Building and Environment 44 (2009) 1306–1317

Contents lists available at ScienceDirect

Building and Environment

journal homepage: www.elsevier.com/locate/buildenv

On stairwell and elevator shaft pressurization for smoke control in tall buildings

Richard S. Miller*, Don Beasley

Department of Mechanical Engineering, 210 Fluor Daniel Building, Clemson University, Clemson, SC 29634-0921, USA

A R T I C L E I N F O

Article history:
Received 18 July 2008
Received in revised form
19 September 2008
Accepted 26 September 2008

Keywords:
Stack effect
Smoke
Stairwell pressurization
Elevator pressurization

A B S T R A C T

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. A thirty story building model is considered with exterior leakages calibrated to experimental data for both a residential and a commercial building. 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. These differences between stairwell and elevator shaft pressurization are directly attributable to the much larger leakage areas associated with elevator doors. Relatively large flow rates through the open elevator doors act to pressurize the ground floor of the building, indirectly causing large pressure differences across upper floor elevator doors. 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

This article 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 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. For recent experimental measurements in a high-rise residential building see Ref. [1].

One of the most basic equations describing the stack effect is that of Eq. (5.26) of the *ASHRAE Principles of Smoke Migration* [2]. This correlation predicts that the pressure difference from the elevator shaft to the outside ambient pressure follows the relation:

$$\Delta P_{\mathrm{SO}} = -\frac{gP_{\mathrm{atm}}}{R}\left(\frac{1}{T_{\mathrm{O}}}-\frac{1}{T_{\mathrm{S}}}\right)z, \tag{1}$$

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, $g = 9.81\ \mathrm{m/s^2}$ is the gravitational acceleration, $P_{\mathrm{atm}} = 101325$ Pa is atmospheric pressure, and $R = 287$ J/(kg K) is the specific gas constant for air. In the absence of other interior pressure barriers, this total 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. 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 shaft. The most infamous example of this effect occurred in the MGM Grand Hotel and Casino in 1980. A fire broke out in a restaurant that killed 85 people with the majority on upper floors due to smoke inhalation [2].

A variety of smoke control techniques have been proposed for both stairwell and elevator shafts primarily involving enclosed

---

* Corresponding author. Tel.: +864 656 6248; fax: +864 656 4435.
E-mail address: rm@clemson.edu (R.S. Miller).

0360-1323/$ – see front matter © 2008 Elsevier Ltd. All rights reserved.
doi:10.1016/j.buildenv.2008.09.015

vestibules or lobbies surrounding the doors ways [2–5]. 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. In theory, pressurizing the shaft so that a positive pressure difference occurs on all floors will prevent smoke from entering the shaft. The wisdom of providing the fire with fresh oxidizer is not addressed in this study. The pertinent sections of the International Building Code (IBC) relevant to stairwell-pressurization systems states in part (Section 909.20.5): 'the vestibule is not required, provided that interior exit stairways are pressurized to a minimum of +37 Pa (+0.15 in of water) and a maximum of +87 Pa (+0.35 in of water) in the shaft relative to the building measured with all stairway doors closed under maximum anticipated stack effect pressures.' Minimum pressure differences are required to prevent smoke entrance into the shaft, while maximum limits are meant to ensure proper door functioning that can be impeded by excessive forces. In contrast, the use of elevator shaft pressurization has only recently received approval by the IBC and relatively little research has been done in this area. The recently approved section of the code relevant to elevator shaft pressurization (Section 707.14.2.1) states in part: "Elevator hoist ways shall be pressurized to maintain a minimum positive pressure of +10 Pa (+0.04 in of water) and a maximum positive pressure of +15 Pa (+0.06 in of water) with respect to adjacent occupied space on all floors. This pressure shall be measured… with all elevator cars at the floor of recall and all hoist-way doors on the floor of recall open and all other doors closed." This latter standard for elevator shafts has already been realized to be impractical (see results below) and is currently under revision.

Pressurization systems for stairwells have been used for some time and have been investigated in the literature (Refs. [2,6]). While such studies have shown stairwell-pressurization systems to be feasible, the systems have been shown to be quite sensitive to several design parameters. For example, Wang and Gao [6] found that the stairwell-pressurization system performance was compromised in a 32-story building during field tests when more than two stairwell doors were opened simultaneously. 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. [7] and a limited number of simulation results in Ref. [2]. However, neither of these studies accounted for the shaft temperature or pressurized the building with its exterior doors closed which will be shown below to have a critical impact on system performance.

Two potential problems associated elevator shaft pressurization are described as follows. First, a minimum pressure difference of approximately +12.5 Pa is required by current IBC standards to be maintained at any floor of the building to ensure that no smoke enters the shaft. In practice, the elevator doors are in the "Phase 1" position during such an emergency: all cars on the first floor with the elevator doors in the open position (thereby allowing easy access for fire fighters). No exception for minimum pressure differences across open elevator doors exists in the current IBC code. Since the pressure differences within the shaft continue to increase with elevation another problem associated with too large pressure differences is likely to occur due to large forces on the elevator doors impeding their proper functioning. Consider that a 100-Pa pressure difference acting on even a 1 m × 2 m elevator door will produce a 200 N (≈45 lbf) force on the door. While general maximum pressures are unavailable in the literature, for the present purposes 100 Pa (40 in water) is considered to be the approximate maximum suggested pressure difference allowed across the elevator doors. Consequences of this will be discussed below.

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 the 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 (Ref. [2]).

Results are presented for a 30-story building model. A schematic representation of the building model's typical floor plan is shown in Fig. 1 (not to scale) along with prescribed leakages. The building is specified as a 30-story building with a floor height of 3.0 m and a floor area of 930 m^2. On each floor there are two stairwells located at opposite corners of the building. Each stairwell has a floor area of 23.2 m^2 with a perimeter of $P' = 19.27$ m. In the center of the building are two (open) elevator shafts having four sets of elevators and elevator doors. The open shafts each have a floor area of 83.6 m^2 and a perimeter of $P' = 45.72$ m. All interior building leakage areas are based on typical values reported in the literature [2]. Each of the closed elevator doors (four per shaft) has a leakage area of 0.0484 m^2 (75 in^2). However, the first floor elevator doors have a 0.558 m^2 (865 in^2) leakage area modeling the elevator doors being open with the car on that floor. Each stairwell has a single door with leakage area of 0.0103 m^2 (16 in^2). The building temperature is maintained at 21 °C on all floors. No wind is present.

Each floor of the building has exterior leakages calibrated for either a 'residential' or a 'commercial' building. The specific values of the exterior wall leakages were obtained by calibrating the model predictions with experimental measurements. For the residential building, model data taken in a Korean residential building

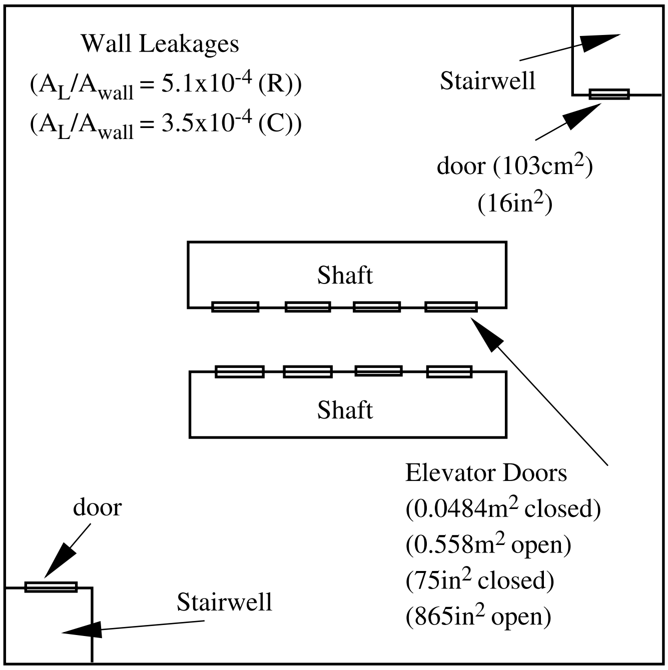

Fig. 1. Schematic representation of the 30-story building floor plan: external leakages correspond to either a residential (R) or a commercial (C) building model.

from Ref. [1] are used. The building is a 37-story tall modern (completed in 2005) residential building and the pressure measurements were made on an $-11.9\,^{\circ}\mathrm{C}$ day. These same data were also used to calibrate the ground floor leakages. The ground floor is identical to the upper floors with the exception of an additional leakage to the building exterior. The calibration procedure is illustrated in Fig. 2 which shows pressure differences across elevator doors for both the experimental measurements and the current building model without shaft pressurization. The standard stack effect causes a pressure difference between the elevator shaft and the building exterior as predicted by Eq. (1) [2]. In the limits of very small and very large exterior building leakages, the total stack effect pressure difference will appear across either the external wall or the elevator doors, respectively. A similar phenomenon occurs on the ground floor. Based on this, the external leakage area for the upper floors was adjusted in the model to match the relative proportion of the stack effect pressure difference across the elevator doors to the experimental data. The ground floor was treated in a similar manner. The calibrated total leakage area per upper floor for the residential building model is 0.206 m^2 (320 in^2) and the ground floor has an additional leakage area of 0.194 m^2 (300 in^2). The upper floor relative leakage area (to the wall area; as indicated in Fig. 1) corresponds to 'loose' to 'very loose' construction as specified in Ref. [2].

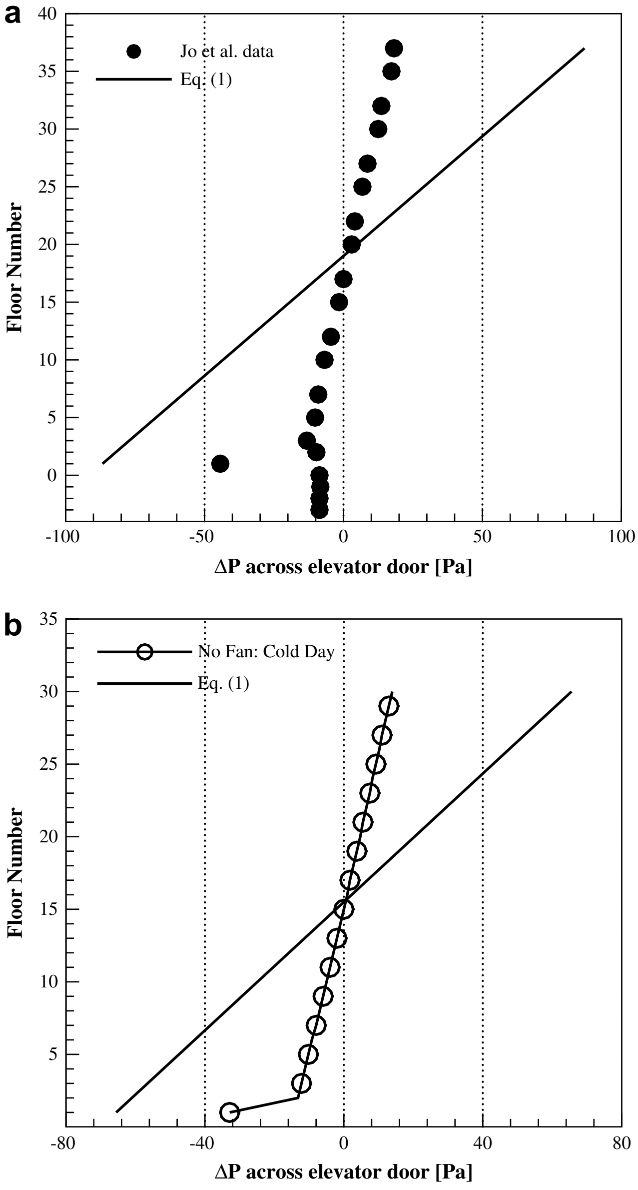

Fig. 2. Pressure differences across elevator doors as a function of the floor number for the 'residential' building model: (a) experimental measurements from Ref. [1] for a 37-story Korean residential building on a $-12\,^{\circ}\mathrm{C}$ day as a function of the floor number (taken from Fig. 7 of the citation), and (b) simulation model after calibration of external leakages on upper floors and the ground floor.

A similar approach was used to determine the building leakages for the commercial building model. However, no analogous pressure measurement data were found in the literature for commercial buildings. Therefore, measurements were commissioned for the present study through Ro-Bar Technical Services, Inc. Measurements were taken in a Commercial Bank building in Boise, Idaho on May 30, 2008 between 6:00am and 7:00am during a time when the bank was closed and relatively unoccupied. The building is 80.8 m tall and the main elevator shaft traverses the first 19 floors of the building (the twentieth floor penthouse is only accessible via the service elevator). The building was constructed in 1985. The building's HVAC system was turned off for the measurements as would be the case in a fire situation. Furthermore, all exterior doors were kept in the closed position and doors to the basement parking garage were also closed for the measurements. As will be shown below, the closed door situation represents the worst case scenario for an elevator shaft-pressurization system. Effects of calibrating the system with the exterior doors open are addressed below. Pressure measurements were made with a Shortridge #880C Airdata Multimeter, and temperature data were taken with a Fluke model #52 K/J digital thermometer. The data obtained for this study are given in Table 1 and Fig. 3(a). The Eq. (1) curve in Fig. 3(a) corresponds to an ambient temperature of $13.3\,^{\circ}\mathrm{C}$ and a shaft temperature of $23.7\,^{\circ}\mathrm{C}$. These values were obtained using 'averaged' measured temperature data and matching the total pressure difference from the first floor shaft to the outside (ie. summing the pressure differences from shaft to floor and floor to outside). In the calibrated commercial building model, each upper floor has a total leakage area of 0.142 m^2 (220 in^2) and the ground floor has an additional 0.0516 m^2 (80 in^2) leakage area to the building exterior [see Fig. 1 and Fig. 3(b)].

Note that all interior leakages in both building models are obtained from the published data. The only parameter distinguishing the models referred to as residential and commercial are the exterior leakages that are calibrated to experimental data for two specific buildings. The names 'residential' and commercial are therefore only used as references and are not meant to be typical of all classes of such buildings.

Each building model also has a roof level with only the stairwells and elevator shafts (where the fans are installed for cases having fans). The stair door openings are identical on these levels but the elevator shaft is sealed unless a fan is installed. Elevator shaft and stairwell shaft pressurizations are considered in a similar manner. A specified volumetric flow rate fan (comparable to a constant speed fan with fixed damper setting) is installed at the top of each shaft on the roof level. The volumetric flow rate of the fan is increased from a zero rate (no fan) until a minimum pressure difference of +12.5 Pa

Table 1
Pressure and temperature measurements in a 20-story commercial bank building in Boise, Idaho, commissioned for this study.

Floor	Elev. shaft to floor (ΔP) (Pa)	Outside to floor (ΔP) (Pa)	Elev. lobby temp. (°C)
19	+1.54	N/A	23.7
2	−1.59	N/A	23.8
1	−3.01	−12.4	21.2

The ambient temperature was measured to be $15.1\,^{\circ}\mathrm{C}$ on the ground floor and $12.8\,^{\circ}\mathrm{C}$ on the roof.

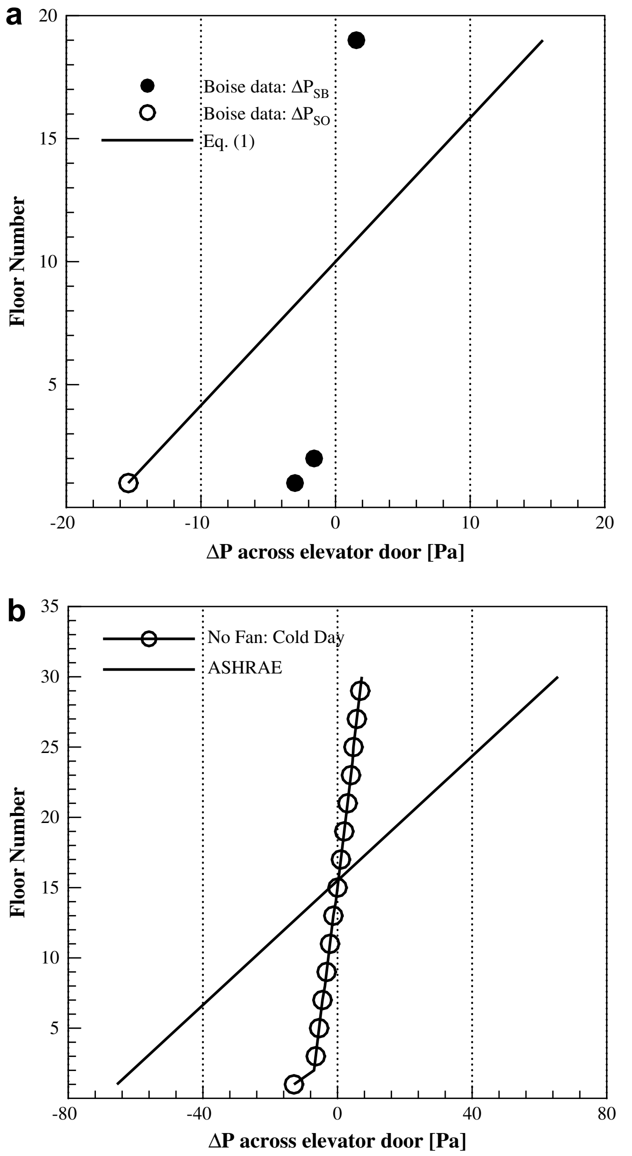

Fig. 3. Pressure differences across elevator doors as a function of the floor number for the commercial building model: (a) experimental measurements from a 19-story commercial bank building in Boise, Idaho on a 13 °C day as a function of the floor number and (b) simulation model after calibration of external leakages on upper floors and the ground floor.

is achieved across any sets of elevator doors or 37 Pa across any set of stairwell doors for stairwell pressurization. The process is iterated with a model for the average shaft temperature described below. 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 and stairwell doors are in the closed positions. Simulations are conducted for both pressurized and non-pressurized shafts for comparisons. Both 'cold day' (−12 °C) and 'hot day' (38 °C) conditions are considered.

3. Results

This article presents results for both stairwell and elevator shaft pressurization in tall buildings. Unless otherwise specified, all results are based on the following assumptions.

- Flow areas are identical on all floors other than the first floor that has an additional leakage (both upper and ground floor exterior leakages are calibrated to either the residential or the commercial building data below).
- The leakage between floors is negligible.
- The flow through shafts other than the stairwell or elevator shafts is negligible (mail chutes, HVAC system, etc.)
- The HVAC system is turned off (as would be the case in a fire situation).
- Friction pressure losses in stairwell and elevator shafts are negligible.
- No wind is present.
- Specified minimum pressure differences of +37 Pa or +12.5 Pa must be maintained across all stairwell or elevator doors. This includes open ground floor elevator doors in the Phase 1 position or open elevator doors on upper floors. Consequences of this assumption are addressed below.
- Both elevator and stairwell-pressurization systems must meet all across door pressure difference requirements with the exterior building doors in the closed position (as would be the case at the beginning of a fire on either very hot or very cold days, during night time hours, etc.). Consequences of this assumption are addressed below.
- An averaged temperature is used to describe the air temperature within both the stairwell and elevator shafts as inputs to the CONTAM software.

One novel feature of the current work is the last assumption. The CONTAM software is based on a zonal model that uses a single value for the temperature within an entire zone; including the stairwell and elevator shafts (although pressure varies hydrostatically within a zone). However, as ambient air entrained into the shaft by the pressurization system is at a different temperature than the building, a variable temperature profile exists within the shaft. To date this effect has been neglected in the literature and is addressed as follows.

3.1. Modeling the elevator shaft temperature

The starting point for the analysis is considering heat transfer within a duct with dimensions equivalent to the elevator shaft (ie. neglecting leakages along the length). For duct flow, the axially varying bulk fluid temperature (averaged over the cross-sectional area) is related to the constant wall temperature (T_B) and the intake air temperature (T_O) as [8]:

$$T_S(x) = T_B - (T_B - T_O)\exp\left[-\frac{P' h R T_O x}{C_{p,o} Q P_{atm}}\right] \qquad (2)$$

The shaft position is x (from the intake; top or bottom), and the shaft perimeter is P'. The other parameters are the convective heat transfer coefficient, h; the volumetric flow rate of the ambient intake air, Q; and the heat capacity of the intake ambient air, $C_{p,o}$. In what follows, the heat capacity of air is taken to be constant over the range of temperatures of interest: $C_{p,o} = 1.007$ kJ/(kg K) [9].

Two methods are considered for evaluating the convective heat transfer coefficient. First, high Reynolds number and fully developed pipe flow is assumed (Reynolds numbers $\sim 10^5$ are found in this study). In this case, the Dittus Boelter equation predicts $h = h_\infty = 20\ W/(m^2\,K)$ [8] where the subscript indicates the fully developed value. This is typically considered as valid for distances greater than approximately 10 hydraulic diameters downstream of the entrance. However, the shafts considered in this study are relatively short (only 12.3 hydraulic diameters for the 30-story building). Therefore, a correction for entrance length effects relevant to the current building parameters is also considered [8]:

$$\frac{h}{h_\infty} = 1 + \frac{2D_h}{x}, \tag{3}$$

where the hydraulic diameter is $D_h = 4A/P'$ (A is the shaft cross-sectional area) and h_∞ is the above-mentioned fully developed value. Note, however, that this form is also not valid too near the entrance due to the singularity at $x = 0$. Both forms are considered below.

CONTAM is not capable of including the effects of variable temperature within a zone (ie. the elevator shaft). Therefore, a single average value of temperature averaged over the entire shaft of height H is sought as an input for the model:

$$T_S = \frac{1}{H}\int_0^H T_S(x)dx. \tag{4}$$

Consequences of using an average shaft temperature are addressed below. Substituting for $T_S(x)$ from Eq. (2) yields

$$T_S = T_B + \frac{(T_B - T_O)C_{p,o}QP_{atm}}{P'h_\infty RT_O H}\left[\exp\left(-\frac{P'h_\infty RT_O H}{C_{p,o}QP_{atm}}\right) - 1\right], \tag{5}$$

for fully developed flow. A similar version exists for the entrance length-corrected heat transfer form, Eq. (3). However, as will be shown below, the form Eq. (5) above will be recommended for predicting the average shaft temperature during pressurization with ambient air.

The above expressions for the elevator shaft temperature are displayed in Fig. 4 for the conditions of the 30-story building on the cold day conditions ($T_O = -12$ °C). Both curves correspond to Eq. (2); one with a constant $h = h_\infty$ for fully developed flow and the second using the entrance length correction of Eq. (3). Although the entrance length correction is meant to improve the accuracy for $x/D_h < 10$ the effects of the heat transfer coefficient singularity at $x = 0$ are clear in the figure. The temperature at the inlet should be -12 °C but is approximately -12 °C higher due to the singularity. In reality, this correction is only considered to be accurate after several hydraulic diameters downstream of the entrance. Therefore, the expected trend would be something starting at the ambient temperature at the entrance and falling between the two curves in Fig. 4. The average values over the entire shaft are also indicated on the figure. The difference between using either of these values is also relatively insignificant in conjunction with a CONTAM simulation. Therefore, the average shaft temperature given by Eq. (5) is hereafter used for providing the constant temperature input to CONTAM. Note that although Eq. (5) somewhat over predicts the true average temperature in Fig. 4, the neglected effects of flow losses to upper floors and wall heating act to negate this over prediction.

The final consideration in assessing the accuracy of Eq. (5) for predicting the average shaft temperature during pressurization is the assumption of constant wall temperature. In reality, the concrete walls lining the shaft interior will be cooled or heated during the pressurization process. However, during system operation for an actual fire situation the first hour is the primary consideration. This is the time crucial to building evacuation, fire fighter response, and, therefore, proper system operation. Pertinent building codes also only address the first hour of operation for secondary power systems. Consider the characteristic penetration depth for thermal diffusion in concrete over the course of an hour: $l \sim \sqrt{\alpha t}$, where $\alpha = 6.9 \times 10^{-7}$ m^2/s for concrete [9]. In this case, for a 3600 s exposure time thermal energy will diffuse into the concrete only ~0.05 m. The temperature change of the concrete walls is therefore expected to be relatively small over an hour duration. An additional 'lumped' thermal analysis for a concrete slab of length 30 × 3 m, width 18.3 m, and depth 0.6 m (corresponding to one wall of the 30-story building shaft) was also performed (data not shown). In this case, the bulk concrete temperature is reduced by less than 4 °C after one hour of exposure to the -12 °C air stream. The assumption of constant temperature wall heat transfer is therefore considered to be valid during at least the first hour of operation.

The impact of assuming a constant shaft temperature rather than the actual spatially varying shaft temperature is addressed in Fig. 5. The figure shows the pressure difference from the shaft to the ambient for the conditions corresponding to Fig. 4. Both variable and constant average temperature shafts are considered. The shaft to ambient pressure difference is that consistent with the standard stack effect equation, Eq. (1). For the variable density case the basic hydrostatic relationship ($dP/dx = \rho g$) has been numerically

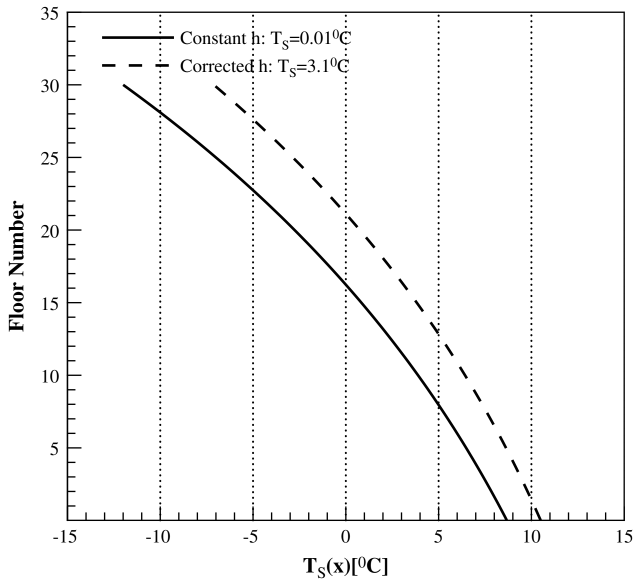

Fig. 4. Thermal model predictions of the shaft temperature as a function of the floor number for a building temperature of 21 °C, outside temperature of -12 °C and a fan rate of 3680 m^3/min.

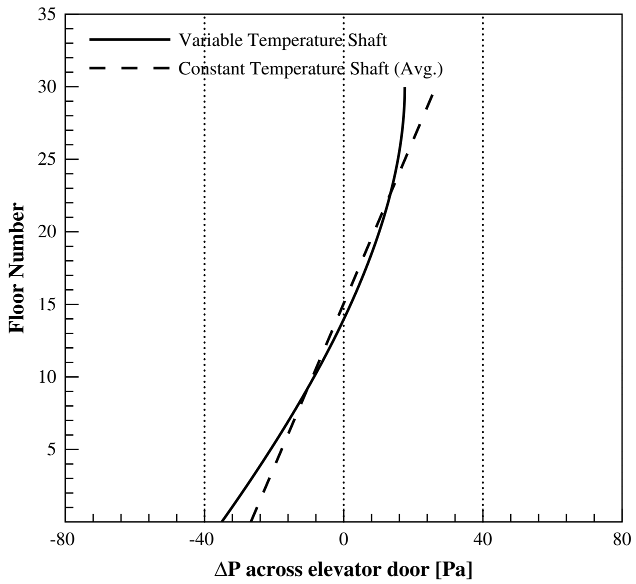

Fig. 5. Pressure difference between the shaft and the ambient (shaft effect) for both variable and constant (average) shaft temperature (0.01 °C) corresponding to Fig. 4 as a function of the floor number.

integrated to give the shaft pressure. The neutral plane is identified by assuming uniform leakages across the length of the shaft and by requiring that the net mass flow rate be null. In this case the differential mass flow rate is assumed to be proportional to $\sqrt{(\rho\Delta P)}dx$ [2]. This is integrated over the length of the shaft and set to zero to find the neutral plane. The results show that even on the most severe day considered ($T_O = -12\,^\circ\mathrm{C}$) assuming a constant average shaft temperature is reasonable. Lesser temperature differences between the shaft and the ambient fan air will more closely follow the linear form given by Eq. (1) making the assumption of constant mean shaft temperature even more accurate. Therefore, constant mean shaft temperature is assumed as follows. The reader should note, however, that the actual pressure profiles would be slightly curved similar to the profile in Fig. 5 if a variable shaft temperature was incorporated into the software.

3.2. Stairwell pressurization only

Results for stairwell shaft pressurization only are presented in Fig. 6 for the residential and commercial building models. Additional simulation data are given in Table 2. These include the fan volumetric flow rate of ambient air, the average shaft temperature, and the maximum absolute pressure difference across any stairwell door. Stairwell pressurization is observed to work well within the limits allowed by the current code ($+37\ \mathrm{Pa} \le \Delta P \le +87\ \mathrm{Pa}$). The stairwell pressurization results presented here are completely consistent with recently published experimental measurements reported in Ref. [6]. This study addressed stairwell pressurization in a 32-story high rise in Harbin, China. The primary difference is that the Chinese code requires a minimum pressure difference across the stairwell doors of 50 Pa (+0.20 in water). As such, the resulting

Table 2
Summary of results for stairwell shaft pressurization only.

Model	Pressurized	Fan output (m^3/min)	Ambient	Shaft (°C)	$\lvert\Delta P\rvert_{\max}$ (Pa)
R	No	N/A	Cold, −12 °C	21	+33.9
R	Yes	109	Cold, −12 °C	19	+76.2
R	No	N/A	Hot, 38 °C	21	+13.4
R	Yes	100	Hot, 38 °C	22	+54.0
C	No	N/A	Cold, −12 °C	21	+13.7
C	Yes	92.7	Cold, −12 °C	19	+50.8
C	No	N/A	Hot, 38 °C	21	+5.23
C	Yes	96.7	Hot, 38 °C	22	+42.1

Both the residential (R) and commercial (C) building models are considered.

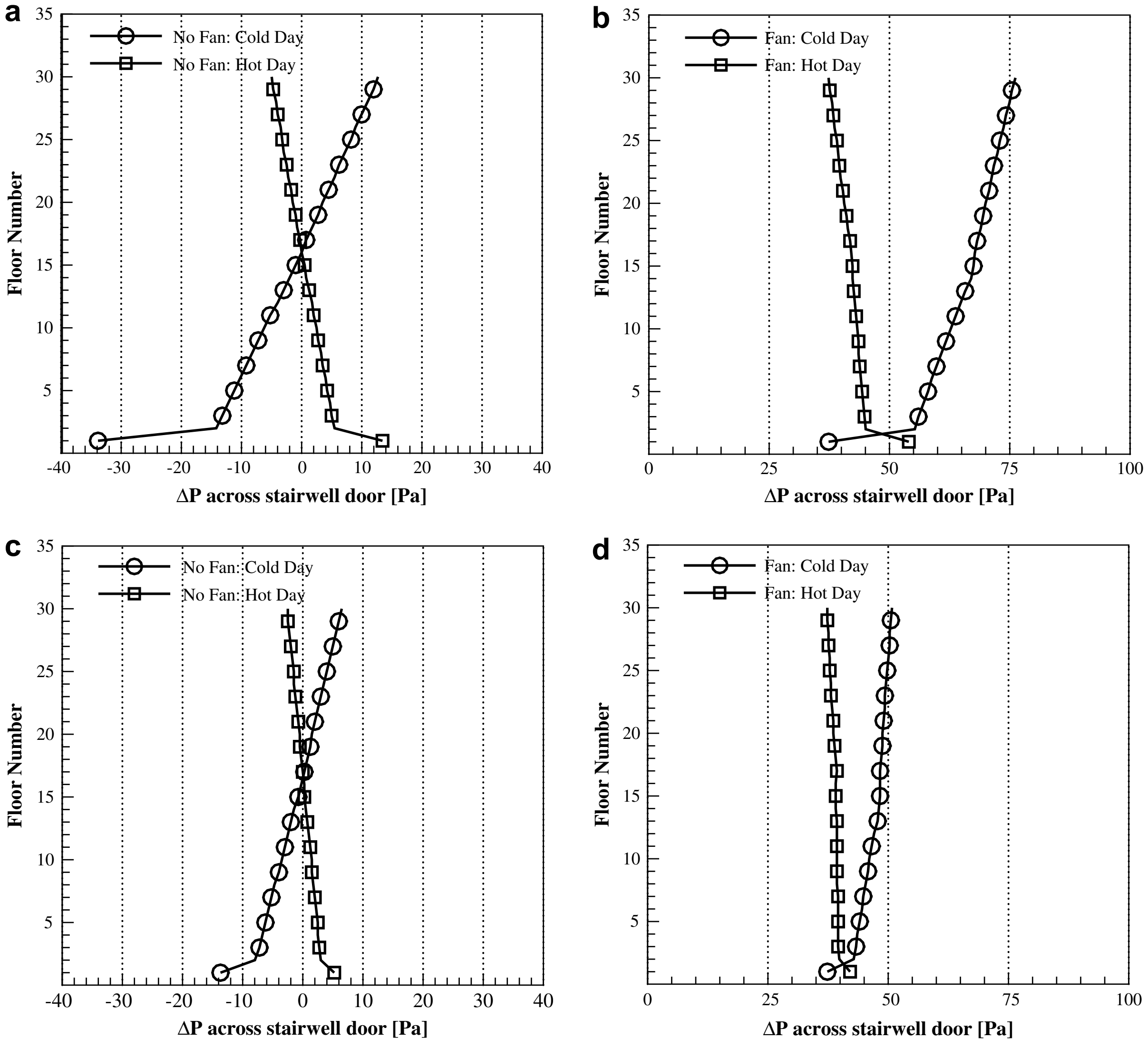

Fig. 6. Pressure difference across the stairwell doors as a function of the floor number for a stairwell-only pressurization system: (a) residential building with no pressurization, (b) residential building with pressurization, (c) commercial building with no pressurization, and (d) commercial building with pressurization.

fan flow rate requirements are larger than those observed in the present work. They also conclude that stairwell pressurization is feasible, although they caution that care must be taken in accounting for door openings that may cause the system to fail in some situations (an effect not addressed in the present work). Note also that the simulation 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 building temperature. Fan output is also dependent on the ambient temperature.

3.3. Elevator shaft pressurization only

Results for elevator shaft pressurization are presented in Fig. 7 for the residential and commercial building models. Additional data are provided in Table 3. Several of the major potential problems with elevator shaft-pressurization systems are illustrated. Elevator shaft pressurization is markedly different than stairwell shaft pressurization. The current code limits of $+10\ \mathrm{Pa} \le \Delta P \le +15\ \mathrm{Pa}$ are 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 $+12.5$ Pa pressure difference across the first floor open elevator doors due to their much larger leakage areas. The 'orifice equation' used to describe flow through the leakages directly relates the required volumetric flow

Table 3
Summary of results for elevator shaft pressurization only.

Model	Pressurized	Fan output (m^3/min)	Ambient	Shaft (°C)	$\lvert\Delta P\rvert_{\max}$ (Pa)
R	No	N/A	Cold, −12 °C	21	+32.9
R	Yes	4790	Cold, −12 °C	−2	+345
R	No	N/A	Hot, 38 °C	21	+13.2
R	Yes	5270	Hot, 38 °C	32	+330
C	No	N/A	Cold, −12 °C	21	+12.9
C	Yes	6940	Cold, −12 °C	−5	+753
C	No	N/A	Hot, 38 °C	21	+4.98
C	Yes	7650	Hot, 38 °C	34	+732

Both the residential (R) and commercial (C) building models are considered.

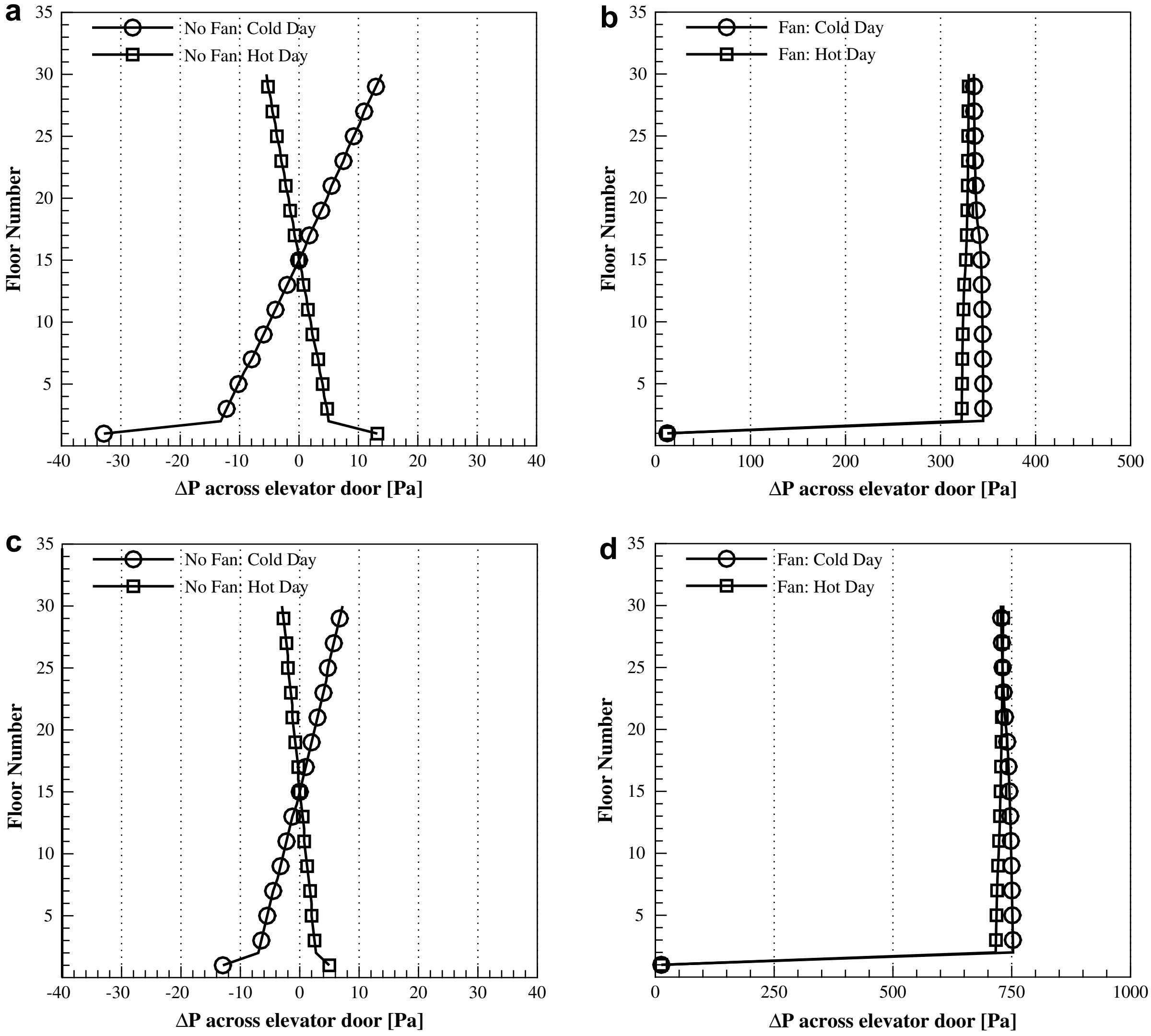

Fig. 7. Pressure difference across the elevator doors as a function of the floor number for an elevator shaft-only pressurization system: (a) residential building with no pressurization, (b) residential building with pressurization, (c) commercial building with no pressurization, and (d) commercial building with pressurization.

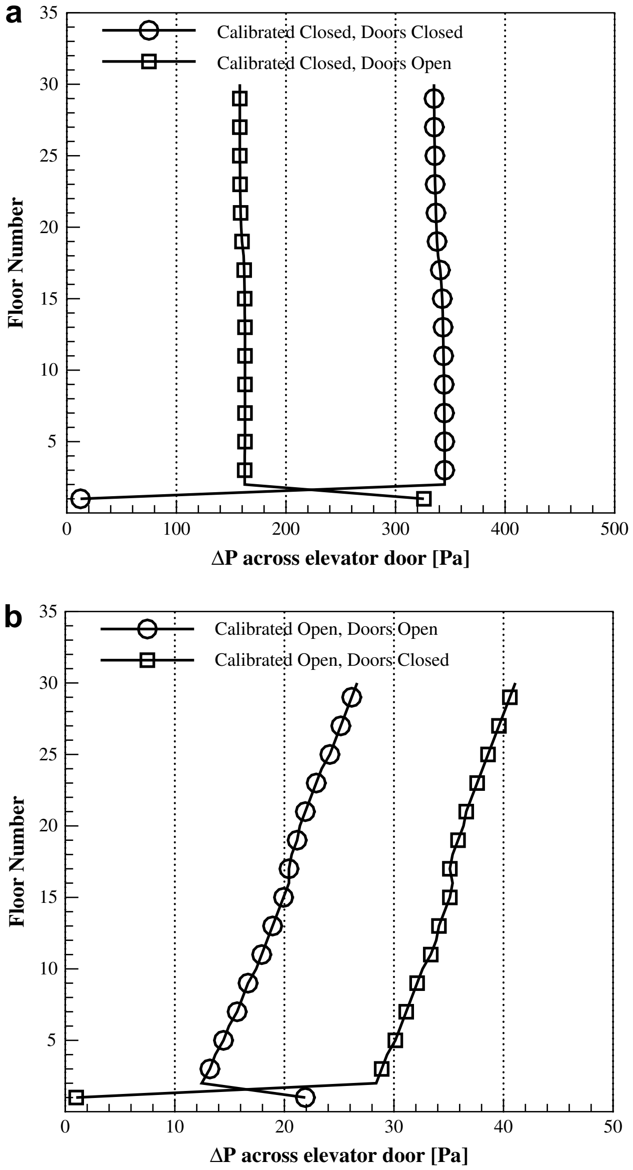

Fig. 8. Pressure differences across elevator doors as a function of the floor number for the residential building model. Data are for a system calibrated with the exterior building doors in either the (a) closed or (b) open position and show the effects of opening or closing the exterior building doors. All data are for cold day conditions (−12 °C).

rate of air through the elevator doors (Q), the required across elevator door pressure difference, and the total leakage area (A_t) on the ground floor: $Q \sim A_t\sqrt{\Delta P}$ [2]. This specifies the flow rate of air that must reach the ground floor after leakages to upper floors through the closed elevator doors. As the ground floor elevator doors are open and have relatively large leakage areas, this required flow rate can be considerable.

Table 4
Summary of results for the residential building model studying the effects of the exterior building door position on elevator (only) shaft pressurization.

Ext. door	Fan output (m^3/min)	Ambient	Shaft (°C)	$\lvert\Delta P\rvert_{\max}$ (Pa)
Closed	4790	Cold, −12 °C	−2	+345
Open	1490	Cold, −12 °C	9	+26.6

The elevator fan is calibrated with the exterior building doors in either the open or closed positions.

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 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 on all the 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, substantially different fan flow rates are required based on the exterior temperature (Table 3). Therefore, a system calibrated and tested during one season may have significantly different behavior during other seasons.

3.3.1. *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. This approach was taken in the elevator shaft pressurization results in Ref. [2] (see Figs. 11.3–11.4) without explanation. However, we argue that this is not a proper approach as fire is more likely to occur with the exterior building doors in the closed position in modern buildings, particularly on either very cold or very hot days. Furthermore, the fire could occur during night hours when the (commercial) building is closed and locked but night shift workers and other occupants may still be present. Even if the system is properly calibrated with the building doors closed, fire fighters arriving at a later time may prop open the building doors (or windows could be blown out by the fire);

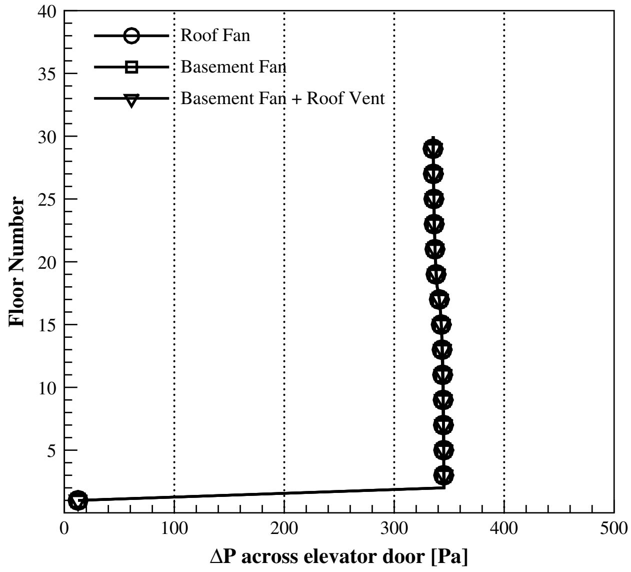

Fig. 9. Pressure differences across elevator doors as a function of the floor number for the residential building model with elevator shaft-only pressurization on a cold day (−12 °C). The effects of the fan location and the addition of a roof-mounted vent in conjunction with a basement-mounted fan are examined.

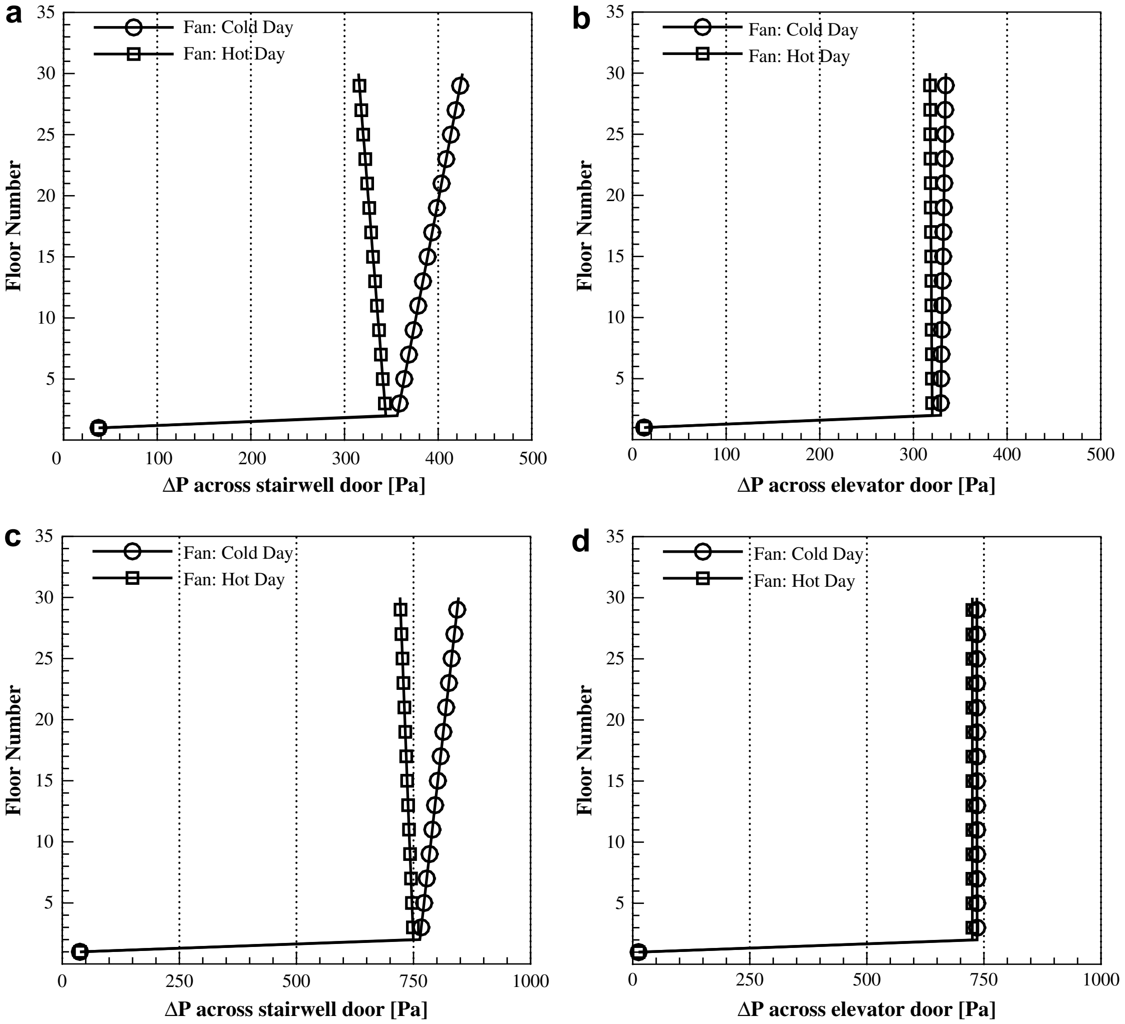

Fig. 10. Pressure differences across either stairwell or elevator doors as a function of the floor number for coupled stairwell and elevator shaft-pressurization systems: (a) residential building, stairwell doors, (b) residential building, elevator doors, (c) commercial building, stairwell doors, and (d) commercial building, elevator doors.

therefore, both limits should be accounted for in a properly calibrated elevator (or stairwell) pressurization system.

Fig. 8 and Table 4 show 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 3.90 m^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 significantly 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. If the exterior doors are then propped open the minimum pressure difference is still maintained across all elevator doors (although very large pressure differences exist). However, a system calibrated with the exterior doors in the open position will fail to satisfy the minimum pressure difference across the ground floor elevator doors if the system is turned on with the exterior doors closed. As a properly functioning system must account for both exterior door positions, the authors recommend that the system should ideally be calibrated with the exterior doors closed. However, the current results suggest that this may not be possible while maintaining reasonable across elevator door maximum pressure differences. Note that additional results for stairwell pressurization show only relatively minor alterations to across door pressure differences as a function of the exterior door position. Stairwell systems have much lower fan rates and the presence of the elevator shafts allows for the pressure changes to be relatively easily distributed throughout the entire building.

Table 5
Summary of results for coupled stairwell (S.) and elevator (E.) shaft pressurization.

Model	Ambient	E. Fan (m^3/min)	S. Fan (m^3/min)	E. Shaft (°C)	S. Shaft (°C)	$\|\Delta P\|_{E.,max}$ (Pa)	$\|\Delta P\|_{S.,max}$ (Pa)
R	Cold, −12 °C	4730	268	−2	15	+335	+426
R	Hot, 38 °C	5210	288	32	24	+320	+344
C	Cold, −12 °C	6910	392	−5	17	+735	+846
C	Hot, 38 °C	7650	440	34	25	+735	+750

Both the residential (R) and commercial (C) building models are considered.

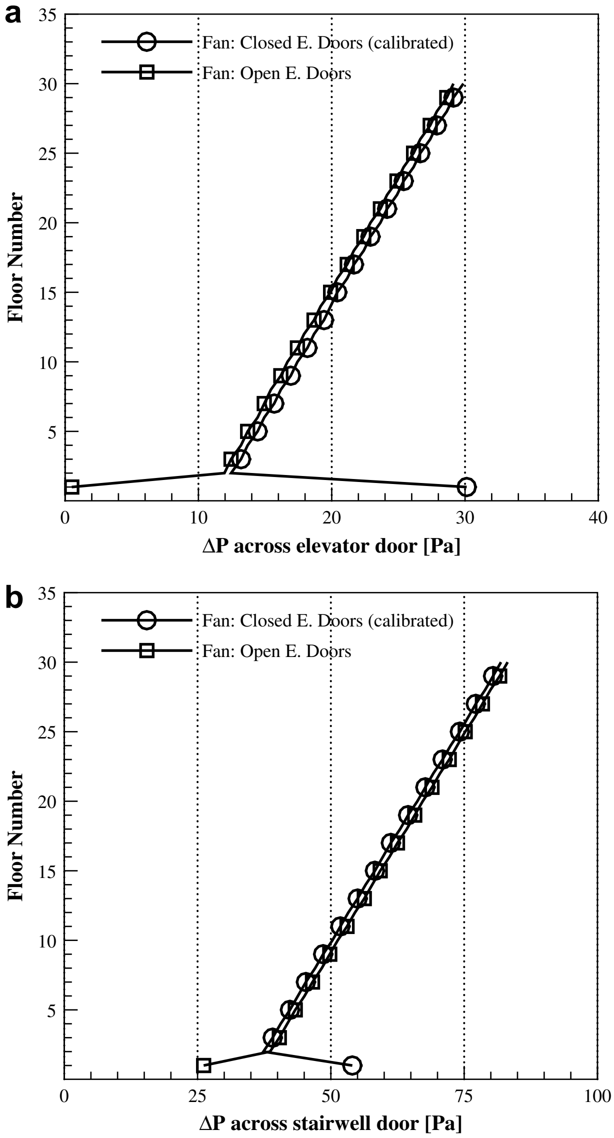

Fig. 11. Pressure differences across doors as a function of the floor number for the residential building model with coupled stairwell and elevator shaft pressurization for a system calibrated with the elevator doors all in the closed position on a cold day (−12 °C): (a) pressure differences across elevator doors and (b) pressure differences across stairwell doors.

3.3.2. *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 is 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. For the shaft conditions considered in Fig. 4 the frictional pressure drop is calculated to be $\sim 10^4 \rightarrow 10^5$ times smaller than the hydrostatic pressure drop within the length of the shaft for the conditions of this study. The shaft pressure is therefore independent of the fan location or to multiple injection points. Fig. 9 shows the negligible effect of fan location for the residential building model on a cold day for both a roof-mounted and a basement-mounted fan.

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 +12.5 Pa being violated as the first-floor pressure difference drops. For example, if a louver system is installed that allows 70 m^3/min of air to flow from the top of the shaft, the fan speed would need to be increased by the same 70 m^3/min to compensate and to re-acquire the minimum +12.5 Pa 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. Fig. 9 shows exactly this case for a basement-mounted fan used in conjunction with a roof-mounted vent.

Relying on transients is also ineffective as any pressure disturbance introduced into the shaft will equilibrate at the speed of sound. A pressure wave will travel the length of the 30-story shaft in approximately a third of a second; thereby quickly equilibrating the entire pressure distribution. Furthermore, additional analyses for a lumped-system model show that the system response time to changes in door positions, fan flow rates, etc. is found to be ∼5 s for the current model building.

3.4. *Coupled stairwell and elevator shaft pressurizations*

Results for simulations of the building models with coupled stairwell and elevator shaft-pressurization systems are presented in Fig. 10 for the residential and commercial building models. Additional data are given in Table 5. The simulation results illustrate an additional and a very serious problem for elevator shaft-pressurization systems if used in conjunction with a stairwell-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, and more importantly, another problem occurs after the stairwell system is recalibrated to acquire a minimum +37 Pa 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 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 1 m × 2 m stairwell door has a 375 Pa pressure difference this would require a force of 750 N (≈170 lbf) 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.

Table 6
Summary of results for coupled stairwell (S.) and elevator (E.) shaft pressurization with the elevator-pressurization system calibrated with all elevator doors in the closed position.

Ambient	E. Fan (m^3/min)	S. Fan (m^3/min)	E. Shaft (°C)	S. Shaft (°C)	$\lvert\Delta P\rvert_{E.,max}$ (Pa)	$\lvert\Delta P\rvert_{S.,max}$ (Pa)
Cold, −12 °C	1120	104	11	19	+30.1	+81.9

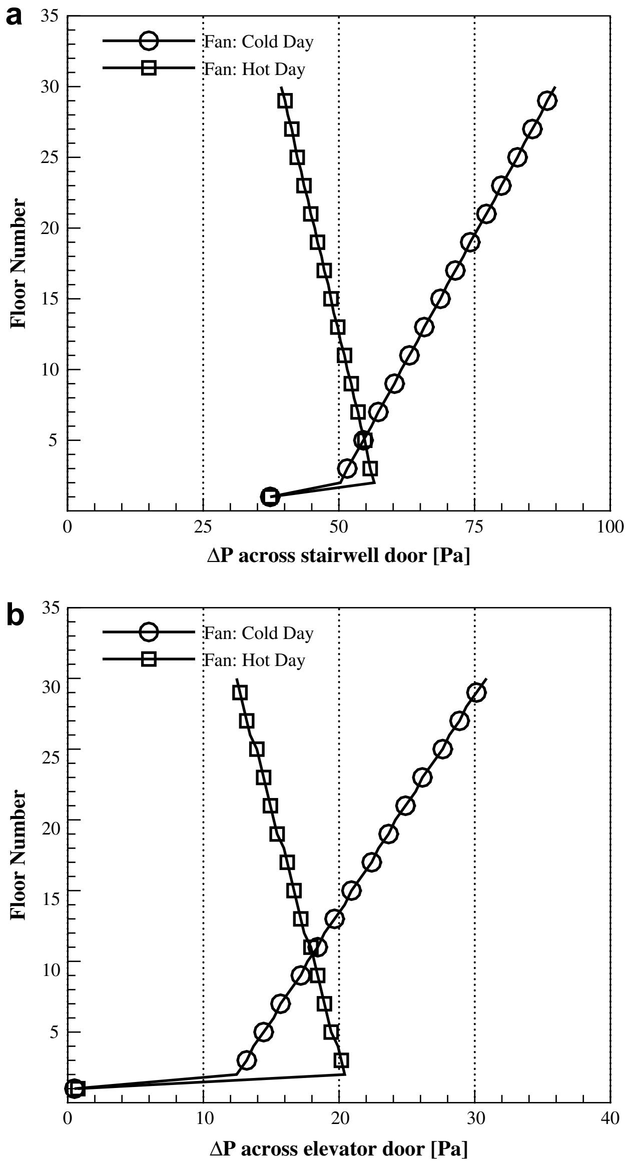

Fig. 12. Pressure differences across doors as a function of the floor number for the residential building with coupled stairwell and elevator shaft pressurization: (a) stairwell doors and (b) elevator doors. Pressure differences across the open elevator doors on the ground floor are ignored for system calibration.

3.4.1. *Effects of the ground floor elevator door position*

Attention is now directed to the effects of pressurizing the elevator shafts with the elevator doors all in the closed position (coupled with stairwell pressurization). This would not satisfy current codes and is only investigated as an alternative means of achieving reasonable pressure differences if the elevator was not to be used and all doors could be kept shut. Results for a simulation on a cold day are shown in Fig. 11 and Table 6. As observed for the elevator shaft-pressurization-only cases, 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 the minimum pressure difference nearly vanishes on the ground floor when the elevator doors are opened. This occurs for both the elevator doors and the stairwell doors on the ground floor. In this case, there is a strong potential for smoke to enter either shaft.

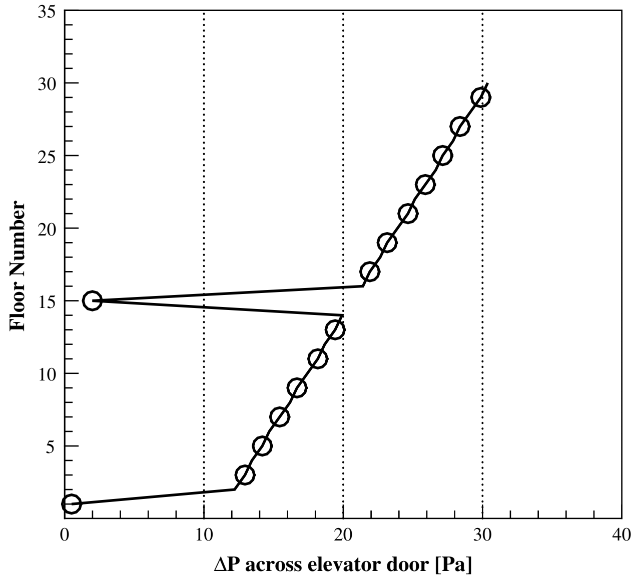

Fig. 13. Pressure differences across elevator doors as a function of the floor number for the residential building model with coupled stairwell and elevator shaft pressurization on a cold day (−12 °C). Pressure differences across the open elevator doors on the ground floor are ignored for system calibration. The results show the effects of having two elevator cars move to the 15th floor with open elevator doors.

3.4.2. *System calibration ignoring the open elevator door pressure difference*

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 elevator doors. This concept is tested as follows. A fully coupled (elevator and stairwell shaft pressurization) building model is considered. All system calibration is performed with the exterior building doors in the closed position and with all elevator cars on the ground floor with their doors open (Phase 1 position). The results correspond directly to those of Fig. 10 and Table 5, except that the minimum pressure difference of +12.5 Pa is only applied to the closed elevator doors (ie. ignoring the pressure difference across the open ground-floor elevator doors). Results are shown in Fig. 12 and Table 7. Apart 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 with the stairwell doors only slightly exceeding the +87 Pa maximum for the residential building on a cold day (the maximum is +89.9 Pa).

However, the open elevator doors may still be problematic. In all cases these pressure differences are essentially null. In the event of a fire on the first floor, it is highly likely that smoke would enter the

Table 7
Summary of results for coupled stairwell (S.) and elevator (E.) shaft pressurization for the residential (R) building model.

Ambient	E. Fan (m^3/min)	S. Fan (m^3/min)	E. Shaft (°C)	S. Shaft (°C)	$\lvert\Delta P\rvert_{E.,max}$ (Pa)	$\lvert\Delta P\rvert_{S.,max}$ (Pa)
Cold, −12 °C	1150	112	12	18	+30.9	+89.9
Hot, 38 °C	1200	109	25	22	+20.4	+56.5

Pressure differences across the open elevator doors on the ground floor are ignored.

shaft through the open elevator doors. Although the pressure differences are slightly positive in the simulations, heat from a fire will have a thermal expansion effect, thereby raising the pressure and forcing smoke into the shaft. For a roof-mounted pressurization system, smoke entering the shaft on the ground floor may not be a major problem as air being forced down the shaft could prevent the smoke from spreading to upper floors (although it would be forced into the lower level floors just above the ground 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. A schematic representation of a ground-floor-mounted fan system is shown in Fig. 11.6 of Ref. [2].

Another potential problem with a system calibrated ignoring the open elevator door pressure differences is illustrated in Fig. 13. In this case, the calibrated system for the residential building model on the cold day conditions is examined. The calibrated building model from Table 5 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 shaft 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.

3.5. 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 30-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. The primary reason for this is pressurization of the ground floor due to large air flow rates through the open, Phase 1 position, elevator doors and the relatively well-sealed first floor when the exterior 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 (data not shown). The results show that as the number of elevator cars is decreased there is lesser leakage area for ambient air to enter the building. Therefore, the ground floor experiences lesser pressurization and the overall pressure differences across elevator doors are reduced. In contrast, if only the building size is reduced, then the same amount of air flow is required through the ground-floor elevator doors to achieve the $+12.5$ Pa across door pressure difference (ie. the pressure difference is only a function of the flow rate and the leakage area). Although a smaller fan is required to force the same amount of air to the ground floor due to lesser upper floor leakages, the same pressure differences persist across the doors on the existing floors. The resulting pressure difference profiles simply overlap those of the lower floors for the taller building. 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 that directly causes the behavior observed in this study.

4. Conclusions

Stairwell and elevator shaft-pressurization systems have been studied in 30-story model residential and commercial building models using the CONTAM software. External building leakage areas were calibrated to experimental data, for two specific buildings. The operation of stairwell shaft-pressurization systems was 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. This occurs due to the much larger leakage areas for elevator doors than for stairwell doors, resulting in substantial pressurization of the ground-floor building interior. 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, substantially different fan speeds are required.

Acknowledgments

This study was funded in part by the Smoke Safety Council.

References

[1] Jo J, Lim J, Song S, Yeo M, Kim K. Characteristics of pressure distribution and solution to the problems caused by stack effect in high-rise residential buildings. Build Environ 2007;42:262–77.

[2] Klote JH, Milke JA. Principles of smoke management. Atlanta, Georgia: American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE), Inc.; 2002.

[3] Klote JH. An overview of smoke control research. ASHRAE Trans Symp 1995;101:979–90.

[4] J.H. Klote. Design of smoke control systems for elevator fire evacuation including wind effects. In the Proceedings of the Second Symposium on Elevators, Fire, and Accessibility, Baltimore, M.D., April 19–21, New York: American Society of Mechanical Engineers (1995), pp. 59–77.

[5] Klote JH, Evans DH. Smoke control and the international building code. ASHRAE J 2004;110:638–45.

[6] Wang Y, Gao F. Tests of stairwell pressurization systems for smoke control in a high-rise building. ASHRAE Trans 2004;110:185–93.

[7] Tamura GT, Klote JH. Experimental fire tower studies of elevator pressurization systems for smoke control. Elevator World 1989:80–9.

[8] Burmeister LC. Convective heat transfer. 2nd ed. New York: John Wiley and Sons, Inc.; 1993.

[9] Incoprera FP, De Witt DP. Fundamentals of heat and mass transfer. 3rd ed. New York: John Wiley and Sons, Inc.; 1990.