Positive Pressurization and Ventilation for Fighting Fires in High-Rise Structures with Multiple Stairwells

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ABSTRACT

This study addresses the selection of the pressurization stairwell and the ventilation stairwell for fighting fires in a high-rise structure with multiple stairwells. The specific case of three stairwells, where one is regular and the other are paired scissor stairwells, has been considered in this study and various scenarios have been analyzed. Through simulations of a model that has been validated by on-site pressure tests, it is found that the most effective scenario which provides a safer environment for the rescue-operation is choosing the closest stairwell to the fire apartment as the pressurization stairwell, and the farthest stairwell to the fire apartment as the ventilation stairwell.

KEYWORDS:
Positive Pressure Attack (PPA), Positive Pressure Ventilation (PPV), Firefighter safety, Fire Dynamics Simulator (FDS)
INTRODUCTION

Flow of smoke, heat and other combustion products created by spread of fire can be efficiently driven away by pressurization of stairwells that creates safer environment for firefighters than without pressurization [1–4]. This is achieved by directing a significant amount of air into the building stairwell and public hallways by fan deployment that creates a positive pressure zone [5]. Optimization of positive pressurization for wind-driven high-rise fires in a typical high-rise building with one stairwell has been previously studied [6–8]. However, pressurization in a complex structure with multiple stairwells can be more complicated than that in a typical single stairwell scenario [9]. In a complex building with multiple stairwells, selection of attack (pressurization) stairwell where the fan is deployed and ventilation stairwell through which combustion products are vented can be critical [10]. Commonly found return stairs (also referred to "U return stairs") vertically returns to the same location of the building at each floor landing. In contrast, scissor stairwell contains two separate stairwells in one vertical shaft that are separated by a wall. Stairs exit on the opposite side of the building at each landing and the layout of the fire floor is the same as that of two floors below the fire [10]. Efficacy of the pressurization can vary greatly with respect to fire location, fan location, attack stairwell (stairwell that is pressurized) and ventilation stairwell (stairwell used to remove smoke and heat), as well as the sequence of venting tactics.

Building on results of previous studies [8, 11], this paper analyzes the performance of positive pressurization tactics in high-rise fires in complex structures with return and scissor stairwells. The influence of concerned parameters as well as their relative impacts on the fire-rescue operation is investigated through simulations.

ON-SITE TESTS

In order to validate the simulation model, on-site pressurization tests, in the absence of fire, were conducted in a vacant modern seven-story residential high-rise structure with a scissor stairwell and a single typical return stairwell in Brooklyn, New York (average atmospheric condition: 76°F/24.5°C, average humidity: 80%, average pressure: 29.95 in/101.422 kPa). The apartments on each floor are connected via a long public hallway. A positive pressure zone was created utilizing pressurization fans (BD27-H-9.0 by Tempest Technology, http://www.tempest.us.com) placed 3 ft (0.9 m) away from the stairwell door such that the horizontal axis of the fan is parallel to the ground. Each fan blows approx. 24,000 CFM (11.23 m³/s) air into the stairwell. To measure the increase in the static pressure, differential pressure sensors were located on floors 2.5, and 7. The high port of a sensor was open to pressure inside the stairwell while the low port was open to atmospheric pressure via a flexible tube. The results of different fan arrangements were compared with those of the simulations. The bulkhead door (or the roof door) was closed to maintain desired pressure levels [8, 12]. Only parallel combinations (side-by-side) for the fan arrangements are considered subsequently since it was found that the series combination of the fans (back-to-back placement of the fans) is not efficient for increasing the volume of the air entering the stairwells [13]. Also, it was observed that two parallel fans at the first floor (i.e., ground floor) create better positive pressure zone inside the stairwell to effectively drive away the combustion products than placing them in the floors other than the first. Therefore, this strategy is used and tested with the fire scenes described below. As the simulations results are in good agreement (less than 10% difference) with those of the on-site tests, the simulation model is considered validated, and thereby it is used for further analysis.

MODELING

A seven-story building model (73m x 11m x 20.91m) consisting one scissor stairwell (Stairwell A and B in Figs. 1 and 2) and one single typical stairwell (Stairwell C), and a long public hallway is considered for the simulation. All stairwells have the dimensions of 5.6m x 2m x 20.91m, and each has eight landings with a door on each floor, the topmost door being the roof door. Each floor consists of doors of each stairwell leading to a public hallway that connects the apartments. It is assumed that the fire ignites on the sixth floor, noting that the ground level is considered as the first floor throughout this study. The apartment door opens into the living room which is connected to the kitchen, the bedroom, and the restroom/bathroom. There is a double window (2m x 1m) in the living room and a single window (1m x 1m) in the bedroom (see Figs. 1, and 2). All the doors have dimensions of (2.1m x 0.9m). There are apartments on both sides of the public hallway, but only one side is shown on Fig. 1. Also details of only three apartments layout are shown in the figure for clarity. The apartment has a typical fuel load that consistent with commonly used furniture items such as a bed, TV, sofa, wooden chairs, with thermophysical properties mentioned in the previous study [8]. The fuel load is same in all apartments for all simulations allowing a valid comparison of positive pressurization tactics [14]. As FDS allows only rectilinear meshing, pressurization fan is considered as a square surface [8, 11] of 0.5 m² area and is placed 3 ft (0.9 m) away from the stairwell door that provides air at the rate of approx. 24,000 CFM (11.23 m³/s) into the stairwell. To perform the simulations, FDS 5.0 is used. Although the later versions of FDS are available, the accuracy of the results obtained by FDS 5.0 has been previously examined and proven [8].
Fig. 1: 3-D model of the building structure, the layout of each floor consists of several apartments, of which three apartments are shown: leftmost, central, and rightmost one.

**Meshing and boundary conditions**

FDS is second order accurate in space and time. FDS can predict temperatures in similar fire scenarios to an accuracy of 5-20% in comparison to experimental results [15]. Grid convergence tests are performed by repeating the same scenario several times with increasing number of cells. The mesh is refined until the recorded values at all locations stabilized and the difference in final mean temperature (moving average of the fluctuations over 10 s) became relatively small (see Fig. 3). This procedure was also repeated with the soot density readings to ensure accuracy. Although multiple mesh schema are available in FDS, the model used for all simulations in this study has single uniform rectilinear mesh in all regions that includes 1,890,000 total number of cells of equal volume of 0.0088 m$^3$ (0.35m x 0.18m x 0.14m) and has the time-step of 0.143 second. The computational areas of interest include the stairwells, the public hallway, the apartment on fire, small regions around the fans, and a region outside the window through which wind conditions are introduced. The floors, ceilings, surfaces of furniture, walls, stairwell steps and all other solid surfaces of the structure are assigned as wall boundaries. The opening of windows and doors are simulated by creating holes in the surfaces at certain time instances. The computational domain has air at 25°C and open boundary conditions in all directions except the ground.

Fig. 2: Location of the temperature sensors in the 6th floor public hallway where fire is in one of the apartments.

**Timeline of fire events**

Although the unplanned sequence of random events in real-life fires can be much more complex than the simple timeline followed in the simulations, the following time line serves the purpose of this study. The attack stairwell (or pressurization stairwell) has the positive pressure zone allowing the firefighters to stretch the hose-line. The ventilation stairwell can be one of the stairwells other than the attack stairwell through which the heat and smoke is vented from the public hallway creating better thermal conditions as well as visibility for the firefighters. Depending on the fire location, attack stairwell, and the ventilation stairwell, several scenarios can be assumed as listed in Table 1. It is assumed that the fire ignites in the bedroom of an apartment on the sixth floor and the apartment door is left open by the occupants. Stairwell doors and roof doors are initially closed. As the fire continues to grow, windows in the bedroom fail at the 120th second allowing 10 mph (4.4 m/s) wind to enter the apartment which results in the rapid spread of the heat and smoke into the public hallway. Wind is introduced to consider more severe conditions and were simulated by inflow of air from a boundary surface [8, 11, 16]. However, similar trends are anticipated for non-wind conditions as the fresh air enters from the broken window. At the 180th second, a firefighters open the sixth floor door and start the fan at the attack (pressurization)
stairwell. At the same moment, another firefighter opens the sixth floor stairwell door and the roof door of one of other two stairwells which is acting as ventilation stairwell. The simulation continues for another 70 seconds and is stopped at 250th second. This is considered enough time for firefighters to enter the fire floor with the hose-line through the pressurized attack stairwell and reach the door of the apartment on fire. The response time of fire departments vary to a great extent. Through another set of simulations, it has been verified that if firefighters open the door at later time, the temperature in hallway upon stairwell pressurization are relatively higher, but the overall trend of results obtained in this study remain valid.

The temperature variations inside the public hallway are recorded at six thermal sensor points (a-f) as shown in Figs. 1 and 2. Considering the crawling motion of firefighters during the search-rescue operation on fire floor, the measurement recording points, both temperature and soot density, are located in the middle of the public hallway outside the entrance doors of apartments and stairwells, at the mid-level of the apartment’s height (i.e. 1.3 m above the floor level). As heat and smoke move upwards, the temperature increases from the floor towards the ceiling, this height is appropriate to indicate whether the temperatures are tenable for the firefighters or not.

RESULTS AND DISCUSSION

In a complex structure with multiple stairwells, there are several possibilities for attacking and venting fire as listed in Table 1. Ventilation of smoke inside the public hallway is performed through one stairwell as more than one venting stairwell can decrease the effectiveness of the pressurization at the fire apartment [8, 17]. Simulations are repeated for all corresponding cases assuming fire is ignited in the sixth floor in one of the following apartments: the central, the rightmost, or the leftmost one. The pressurization in all cases is provided by two parallel fans, based on on-site results, that are placed 0.9 m from the door on the first floor (i.e. ground floor). In all simulations, initial fire behavior is qualitatively similar to previous studies [8, 11]. When window fails it rapidly grows and spreads into the public hallway because of availability of more air from the window resulting in temperature increase at all locations. As the fuel in the apartment quickly becomes ventilation-limited, the temperature in the apartment begins to drop slightly. In all cases, the deployment of pressurization fan mitigates the spread of smoke and heat in the attack (pressurization) stairwell. The combustion products which are pushed back by pressurization in attack stairwell are vented through the ventilation stairwell or driven back into the fire apartment and escape through the broken window resulting in an increase in the temperature at those locations. In contrast, the temperatures at the pressurized stairwell drops creating a safer environment.

| Fire Apartment | Attack Stairwell | Ventilation Stairwell | Case No. |
|----------------|-----------------|-----------------------|---------|
| Leftmost Apartment | Stairwell A (scissor) | Stairwell B | 1 |
| | Stairwell C | 2 |
| | Stairwell B | 3 |
| | Stairwell C | 4 |
| | Stairwell B | 5 |
| | Stairwell C | 6 |
| Central Apartment | Stairwell A | Stairwell B | 7 |
| | Stairwell C | 8 |
| | Stairwell B | 9 |

| Fire Apartment | Attack Stairwell | Ventilation Stairwell | Case No. |
|----------------|-----------------|-----------------------|---------|
| Central Apartment | Stairwell B | Stairwell C | 10 |
| | Stairwell C | 11 |
| | Stairwell B | 12 |
| Rightmost Apartment | Stairwell A | Stairwell B | 13 |
| | Stairwell C | 14 |
| | Stairwell A | 15 |
| | Stairwell C | 16 |
| | Stairwell B | 17 |
| | Stairwell B | 18 |

For fire in each apartment, the effectiveness of pressurization varies depending on choice of attack stairwell and ventilation stairwell which has been shown in Figs. 4, 5, and 6. At the end of simulation (70 seconds after opening the door of attack stairwell), the recorded temperatures stabilizes to some extent as the constant pressurization flow continues to interact with the continuous generation of heat and smoke. Therefore, the final mean temperature (moving average of fluctuations over 10 seconds) in the public hallway (entry location for firefighters) are used to compare the efficacy of the possible pressurization/ventilation tactics listed in Table 1. As the main purpose of pressurization is to assist firefighters in making an effectively safer entry on the fire floor, the efficacy is primarily evaluated based on the heat and smoke conditions inside the public hallway. In all cases, it was found that pressurization is more effective if the attack stairwell is closer to the fire apartment.
and the ventilation stairwell is farther from the attack stairwell. For example, in case of rightmost location, firefighters would experience safer environment if they choose stairwell C (which is closer to the fire location) as the attack stairwell, and vent the heat and smoke in the public hallway through stairwell A or B (which are farther from attack stairwell) (see Cases 17 and 18 in Fig. 4). Whereas, for the leftmost location, firefighters should choose stairwell A or B as the attack stairwell, and vent the heat and smoke through stairwell C (see Cases 2 and 4 in Fig. 5). In case of fire in central location, firefighters can choose any of the stairwells as they are at almost the same distance from the fire location but the heat and smoke should be vented through the farthest stairwell from the attack stairwell (see Cases 8, 10, 11, and 12 in Fig. 6).

CONCLUSION

The present study examines fire behavior that only includes assumptions of essential firefighter actions such as initiating pressurization and opening stairwell doors on the fire floor. Other related operating procedures are not
addressed, nor are possible evacuation plans, etc. It is anticipated that fire professionals will use the results of the study to understand fire behavior for various scenarios, and to guide fire ground procedures. Several possible fire scenarios with pressurization have been simulated for a large high-rise structure with return and scissor stairwells that provide multiple options for attacking and venting points. It was found that pressurization is more effective if the attack stairwell is chosen to be the one that is closer to the fire apartment while the ventilation stairwell is chosen as the one that is farthest from the fire apartment. The results are developed for buildings where three or more stairwells are available. Since only two stairwells are used in each scenario for pressurization and ventilation, the conclusion that the stairwell closest to the apartment on fire should be used for pressurization is also valid if only two stairwells are available.

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REFERENCES

[1] Garcia, K., Reinhard, K., Schelble, Raymond, and Schelble, Ray. (2006) Positive pressure attack for ventilation & firefighting. PennWell Books.
[2] Reick, M. (2009) Mobiler Rauchverschluss Erfahrungen aus dem Einsatzalltag, brandSchutz/Deutsche Feuerwehr-Zeitung, S. (7), pp. 563-569.
[3] Madrzykowski, D., Kerber, S., Kumar, S., and Panindre, P. (2010) Wind, fire & high-rises: firefighters and engineers conduct research to combat a lethal threat. Mechanical Eng.-CIME 132 (7) 22-28.
[4] Miller, R. S., and Beasley, D. (2009) On stairwell and elevator shaft pressurization for smoke control in tall buildings. Building and Environment 44 (6) 1306-1317.
[5] Zinn, B. T., Bankston, C. P., Cassanova, R. A., Powell, E. A., and Koplon, N. A. (1974) Fire spread and smoke control in high-rise buildings. Fire Technology 10 (1) 35-53.
[6] Feng, X., and Li, Y. F. (2012) Evaluation of Positive Pressure Ventilation for High-Rise Buildings in Compartment Fire Situation, Advanced Materials Research, Vols. 446-449, pp. 2908-2913.
[7] Lambert, K., and Merci, B. (2014) Experimental study on the use of positive pressure ventilation for fire service interventions in buildings with staircases, Fire Technology 50 (6) 1517-1534.
[8] Panindre, P., Mousavi, N.S., and Kumar, S. (2017) Positive pressure ventilation for fighting wind-driven highrise fires: Simulation-based analysis and optimization. Fire Safety Journal 87, 57-64.
[9] Wang Y., and Gao F. (2004) Tests of stairwell pressurization systems for smoke control in a high-rise building.ASHRAE Trans 110, 185-93.
[10] McGrail, D. M. (2007) Firefighting operations in high-rise & standpipe-equipped buildings. PennWell.
[11] Panindre, P., Mousavi, N.S., and Kumar, S. (2017) Improvement of Positive Pressure Ventilation by optimizing stairwell door opening area. Fire Safety Journal 92, 195-198.
[12] Li, M., Gao, Z., Ji, J., and Li, K. (2018) Modeling of positive pressure ventilation to prevent smoke spreading in sprinklered high-rise buildings. Fire Safety Journal 95, 87-100.
[13] Kerber, S., Madrzykowski, D., and Stroup, D. (2007) Evaluating Positive Pressure Ventilation in Large Structures: High-Rise Pressure Experiments. National Institute of Standards and Technology, Building and Fire Research Laboratory, Gaithersburg, Maryland, NISTIR 7412.
[14] Shu, S.B., Chuah, Y.K., and Lin, C.J. (2012) A study on the spread of fire caused by the stack effects of patio-A computer modeling and a reconstruction of a fire scenario. In Building Simulation vol. 5, no. 2, pp. 169-178. Tsinghua Press.
[15] Smardz, P., and Novozhilov, V. (2006) Validation of Fire Dynamics Simulator (FDS) for forced and natural convection flows. University of Ulster pp. 16-20.
[16] Zhang, C. F., Chen, S. Y., and Chow, W. K. (2014) Wind effects on the smoke spread of high-rise buildings. The 2014 International Conference on Advances in Wind and Structures (AWAS14), Busan, Korea, 24-27 Aug 2014, paper no. W5B.3.WS116_407FR.
[17] Beal, C.M., Fakhreddine, M., and Ezekoye, O.A. (2009) Effects of leakage in simulations of positive pressure ventilation, Fire Technology 45 (3) 257-286