On Smoke Control by Pressurization in Stairwells and Elevator Shafts

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Abstract

Elevator shaft and stairwell shaft pressurization systems are studied as means of smoke migration prevention through the stack effect in tall buildings using the CONTAM simulation software. Stairwell pressurization is found to be completely feasible in the absence of elevator shaft pressurization. In contrast, coupled elevator shaft pressurization systems are found to produce prohibitively large pressure differences across both the elevator and stairwell doors if: (1) minimum pressure differences must be maintained at both open and closed elevator doors, and (2) if the system must function properly when the ground floor exterior building doors are closed. Even in these cases situations arise in which smoke may enter the shaft and be actively distributed throughout the building by the fan system. Furthermore, the results show that there is a strong coupling between the fan speed requirements of the stairwell and elevator shaft pressurization systems. Fan requirements are also found to be sensitive to the ambient temperature. Effects of the fan location, louvers, vents, the building height, and the number of elevator cars and/or shafts are also addressed.

1 Introduction

The following report addresses the use of pressurization systems for the prevention of smoke migration in tall buildings due to the "stack effect" in elevator shafts and stairwells. The results herein are a summary of technical results to be presented at the 2008 SFPE Professional Development Conference and Exposition [1] as well as results presented in an article recently submitted to the technical journal *Building and Environment* [2]. The reader is referred to the citations for additional technical details omitted from this report. The stack effect is created in tall building shafts when there is a temperature difference between the building interior and the ambient. For a cold ambient, the lower floors have a net negative pressure difference while the upper floors show a net positive. In physical terms, air is being entrained into the shaft on lower floors and forced out into the building on the upper floors. The conventional calculation of the stack effect pressure difference [3] is actually the difference in pressures between the elevator (or stairwell) shaft and the outside world. In the absence of other interior pressure barriers, this total stack effect pressure difference is comprised of the sum of the pressure differences across the elevator (or stairwell) doors plus that across the building exterior. The primary problem associated with the stack effect in tall buildings related to the current study is its effect on smoke migration during fires. In this regard, it is the across door portion of the stack effect pressure difference that is directly related to smoke migration and control. A fire located on a lower floor can cause substantial damage, injury, and even death on upper floors due to the smoke migration through the elevator or stairwell shaft. The most infamous example of this effect occurred in the MGM Grand Hotel and Casino in 1980. A fire broke out in a ground floor restaurant that killed 85 people with the majority on upper floors due to smoke inhalation [3].

A variety of smoke control techniques have been proposed for both stairwell and elevator shafts primarily involving enclosed vestibules or lobbies surrounding the doors ways [3, 4, 5, 6]. However, the subject of the current study is to investigate the feasibility of solely using shaft pressurization as a means of smoke migration prevention in elevator shafts. Pressurization systems for stairwells have been used for some time (eg. Refs. [3, 7]). The available literature has shown stairwell pressurization systems to be feasible; although the system performance can be quite sensitive to several design parameters, including the opening of stairwell doors. In contrast, elevator shaft pressurization has only been recently approved by the IBC for smoke prevention in elevator shafts and relatively little research has been done to date. Two exceptions are experimental measurements in a fire tower reported in Ref. [8] and a limited number of simulation results in Ref. [3]. The primary objectives of the current work are to both illustrate the fundamental differences between stairwell and elevator shaft pressurization systems and to provide input for future code changes. Effects of the elevator and exterior building doors, ambient temperature, fan location, and shaft venting on the pressurization system performance are also addressed.

2 Modeling Approach

The following document presents results from an investigation of stairwell and elevator shaft pressurization on potential smoke distribution through the shaft effect. All results were obtained via computer simulations using the CONTAM software developed by the Indoor Air Quality and Ventilation Group at the National Institute of Standards and Technologies. The CONTAM software has been used extensively for similar simulations of air flow and for both stairwell and elevator shaft pressurization (eg. Ref. [3]).

Results are presented for a thirty story building model. A schematic of the building model's typical floor plan is provided in Fig. 1 (not to scale) along with prescribed leakages. The building is specified as a 30 story building with a floor height of $9.85ft$ ($3.0m$) and a floor area of $10,000ft^2$ ($930m^2$). On each floor there are two stairwells located at opposite corners of the building. In the center of the building are two (open) elevator shafts having four sets of elevators and elevator doors. All interior building leakage areas are based on typical values reported in the literature [3]. Each of the closed elevator doors (four per shaft) has a leakage area of $75in^2$ ($0.0484m^2$). However, the first floor elevator doors have a $854in^2$ ($0.558m^2$) leakage area modeling the elevator doors being open with the car on that floor. Each stairwell has a single door with leakage area $16in^2$ ($0.0103m^2$). Each floor of the building has exterior leakages calibrated with experimental data for either a "residential" (37 story building in Korea [9]) or a "commercial" (data measured in a 20 story bank in Boise, Idaho for this report) building. The two models take account of the presence or absence of openable windows, balcony doors, and other features associated with the two specific buildings used for the calibration. The parameters are not meant to imply that all residential buildings will have more porous skins

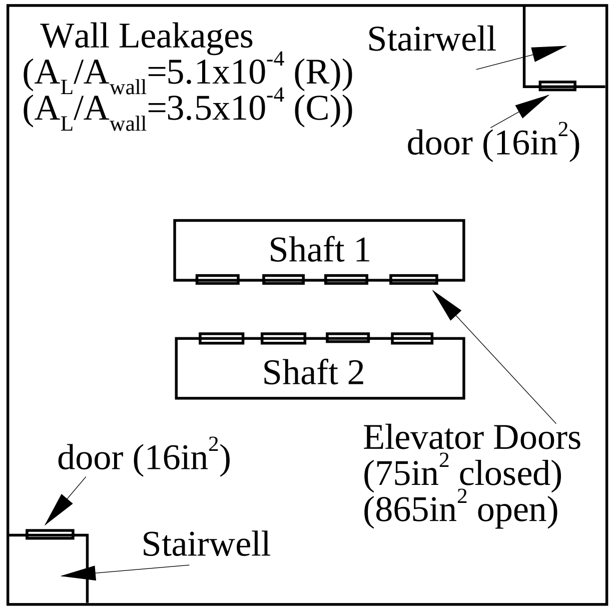

Figure 1: Schematic representation of the thirty story building floor plan: external leakages correspond to either a residential (R) or commercial (C) building model.

than other buildings. Note that the ground floors have larger leakage areas than upper floors due to the presence of exterior doors and/or other unique features. The building temperature is maintained at $70°F$ ($21°C$) on all floors. No wind is present.

Each building model also has a roof level with only the stairwells and elevator shafts (where the fans are installed for cases having fans). Elevator shaft and stairwell shaft pressurization are considered by pressurizing the shafts until a specified minimum pressure difference across any elevator or stairwell door is achieved. This corresponds to a minimum pressure difference of $+0.05in$ water ($+12.5Pa$) across elevator doors or $+0.15in$ water ($37Pa$) across stairwell doors. The process is iterated with a model for the average shaft air temperature based on turbulent duct theory along with the Dittus Boelter heat transfer correlation [10]. For elevator shaft pressurization the elevator cars are on the first floor with all doors in the open positions and with all stairwell doors closed unless otherwise specified (cases with no pressurization system have all elevator doors in the closed position). For stairwell pressurization all elevator doors and all stairwell doors are in the closed positions. Simulations are conducted for both pressurized shafts and for non-pressurized shafts for comparisons. Both "cold day" ($-12°C$, $10°F$) and "hot day" ($38°C$, $100°F$) conditions are considered.

3 Results

The following paper presents results for both stairwell and elevator shaft pressurization in tall buildings. One finding of this study is the importance of the elevator or stairwell air temperature on the simulation results. On very warm or very cold days the ambient air is at a substantially different temperature than the building and this difference affects the pressure profiles within the

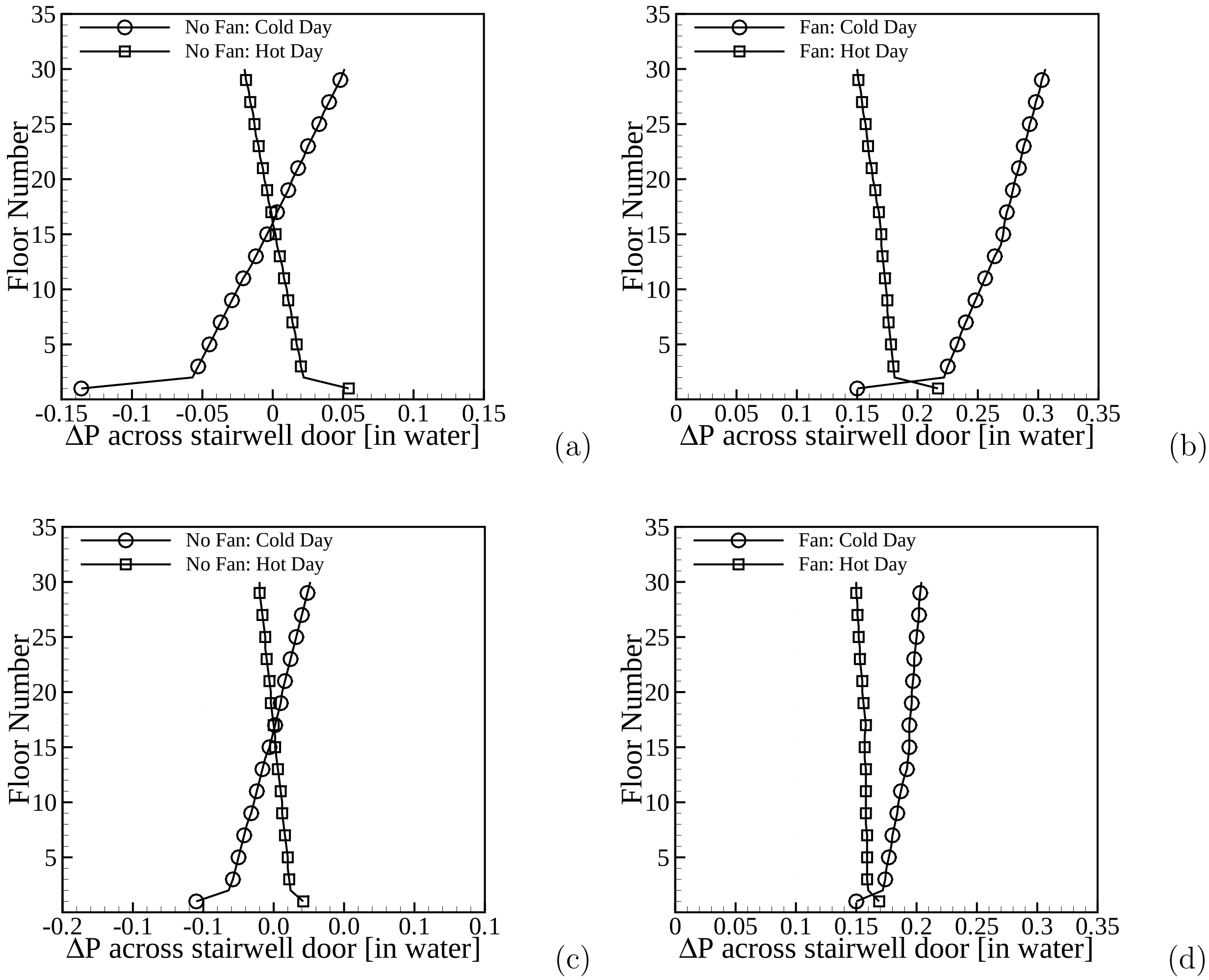

Figure 2: Pressure difference across the stairwell doors as a function of the floor number for a stairwell only pressurization system: (a) residential building with no pressurization, (b) residential building with pressurization, (c) commercial building with no pressurization, and (d) commercial building with pressurization.

shaft. A detailed model for the average shaft temperature was therefore derived from turbulent duct flow theory and incorporated into the simulations. The reader is referred to Refs. [2] and [1] for details on the assumptions and formulation.

3.1 Stairwell Pressurization Only

Results for stairwell shaft pressurization only are presented in Fig. 2 for the residential and commercial building models. Stairwell pressurization is observed to work well within the limits allowed by the current code limits of $+0.15in(+37Pa) \leq \Delta P \leq +0.35in(+87Pa)$. Note also that the simulations results show that the system calibration is highly sensitive to the ambient temperature. The location of the minimum pressure difference across stairwell doors is the ground floor when the ambient temperature is less than the building temperature. However, the minimum pressure difference occurs on the top floor when the ambient is warmer than the

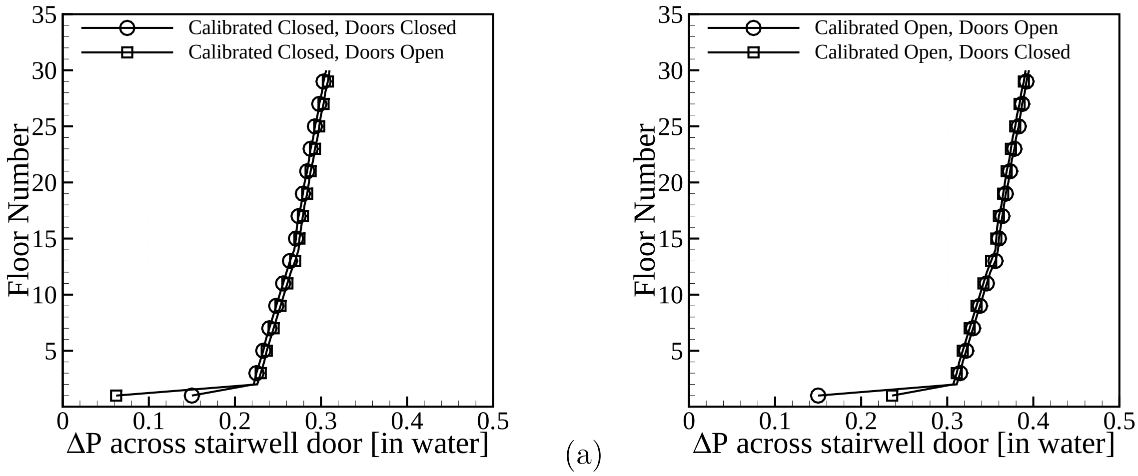

Figure 3: Pressure differences across stairwell doors as a function of the floor number for the residential building model. Data are for a stairwell only pressurization system calibrated with the exterior building doors in either the (a) closed or (b) open position and show the effects of opening or closing the exterior building doors. All data are for "cold day" conditions ($10°F$).

building temperature. Fan output is also dependent on the ambient temperature.

3.1.1 Effects of the Exterior Building Door Position

While not particularly sensitive, stairwell pressurization systems can be affected by the position of the building's exterior doors. Figure 3 illustrates the effects of the ground floor exterior door position on the system performance for the residential building model on a cold day. Results are presented for systems that are calibrated with the exterior building doors either closed [Fig. 3(a)] or open [Fig. 3(a)]. The effect of then opening (or closing) the exterior doors is also shown in each figure. Required fan speeds also change and are approximately 15% larger for the open door cases. To understand the results consider the system calibrated with the building doors closed. As the doors are opened the slightly pressurized building loses pressure to the ambient. The effect is felt throughout the building as the elevator shafts provide a relatively unrestricted flow of air between floors. The resulting pressure difference across the first floor stairwell doors is slightly reduced below the code specified minimum but remains large enough to inhibit smoke penetration. As will be discussed below, a very different behavior results with elevator shaft pressurization systems as the stairwells are relatively well sealed and do not provide an equivalent route for air flow between floors.

3.2 Elevator Shaft Pressurization Only

Results for elevator shaft pressurization are presented in Fig. 4 for the residential and commercial building models. Several of the major potential problems with elevator shaft pressurization systems are illustrated. Elevator shaft pressurization is markedly different than stairwell shaft pressurization. Required fan flow rates are approximately 50 times larger for elevator shaft pressurization systems than for stairwell pressurization systems. The current code limits of

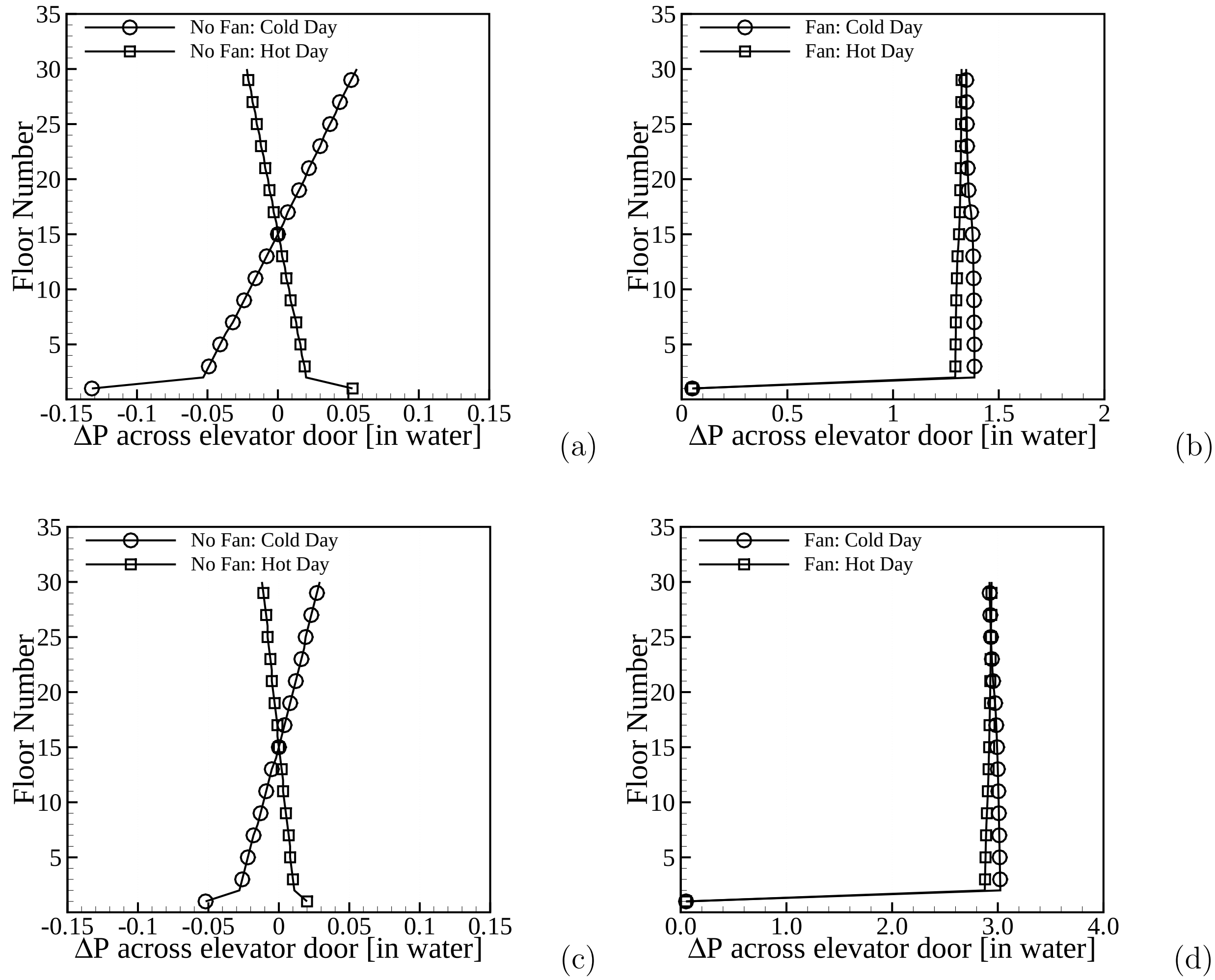

Figure 4: Pressure difference across the elevator doors as a function of the floor number for an elevator shaft only pressurization system: (a) residential building with no pressurization, (b) residential building with pressurization, (c) commercial building with no pressurization, and (d) commercial building with pressurization.

$+0.04in(+10Pa) \leq \Delta P \leq +0.06in(+15Pa)$ are also impossible to meet. Furthermore, pressure differences across upper floor elevator doors far exceed any reasonable limits for proper door functioning. The resulting across elevator door pressure differences are explained as follows: Air is forced into the shaft from the roof and some is "lost" along the way through the closed elevator doors and into the building interior. However, a relatively large flow rate is needed to achieve the $+0.05in$ water ($+12.5Pa$) pressure difference across the first floor open elevator doors due to their much larger leakage areas. As the ground floor elevator doors are open and have relatively large leakage areas, this required flow rate can be considerable.

The air flowing into the first floor from the shaft then pressurizes the first floor until the flow rate out of the first floor (through exterior and stairwell leakages) equilibrates with the flow rate entering through the elevator shafts. The second floor interior building pressure is much less than on the first floor as the closed stairwell doors have a relatively small leakage area (in cases with a

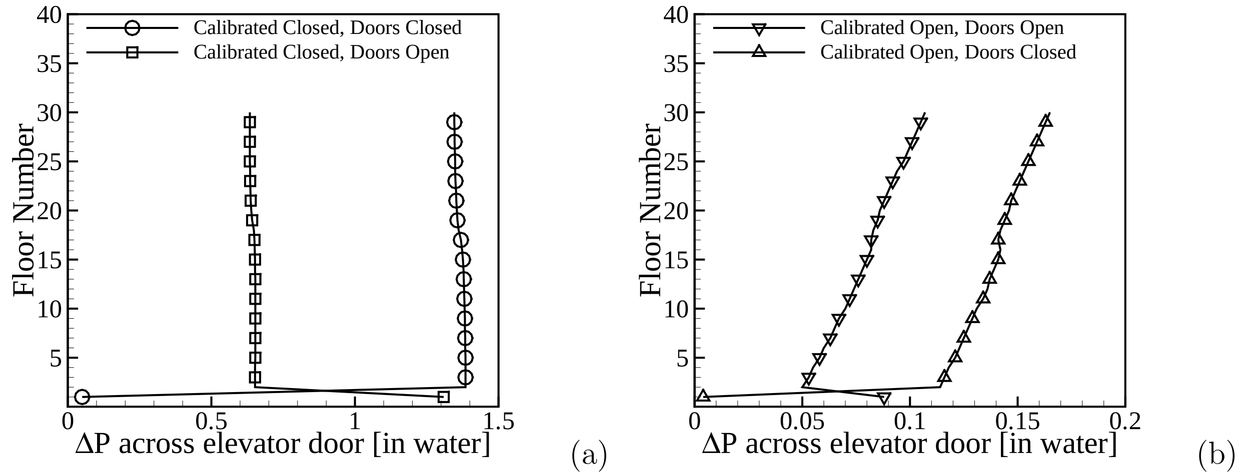

Figure 5: Pressure differences across elevator doors as a function of the floor number for the residential building model. Data are for an elevator shaft only pressurization system calibrated with the exterior building doors in either the (a) closed or (b) open position and show the effects of opening or closing the exterior building doors. All data are for "cold day" conditions ($10°F$).

coupled stairwell pressurization system no air would be allowed to flow into the stairwell shaft). However, the pressure within the shaft only varies hydrostatically so is only slightly lower at the second floor. Therefore, the across elevator door pressure difference is increased substantially on the second floor (as well as all remaining floors). This pressurization of the ground floor is due to the large open door leakage areas and is the primary effect distinguishing stairwell and elevator shaft pressurization systems. The effect is enhanced as the first floor leakage becomes smaller for the commercial building model (and vanishes if the first floor exterior door is open - see below). The outside temperature has relatively little influence on the final system pressure differences; however, significantly different fan flow rates are required based on the exterior temperature (flow rates are approximately 10% larger on hot days than cold days). Therefore, a system calibrated and tested during one season may have significantly different behavior during other seasons.

3.2.1 Effects of the Exterior Building Door Position

One possibly tempting means of overcoming the large pressure differences across elevator doors is to calibrate the system with the exterior ground floor building doors open. This would eliminate the over pressure on the ground floor. However, in contrast to stairwell pressurization systems, elevator shaft pressurization systems are much more sensitive to the ground floor door position. Figure 5 shows the effects of the exterior building door positions for the residential building model on a cold day with elevator shaft pressurization. System performance is considered for systems calibrated with the exterior doors in either the open or closed positions. A set of double doors propped wide open is modeled with a $42ft^2$ ($3.90m^2$) leakage area on the ground floor. The effects of then changing the exterior door position are also included in the figure. System performance and fan requirements change dramatically based on the exterior doors. If the system is calibrated with the exterior doors in the closed position a relatively large fan speed is required (greater than 300% larger than if the doors are open). If the exterior doors are then propped open the minimum pressure difference is still maintained across all elevator doors (although prohibitively large pressure differences exist). In contrast, if the system is calibrated with the exterior doors open and then operated with the doors closed there will be essentially no pressure difference across the ground floor elevator doors. In this situation there is a high probability of smoke entering the shaft if a fire is present on the ground floor. In summary, the only way to achieve a potentially code compliant system performance is with the ground floor doors open. However, the system will fail if it is operated with the doors closed as may very well be the case in an actual fire situation.

3.2.2 Effects of Fan Location, Vents, Louvers, etc.

Further studies have also examined the effects of the fan location, secondary pressurization systems, multiple injection points, and the effects of various louver/vent systems to alleviate over pressures. The results clearly show that each of these approaches are incapable of alleviating the above problems. Since the elevator shaft is relatively wide it experiences negligible frictional resistance and the shaft pressure simply equilibrates to pressure changes as would occur in a large tank. The shaft pressure is therefore independent of the fan location or to multiple injection points. Louvers and vents are similarly incapable of properly controlling the shaft pressure distribution because they are only capable of uniformly changing the pressure in the entire shaft. Therefore, any reduction in the maximum shaft pressure due to a roof (or otherwise located) vent or louver simply shifts the entire pressure distribution within the shaft evenly. This results in the minimum $+0.05in$ ($+12.5Pa$) being violated as the first floor pressure difference drops. For example, if a louver system is installed that allows $2,500ft^3/min$ ($70m^3/min$) of air to flow from the top of the shaft the fan speed would need to be increased by the same $2,500ft^3/min$ ($70m^3/min$) to compensate and to re-acquire the minimum pressure difference across the ground floor elevator doors. The net effect is to re-acquire the original pressure profile but with a larger fan requirement. Relying on transients is also ineffective. An analysis shows that the system response time to changes in door positions, fan flow rates, etc. is $\sim 5sec$ for the current model building.

3.3 Coupled Stairwell and Elevator Shaft Pressurization

Results for simulations of the building models with coupled stairwell and elevator shaft pressurization systems (ie. operating simultaneously and jointly affecting the building floor pressures) are presented in Fig. 6 for the residential and commercial building models. The simulation results illustrate an additional and very serious problem for stairwell pressurization systems if used in conjunction with an elevator shaft pressurization system. The addition of the elevator shaft system results in an additional flow of air into the building on all floors. This raises the pressure of the building interior and would result in negative pressure differences across the stairwell doors if the stairwell-only fan speeds were used. Therefore, substantial modification of existing stairwell pressurization would be required if an elevator system were later installed. Furthermore, another problem occurs after the stairwell system is re-calibrated to acquire a minimum $+0.15in$ water ($+37Pa$) pressure difference across any stairwell doors. In this case a similar phenomenon occurs as was observed previously for the elevator shaft pressurization systems. The over pressure on the first floor as compared to the second floor of the building

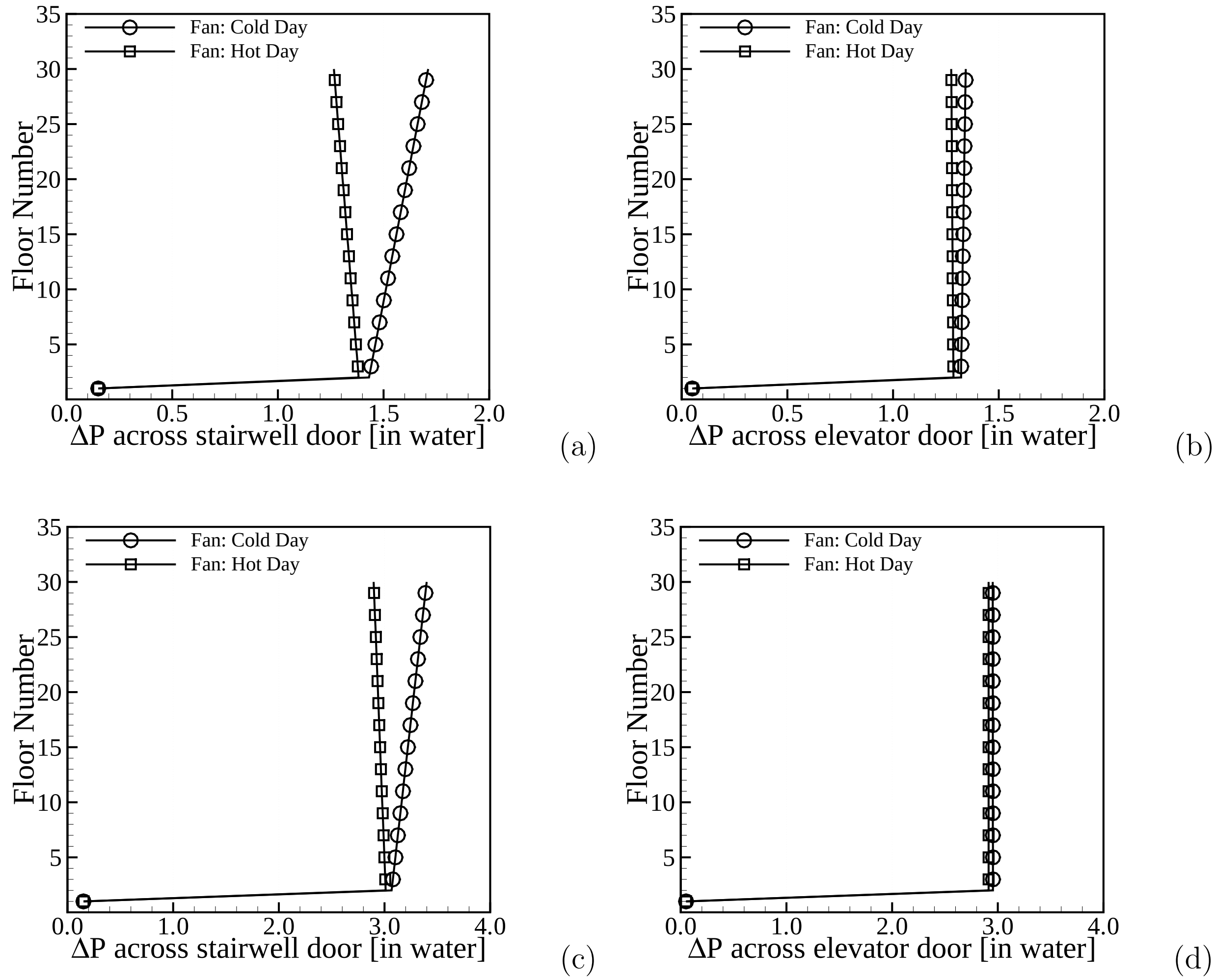

Figure 6: Pressure differences across either stairwell or elevator doors as a function of the floor number for coupled stairwell and elevator shaft pressurization systems: (a) residential building, stairwell doors, (b) residential building, elevator doors, (c) commercial building, stairwell doors, and (d) commercial building, elevator doors.

also creates very large pressure differences across all upper floor stairwell doors. These pressure differences are far too large for proper stairwell door functioning. For example, if a $7ft \times 3ft$ ($\approx 1m \times 2m$) stairwell door has a $1.5in$ water ($\approx 375Pa$) pressure difference this would require a force of approximately $165lbf$ ($\approx 750N$) to open the door! These results show that in addition to the problems described previously for stand alone systems, an elevator shaft pressurization system will also make the standard stairwell pressurization system fail.

3.3.1 Effects of the Elevator Door Position

Simulations were also conducted assuming that the system is calibrated with all the elevator doors in the closed position. The results are similar to those described above for the exterior building door position. Both the stairwell and the elevator pressure differences are within reasonable limits when the elevator doors are closed. However, if the elevator doors are opened

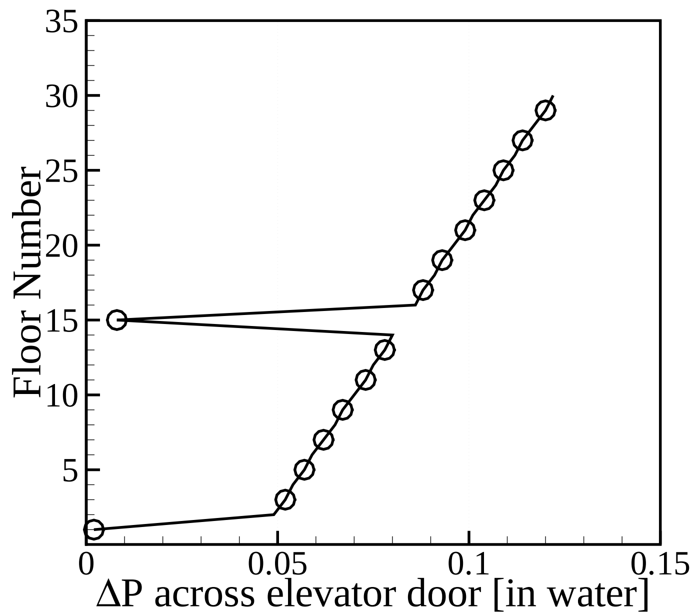

Figure 7: Pressure differences across elevator doors as a function of the floor number for the residential building model with coupled stairwell and elevator shaft pressurization on a cold day. Pressure differences across the open elevator doors on the ground floor are ignored for system calibration. The results show the effects of having two elevator cars move to the 15th floor with open elevator doors.

on the ground floor the minimum pressure difference nearly vanishes on the ground floor when the elevator doors are opened. This occurs for both the elevator doors and for the stairwell doors on the ground floor. In this case there is a strong potential for smoke to enter either shaft if present on the ground floor.

Similar to simply calibrating the pressurization system with either the exterior building doors propped open or with the elevator doors closed, it may be proposed that the system be calibrated by simply ignoring the pressure differences across the open ground floor elevator doors. Aside from the ignored pressure differences all systems are essentially able to meet the specifications. Both the stairwell doors and the elevator doors experience reasonable pressure differences. However, the open elevator doors may still be problematic. In all cases these pressure differences are essentially null. In the event that smoke were present on the ground floor and the elevator doors were opened it could be forced into the lower level floors either just above the ground floor or into the lower (basement) levels. Occupants may be forced to evacuate towards the fire containing floor. In contrast, a pressurization fan mounted on or below the ground floor would prove catastrophic as the smoke would be blown throughout the entire building.

Another potential problem with a system calibrated ignoring the open elevator door pressure differences is illustrated in Fig. 7. In this case the calibrated system for the residential building model on the cold day conditions is examined. The calibrated building model is altered as follows: two of the elevator doors from a single shaft are now closed on the ground floor and the same two doors are opened on the 15th floor (mimicking the effects of two cars in use by either fire fighters or building occupants). In this case, the pressure difference across (all of) the elevator doors is lost on the 15th floor as air from the shaft pressurizes the floor. The results show that if the elevators are brought to a smoke containing floor that there is a high probability of smoke entering the shaft. In this case the fan pressurization system would actively distribute the smoke throughout the building (and at a higher rate than the stack effect the system was originally designed to overcome). The authors therefore recommend against ignoring pressure differences across open elevator doors if there is any potential for elevator usage during a fire situation.

3.4 Effects of the Building Height and Number of Elevator Cars

The results to this point have shown that a robustly operating elevator shaft pressurization system with reasonable pressure differences across elevator doors is nearly impossible to design in the thirty story building model if: (1) these pressure differences apply to both open and closed elevator doors, and (2) if the system must function properly when the ground floor exterior building doors are closed. Additional simulations have shown that these results are not directly affected by the building height but are directly affected by the number of elevator cars and shafts. Therefore, while tall buildings may have the characteristics that produce large across elevator door pressure differences (larger numbers of elevator cars), it is not the building height directly that causes the behavior observed in this study.

4 Conclusions

The operation of stairwell shaft pressurization systems were found to be much simpler than elevator shaft pressurization systems (and quite feasible). In contrast, elevator shaft pressurization was found to require substantially larger fan flow rates to achieve the required minimum pressure differences. Prohibitively large pressure differences across upper floor elevator doors were found for all cases in which the exterior building doors are kept closed and the minimum pressure differences include the open elevator doors. The elevator shaft system also catastrophically interferes with the stairwell pressurization system in these cases. In contrast, systems calibrated with either the exterior building doors open, all elevator doors in the closed position, or ignoring the open elevator door pressure differences were all found to maintain reasonable across door pressure differences on all floors (stairwell and elevator). However, each of these will lead to situations in which nearly null across elevator door pressure differences on some floors could allow smoke to enter the shaft and be actively distributed throughout the building. Fan location, vents and louvers were all found to be ineffective as means of controlling the shaft pressures. Little effect of the ambient temperature was observed on the final elevator door pressure differences; however, significantly different fan speeds are required.

Acknowledgments

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