a different temperature than the building interior. A model for the bulk averaged temperature within the shaft relevant to the CONTAM code has been developed in Ref. [2]. In that paper a constant heat transfer coefficient was assumed. Here, the model is extended to variable heat transfer coefficients. Briefly, the model is based on heat transfer within a constant wall temperature shaft. The axially varying average shaft temperature is then [4]:

\[ T_S(x) = T_B - (T_B - T_O) \exp \left( \frac{P'hRT_Ox}{C_pQP_{atm}} \right) \].

The axial shaft position is \( x \) (from the intake; top or bottom), the convective heat transfer coefficient is \( h \), the volumetric flow of the ambient intake air is \( Q \), \( P' \) is the effective wetted perimeter (discussed below), and the heat capacity of the air is \( C_p \). Equation (2) is then
Table 1: Simulation parameters for the story building Model 1: Case name, ambient temperature, exterior building door position, and calibrated fan flow rates for elevator 1 (tower), elevator 2 (low-rise), and the stairwell for each tower. Cases 1g and 1f are calibrated neglecting the across open elevator door pressure differences.

<table>
<thead>
<tr>
<th>Case</th>
<th>$T_O$</th>
<th>Exterior door</th>
<th>Elevator 1</th>
<th>Elevator 2</th>
<th>Stairwell</th>
</tr>
</thead>
<tbody>
<tr>
<td>1a</td>
<td>$-12^\circ C$</td>
<td>Open</td>
<td>N/A</td>
<td>N/A</td>
<td>2.6 m$^3$/s</td>
</tr>
<tr>
<td>1b</td>
<td>$-12^\circ C$</td>
<td>Open</td>
<td>57 m$^3$/s</td>
<td>28 m$^3$/s</td>
<td>N/A</td>
</tr>
<tr>
<td>1c</td>
<td>$-12^\circ C$</td>
<td>Open</td>
<td>72 m$^3$/s</td>
<td>35 m$^3$/s</td>
<td>3.3 m$^3$/s</td>
</tr>
<tr>
<td>1d</td>
<td>$-12^\circ C$</td>
<td>Closed</td>
<td>N/A</td>
<td>N/A</td>
<td>2.7 m$^3$/s</td>
</tr>
<tr>
<td>1e</td>
<td>$-12^\circ C$</td>
<td>Closed</td>
<td>141 m$^3$/s</td>
<td>29 m$^3$/s</td>
<td>N/A</td>
</tr>
<tr>
<td>1f</td>
<td>$-12^\circ C$</td>
<td>Closed</td>
<td>132 m$^3$/s</td>
<td>26.4 m$^3$/s</td>
<td>8.9 m$^3$/s</td>
</tr>
<tr>
<td>1a-hot</td>
<td>38$^\circ C$</td>
<td>Open</td>
<td>N/A</td>
<td>N/A</td>
<td>2.4 m$^3$/s</td>
</tr>
<tr>
<td>1b-hot</td>
<td>38$^\circ C$</td>
<td>Open</td>
<td>66 m$^3$/s</td>
<td>30 m$^3$/s</td>
<td>N/A</td>
</tr>
<tr>
<td>1c-hot</td>
<td>38$^\circ C$</td>
<td>Open</td>
<td>72 m$^3$/s</td>
<td>34 m$^3$/s</td>
<td>3.3 m$^3$/s</td>
</tr>
<tr>
<td>1d-hot</td>
<td>38$^\circ C$</td>
<td>Closed</td>
<td>N/A</td>
<td>N/A</td>
<td>2.5 m$^3$/s</td>
</tr>
<tr>
<td>1e-hot</td>
<td>38$^\circ C$</td>
<td>Closed</td>
<td>151 m$^3$/s</td>
<td>31 m$^3$/s</td>
<td>N/A</td>
</tr>
<tr>
<td>1f-hot</td>
<td>38$^\circ C$</td>
<td>Closed</td>
<td>147 m$^3$/s</td>
<td>29 m$^3$/s</td>
<td>9.8 m$^3$/s</td>
</tr>
<tr>
<td>1g</td>
<td>$-12^\circ C$</td>
<td>Open</td>
<td>57 m$^3$/s</td>
<td>28 m$^3$/s</td>
<td>N/A</td>
</tr>
<tr>
<td>1h</td>
<td>$-12^\circ C$</td>
<td>Closed</td>
<td>36 m$^3$/s</td>
<td>9.0 m$^3$/s</td>
<td>N/A</td>
</tr>
</tbody>
</table>

integrated over the entire building height ($H$) yielding the average shaft temperature:

$$T_S = T_B + \frac{(T_B - T_O)C_PQ_{atm}}{P'hRT_OH} \left[ \exp \left( \frac{-P'hRT_OH}{C_PQ_{atm}} \right) - 1 \right].$$

(3)

Here, the Dittus-Boelter correlation is employed for modeling the Nusselt number $[4]$: $Nu = 0.023 Re_D^{0.8} Pr^n$, where $Nu = hD_h/\kappa$ and $\kappa$ is the thermal conductivity of the air. The pipe flow Reynolds number is $Re_D = U_{avg}D_h/\nu$; where $U_{avg} = Q/A$, $D_h = 4A/P'$ is the hydraulic diameter based on the cross sectional area ($A$) and the actual wetted perimeter ($P'$), and $\nu$ is the kinematic viscosity of the air. Also, the Prandtl number is $Pr = \nu/\alpha$, where $\alpha$ is the thermal diffusivity of the air. The exponent, $n$, takes the values $n = 0.3$ for cooling and $n = 0.4$ for heating. All properties are taken at the average temperature: $(T_B + T_O)/2$.

The above thermal model is most applicable to the empty elevator hoistways which are effectively simply large ducts upon which the above model is based. In contrast, the stairwells have interior features (the stairs) which provide a significantly larger surface area for heat transfer. For this reason the effective wetted perimeter has been defined above. For elevator shafts $P' = P$. For stairwells, $P' = \beta P$, where $\beta$ is a geometry correction factor. Absent any experimental data the geometry correction is taken to be $\beta = 2$ for stairwells.

Note that the thermal model described above neglects the leakages from the hoistway or stairwell shaft through doors and therefore corresponds to a long sealed channel flow. Incorporating the leakages through individual doors at each floor is possible but is very time intensive as floor by floor flow leakage rates must be read in from a CONTAM simulation and then the process must be iterated. In this case the above model is applied floor to floor and the channel flow rate is adjusted according to each floor’s loss. Averaged air properties can also be adjusted locally.
Table 2: Simulation parameters for the study building Model 2 for cold day conditions (−12°C): Case name, and calibrated fan flow rates for high-rise (HR), mid-rise (MR), low-rise (LR) elevators and primary and secondary stairwells. All cases have the exterior building doors in the closed position except Case 2d which has closed interior lobby doors between the hoistway and the ambient.

This detailed thermal modeling, together with several models for an entrance length correction, was done within a spreadsheet for one test case. The difference between the average shaft temperature between the two approaches was found to be negligible to the final CONTAM pressure distributions. Therefore, Eq. (3) is adopted hereinafter.

Exterior building leakages are calibrated to match the experimentally measured stack effect pressures from Ref. [1]. The calibration procedure is described in detail in Ref. [2]. In summary, a detailed building model is developed within CONTAM for each building model. Realistic and documented values for all interior leakages are used from Ref. [3]. For example, the closed stairwell door leakage area is 100 cm², and elevator door leakage areas are 480 cm² and 580 cm² in the closed and open positions, respectively. Stack effect simulations (no pressurization) are then conducted under the same weather conditions as for the days the experimental stack effect measurements were made for Ref. [1]. Both the exterior building leakage areas and the across residential door leakage areas are then iterated until the experimental stack effect measurements were matched as best as possible. For example, consider a “simple” floor plan with no interior features. The entire stack effect pressure difference from shaft to ambient is in this case distributed over two pressure differences: across the elevator (or stairwell) door plus that across the outer building wall. In the limit of completely open exterior walls there can be no pressure difference across the outer wall and the entire stack effect pressure difference occurs across the elevator doors. In contrast, in the limit of completely sealed exterior walls the entire stack effect pressure difference occurs across the exterior walls. Therefore, the experimental data for across door (elevator, stairwell and residential) pressure differences can be matched by simply varying the exterior building and residential door leakages. This must be done floor by floor in some cases; particularly for the ground floor which has additional pathways to the ambient.

Calibrated stack effect across door pressure differences are depicted in Fig. 2 for both building models with comparisons to the experimental measurements of Jo et al. [1]. Figure 2(b) also
Figure 2: Comparison of the across elevator door pressure differences as a function of the floor number for the calibrated building models with the experimental measurements of stack effect pressures from Jo, et al. [1]: (a) the 40 story building Model 1, and (b) the 69 story building Model 2 (experimental data are indicated by the solid symbols without lines).

shows that the results are relatively insensitive to the presence of an HVAC system. HVAC systems are therefore not included in the building models for the remaining results (they are typically turned off in fire situations as well).

RESULTS

The following numerical investigation addresses the feasibility of both stairwell and elevator pressurization systems under strong stack effect conditions using realistic building models. All results presented hereinafter correspond to “cold day” conditions with an ambient temperature of \(-12^\circ C\) with an internal building temperature of \(21^\circ C\) unless otherwise noted. Three pressurization configurations are addressed for each building model: stairwell pressurization only, elevator pressurization only, and coupled stairwell and elevator pressurization operating simultaneously. Pressurization is achieved via fixed volumetric flow rate fans blowing ambient air into the shaft. The fan flow rates are adjusted until a minimum pressure difference of \(25 Pa\) is achieved across any elevator or stairwell door if pressurized. For elevator systems this includes the open elevator doors on the ground floor as specified by the IBC language. The fan flow rates are then input into the thermal model which provides the average shaft temperature for the CONTAM model. This in turn changes the required fan flow rates; therefore the procedure must be iterated until the solution converges. As an example, the final shaft temperatures for Case 1c (described below and in Table 1) are \(-8^\circ C\), \(-11^\circ C\), and \(-5^\circ C\) for Elevator 1, Elevator 2, and the stairwell, respectively. Across door pressure differences are then examined to determine if the maximum pressure differences are attainable: \(67 Pa\) for elevator doors and \(87 Pa\) for stairwell doors under pressurization. Equilibrium pressure distributions have previously been shown to be independent of the fan location and/or the presence of relief vents at the top of shafts [2]. All fans discussed hereinafter are located on the roof of the buildings for those with roof access, or in the basement if not having roof access.

The 40 story building Model 1 is investigated first. Both cold day \((T_o = -12^\circ C)\) and hot
day ($T_o = 38^\circ C$) conditions are considered in order to examine the influence of stack effect on pressure distributions. Simulations are also performed for conditions in which the exterior building doors are in either the open or closed positions. Miller and Beasley [2] found that the exterior door position has a strong influence on the building pressurization characteristics and required fan flow rates. It is important to consider both building configurations as fire situations may occur under either circumstance.

Across door pressure differences for building Model 1 are presented in Fig. 3 for cold day conditions with the exterior building door in the open position. Stairwell only [Fig. 3(a)], elevator only [Fig. 3(b)], and coupled elevator and stairwell pressurization [Fig. 3(c)] are included. Calibrated fan flow rates are provided for all Model 1 cases in Table 1. Under these relatively strong stack effect conditions even the traditional stairwell only system exhibits minor violations of the IBC pressure difference maximums. The influence of the stairwell only pressurization system
on the across elevator door pressure differences is insignificant. In contrast, elevator only pressurization is somewhat more problematic if strict adherence to the IBC language is to be met. Pressure differences remain near, though slightly larger than, code specified maximums on all upper floors [Fig. 3(b)]. Minimum pressure differences occur on the 8th floor which has doors to both the low-rise and high-rise elevators. Very large pressure differences are observed across the ground floor elevator doors in the Phase 1 position. This occurs because of the relatively large number of open elevator doors and the associated large fraction of the air flow exiting the shaft at the ground floor and exiting the building unrestricted by any pressure barriers. This makes it difficult to achieve minimum pressure differences on upper floors unless relatively large fan speeds (and ground floor pressure differences) are employed. Stairwell door pressure differences remain moderate. However, when both stairwell and elevator systems are acting simultaneously [Fig. 3(c)], substantially larger violations of maximum pressure differences are
observed for all upper level floors for both stairwells and elevators (in addition to the ground floor violations). This indicates a strong coupling of the two systems.

Operation of pressurization systems with the exterior building doors in the closed position is substantially more problematic as illustrated in Fig. 4 for building Model 1 for the same conditions as for Fig. 3. The building door position has little impact on the operation of a stairwell only system [Fig. 4(a)] because the fan flow rates are relatively moderate. However, in order to meet strict adherence to the IBC code language for pressure difference minimums, elevator pressurization systems are characterized by maximum pressure differences up to an order of magnitude larger than allowed by the code across nearly all upper floor elevator doors. Whether operating alone [Fig. 4(b)] or together with a stairwell pressurization system [Fig. 4(c)], elevator fans cause exceedingly large pressure differences across the stairwell doors as well. The reason for the observed behavior is as follows. Air blown down the hoistway exits primarily through the open elevator doors on the ground floor. With the exterior doors closed there is no direct path for the air flow to exit the building. Instead, the air flow pressurizes the ground floor. With the large open door leakage area the pressures tend to equalize across the doors until the fan speeds become large enough to compensate and the code minimums can be achieved on the ground floor. In this situation the ground floor becomes the point of minimum pressure difference. The absolute pressure is in this case much larger on the ground floor than on the upper floors and very large across door pressure differences occur on all upper floors. Much larger fan speeds are also required with the building doors closed (Table 1). Of course, such very large fan flow rates are unrealistic but do suggest that changes to the IBC code language may be necessary as the current code would require systems to operate even with the building doors closed.

The effect of the ambient temperature has also been investigated by repeating the above simulations for hot day conditions \((T_O = 38^\circ C)\). Pressure distributions for elevator systems are
The numerical simulation results described above indicate that the current IBC language governing elevator shaft pressurization is impossible to meet in realistic building models under all changes to the ambient temperature (or, more dramatically, to changes to the exterior building door positions).

Similar but larger problems exist for the taller 69 story building Model 2 as illustrated in Fig. 5 for stairwell only and Fig. 6 for coupled pressurization systems. Much less information was available about this building and more assumptions were made about the interior building features. Fan flow rates are provided in Table 2. Cold day conditions persist for all cases. The exterior building doors are in the closed position as indicated in the legends. The exception is the data of Fig. 6(b) denoted by "Front Door Open." However, for this simulation there is an interior lobby door between the elevators and the exterior door which is in the closed position. Again, very large pressure differences across all upper floors are found if strict adherence to the current IBC code language is maintained. Even the stairwell only system exhibits violations of pressure difference maximums on both mid-rise sections as well as on mechanical floors under these strong stack effect conditions. The results of Fig. 6(b) for open exterior door but with closed interior lobby doors further illustrate the potential problems with meeting strict adherence to the IBC 2009 language. Any pressure barrier between the open ground floor elevator doors and the ambient would result in very large fan flow rates and very large upper floor pressure differences if the 25Pa pressure difference is to be met across the open elevator doors.

The numerical simulation results described above indicate that the current IBC language governing elevator shaft pressurization is impossible to meet in realistic building models under all...
possible modes of operation. Two primary problems have been identified. First is the potential for the system to have to operate with the exterior building doors in the closed position. Without a relief for the hoistway fan air very large pressure differences occur on all upper floors for both elevator and stairwells. Second, the need to maintain a minimum pressure difference across the open elevator doors also requires relatively large fan flow rates and more modest violations of pressure difference maximums. These results suggest that at a minimum the IBC Section 708.14.2.1 governing elevator shaft pressurization be revisited. The results suggest adopting a requirement that a ground floor relief vent be installed and activated during fire situations. The purpose would be to negate the effects of closed exterior building doors. Further specifying that the open Phase 1 elevator across door pressure differences be neglected in achieving pressure minimums is also suggested by the results. This would substantially reduce pressure differences across all remaining elevator (and stairwell) doors as well as reduce the required fan flow rates. There should be no problems with smoke entry through the open Phase 1 elevator doors as the elevators are not recalled to a fire containing floor.

Simulation Cases 1g and 1h (Table 1) address the effects of such changes. These simulations correspond to elevator only system operation for building Model 1. They are the same as Case 1b (building doors open) and Case 1e (building doors closed), respectively, except that the pressure differences across the open elevator doors are neglected during calibration. Across door pressure differences are presented in Fig. 7(a) for open building doors. The pressure distributions and fan flow rates are nearly identical to Case 1b [Fig. 3(b)] because the minimum pressure had previously occurred on the 8th floor. Excessively large pressure differences remain observed on the ground floor; however, upper floors show more reasonable values. In contrast, a dramatic improvement in system performance is observed if the exterior building doors are closed [Fig. 7(b)]. A near zero pressure difference exists across the open elevator doors on the ground floor, and all upper floor pressure differences are near to (though slightly above) the code maximums.
CONCLUSIONS

The numerical simulation results described above indicate that the current IBC language governing elevator shaft pressurization is impossible to meet in realistic building models under all possible modes of operation. While in some ways specific to the two building models under consideration, these results highlight the complex nature of elevator shaft pressurization. The primary problems are associated with the exterior building door position, and the need to have a minimum pressure difference across the open Phase 1 elevator doors. Problems are increased for tall buildings with large numbers of elevator cars. Recommendations for changes to the IBC code language have been made based on the simulation results. In particular, it is recommended that the code specifically neglect any requirement for a pressure difference minimum across the open Phase 1 elevator doors. A relief vent to the ambient may also be required on the ground floor in the event that a fire situation occurs with the exterior building doors in the closed position. Effects of changes to the ambient temperature were found to be relatively minor for elevator pressurization but more substantial for stairwell pressurization systems. However, even elevator shaft pressurization requires different fan flow rates for different ambient temperatures. This suggests that fixed fan flow rate systems (as usually employed) may be calibrated within code limits during one set of weather conditions, but will perform differently in other conditions (possibly outside of the code limits). Dynamically adjustable fan speeds that can compensate for variable operation conditions may be needed. The code could also more specifically allow or address alternative system designs. For example, the author’s are currently examining an alternative design solution being pursued by jurisdictions in the Pacific Northwest where elevator pressurization has been used for a relatively long time. In this solution, the same pressure minimum is required; however, it is measured from the shaft to the ambient. This reduces the actual across door pressure differences to below the values known to prevent smoke migration. The building's HVAC system is then used to suction air from the fire floor, one above, and two below, in order to achieve the 25 Pa pressure difference minimums across any set of doors on these four floors. Preliminary results are very positive, and a forthcoming publication is expected.

ACKNOWLEDGMENTS

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References


