FIRE ASPECTS ON LIFT SHAFTS USED FOR EVACUATION IN SUPERTALL BUILDINGS

N. Cai and W.K. Chow
Research Centre for Fire Engineering, Department of Building Services Engineering
The Hong Kong Polytechnic University, Hong Kong, China

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ABSTRACT

Evacuation has been identified as a key concern when a supertall building is under fire. Stairs alone are inadequate at any significant height. Lifts are not yet designed to be used by most of the occupants in fire. A research project on developing fire safe elevator systems for emergency evacuation of supertall buildings is introduced. Designs for fire and smoke protection for lift systems for evacuation in tall buildings were reviewed. Preliminary case studies on evacuation for tall and supertall commercial buildings and numerical studies on heat release rate in room fire were carried out. Key issues and problems that need to be addressed are discussed.

1. INTRODUCTION

Many supertall buildings were built or to be built in big cities, such as Hong Kong. There is no official worldwide accepted definition or height above which a building is classified as a supertall building. The Council on Tall Buildings and Urban Habitat in the USA used the value of 300 m (984 feet) [1]. In Ireland, this value is 150 m [2]. In Hong Kong, buildings above 40 levels are considered as supertall buildings by most professionals [3], though the new code is under preparation. Supertall buildings are those of height over 250 m in China [4].

Evacuation has been identified [5] as a key concern when a supertall building is under fire. It takes a long time for all occupants to leave the building due to whatever reasons [6,7]. Selective evacuation in high-rise buildings has become an accepted practice. A phased-evacuation or the “stay-in-place” approach [8] appears in the fire safety management plan of many supertall buildings. Refuge floors are required every 20 to 25 floors [3] in tall buildings in Hong Kong since 2000. With the rapid development in China since 2000, such requirements are specified in their fire codes. A protected space was also provided in many new places, such as the refuge place in Taipei 101 building. Occupants can wait in the refuge place for rescue, or to move between stairways of every eight levels [9]. However, the unexpected quick collapse [10] of the World Trade Centre buildings in 2001 led to concerns on using refuge floors and places. Occupants are not willing to delay egress by staying at the refuge places. Consequent to that event, adequacy of phased evacuation plans for tall buildings are under review [9].

Though being a trial approach to evacuation, stairs alone are inadequate at any significant height. Fire safety experts became interested in the usage of elevator system for egress and access all over the world. The number of stairs in many supertall buildings at the Far East appears to be not adequate to give short evacuation time. At least 2 hours were required for total evacuation as reported in the Petronas Towers in Kuala Lumpur, Malaysia [11]. There are starting interests in the use of lift system for egress and access all over the world [12].

Lift has been designated since 1980s to be used in a fire by firefighters and the disabled only, but not for the general public in many countries [12]. Obviously, using lifts would speed up evacuation [13]. The lift system can be an effective alternative if it is reliable, accessible and safe under a big fire. Upgrading the fire safety provisions for the lift system to stand a big fire is necessary.

A project was carried out to investigate how fire safe elevator systems can be developed for emergency evacuation of supertall buildings with the following objectives:

- To better understand the fire environment in lift shafts and adjacent lobbies in supertall buildings, and identification of the safety requirements for elevator systems used for evacuation means;
- To study the difficulties in opening doors to lift and lobbies upon operation of the pressurization system;
- To study the fire resistance of elements of lift shaft and lobbies under a big fire.

Progress on this ongoing project is briefly reported in this paper. Literature review on smoke movement in the lift shafts and lobbies, and using elevator as a means of evacuation was carried out. Research methodology employed and preliminary works done were introduced. A typical design of lift shaft and adjacent lobbies in a supertall building will be selected with up to five fire scenarios identified. Mathematical models with computational fluid dynamics (CFD) and full-scale burning tests on scale models and part of the lift shafts and lobbies will be carried out to study the fire environment in the supertall buildings.

Specified items are:

- Computer simulations with the CFD software Fire Dynamics Simulator (FDS) on the smoke movement including buoyancy, stack effects and wind action.
- Scale modelling technique on part of the full-scale model to study the smoke movement path and pressure distribution.
- Experimental studies based on the cone calorimeter and on part of the full-scale model to investigate the heat release rate.
- Tests relating to the efficacy of lift shaft pressurization and leakage areas.

Key issues and problems need to be addressed in providing lifts for evacuation for supertall buildings are discussed.

2. LITERATURE REVIEW ON SMOKE MOVEMENT IN THE LIFT SHAFTS AND LOBBIES

Many fires happened in high-rise buildings have repeatedly demonstrated that elevator shafts can be a major vertical path for smoke travel throughout a building, and hence transmitted fire from floor to floor. A fire, which resulted in 2 deaths, 30 injuries, and 10 million dollars damage in a fifty-story high-rise building in New York City, started from the 32nd floor and spread rapidly due to the presence of plastic materials and the failure of some smoke dampers [14]. Similarly, in Seoul, South Korea, 163 people were killed in a fire occurred in a 21-story high-rise building. The fire and smoke spread through the shafts then burned from the lower three floors and the upper floor towards the middle floors of the building [15]. When a fire occurred in the First Interstate Bank Building in Los Angeles, California, the service elevator, which connected the ground to the 62nd floor served as a significant path of smoke travel in that building [16]. One of the notable fires in Hong Kong occurred in the high-rise Garley Building presented a similar pattern [17]. The fire started in a lift shaft under reconstruction, then grew significantly and spread to the lower and upper levels, eventually caused flashover in part of the building, and a post-flashover fire with duration longer than twenty hours ensued. Therefore, when considering the usage of elevator system for egress, it is important to understand the smoke movement in the lift shafts which have no protection and how to prevent this phenomenon.

Studying the mechanism of smoke and hot gases spreading through the lift shaft is essential. Smoke can move due to several factors [18], such as buoyancy difference between the hot smoke and the ambient air, the expansion of the hot gases, wind effect, airflow controlled by the mechanical air handling equipment, “stack effect” which is known as the pressure differential created by the temperature difference between the air inside the building and that outside the building, and the turbulent mixing process of a lower hot layer of smoke and an initial upper cool layer of air if the fire occurred within the shaft [19].

A joint project of the National Institute of Standards and Technology (NIST) in the United States and the National Research Council of Canada (NRCC) was set up to evaluate the feasibility of smoke control by pressurization for elevator evacuation systems [20-28]. Detailed review of the concerns in using elevators was reported. A series of full-scale fire experiments were conducted at the NRCC's ten-story fire research tower near Ottawa [23]. Two propane burner sets which are capable of producing heat at an output of 2.5 MW each, were used as the fire sources and located on the second floor of the 10-story test facility. Studies were focused on pressure differences due to the thermal effect of fire across the elevator lobby wall, and fire and smoke spread to the lobbies and the lift shaft. Pressurization was proposed to protect the elevator system from smoke by providing positive pressure in the shafts and at lobbies, and was suggested to activate before the elevator shaft and lobbies are heavily contaminated with smoke. The best results were obtained with both elevator shaft and lobby pressurization. Equations were developed to assist in designing pressurization systems with variable supply air with feedback control or with relief dampers.

Wind effect on the pressure difference across an elevator lobby wall was investigated by Tamura [29]. The wind tests were conducted with wind speeds of 25 to 40 km/h under several different opening conditions. The pressure differences across the elevator lobby wall on the second floor were positive, which represent flows in the direction from the elevator shaft into the lobby, varied from 0.0 to 6.0 Pa when only the leeward vent was opened. In the other cases, the pressure differences were negative, which represent flows from the elevator lobby into the elevator shaft, varied from -0.1 to -0.5 Pa and from -1.5 to -9.6 Pa. The serious case was when only the windward wall vent was open. Mechanical pressurization of the elevator shaft greatly reduced the possibility of smoke contamination of the elevator shaft and lobbies caused by wind and stack effect and in combination with those thermal effects caused by a fire.

Additionally, with the purpose of using elevators for evacuation, the joint project addressed the impact of pressure disturbances caused by elevator car motion on smoke control [20-22]. Such piston effect is a concern, because it is created as an elevator moving pass a fire floor can pull smoke into a normally pressurized elevator lobby, and hence has an adverse impact on controlling the movement of smoke from the fire floor. A method for analyzing the upper limit of the pressure difference across an elevator lobby caused by piston effect was developed by Klote [20]. A set of experiments was conducted in a 15-story hotel in Mississauga, Ontario to investigate the piston effect and evaluate the analysis model [21]. The pressure differential, measured at floor level of the top floor, combined with modeling results indicated that elevator piston effect can be a big concern for fast cars in single car shafts, but was not of significance in the case of low speed cars and multiple car shafts. The impact of piston effect on the performance of elevator smoke control system was investigated by Klote [22]. A method of analysis which can be used to determine smoke infiltration for hazard analysis was presented in this paper.

Besides the joint project mentioned above, other researchers also conducted lots of studies on the motion of smoke in elevator shafts and lobbies in high-rise buildings. Recently, studies on smoke management in high-rise buildings have been conducted. The smoke movement pattern in a lift shaft was studied with a scale model by Chow et al. [30]. Experiments were conducted to investigate the smoke movement in a full-scale six-storey stairwell induced by a fire in an adjacent compartment. Wind effect was also evaluated [31,32].

Jo and his co-workers [33] studied the characteristics of pressure distribution caused by stack effect in high-rise residential buildings by field measurements and simulation case studies. Two high-rise residential buildings in Korea were selected for the field measurements. Characteristics and problems found were confirmed in several simulations of high-rise residential buildings. Excessive pressure difference problems were found to occur around the core area. Installing ‘airlock doors’ between elevator doors and residential entrance doors on typical floors where pressure difference problems occur, was proposed to solve the pressure difference problems.

Elevator shaft and stairwell shaft-pressurization systems were studied as a means of smoke migration prevention through stack effect in a 30-story model of residential building which is the same one studied by Jo, and commercial building models using the CONTAM software by Miller and Beasley [34]. The results showed that, compared with stairwell pressurization, substantially larger fan flow rates were required to achieve the required minimum pressure differences in elevator shaft pressurization system. Prohibitively large pressure differences across upper-floor elevator doors were found for all cases, while smoke may still enter the shaft and be actively distributed throughout the building by the fan system. 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. Moreover, it pointed out that there is strong coupling between the fan speed requirements of the stairwell and elevator shaft pressurization systems.

According to Black’s study [35], a network model is developed for the control of smoke in a high-rise structure. It is described to be capable of accounting for all of the complex interactions among the variables that affect the movement of smoke via an elevator shaft and ultimately into occupied floors within the structure. The program was executed assuming a standard fire and standard building with 45 floors. Some of the parameters that affect smoke movement, such as top vent area, tightness of elevator doors, construction of elevator shaft, building height, floor pressurization equipment, wind velocity and construction of building exterior, were explored. Factors related to the position of the neutral pressure plane (NPP) were discussed.

However, the above results might only be good for tall buildings of normal heights and not much progress was made to implement this alternative for the evacuation of occupants in the following years. Whether this work can also be applied to supertall buildings with bigger fires will be explored in this proposed project.

3. ELEVATOR AS A MEANS OF EVACUATION

Evacuation has been identified as a key concern affecting the fire safety of supertall buildings, since full evacuation via staircases is impossible as it takes a long time to evacuate all occupants, as an example, 2 hours even in a normal fire drill in the Petronas Towers in Kuala Lumpur, Malaysia, which is the second tallest building in the World [11]. Considering the huge cost either of increasing the number or width of the stairwells in a building, especially for existing buildings, using elevators seems to be a viable option for being a safe exit route. It is suggested that a significant potential reduction in total evacuation time can be achieved by using elevators [36,37]. However, elevators are not supposed to be used in a fire emergency at this moment, at least not until the performance of the elevator system during a fire has been precisely evaluated and corresponding fire safety provisions are specified to cope with concerns for evacuation elevator systems. Possible reasons why elevators are unsafe in fire emergencies highlighted by Sumka [38] are:

- Elevators might not respond to a call from a specified floor, causing loss in egress time for the waiting occupants;
- Elevator responds, but stops at the floor where the fire exists because smoke enters;
- Overcrowding stops the closing of the elevator doors;
- Entrapment in the elevator due to power failure.

A research project, funded by the US General Services Administration (GSA), was carried out at NIST to develop techniques for occupant use of elevators during building evacuations [13]. It is focused on fundamental system considerations, engineering design considerations, design analysis, and human behavior. An interactive computer program, ELVAC, was written based on idealized flow. Results showed that use of elevators in addition to stairs during a fire emergency allows occupants and firefighters an additional system of vertical transportation. Guides that are relevant to the design of elevator smoke control were proposed [39].

A set of thirteen requirements to assure safe elevator operation during fire emergencies were described by Chapman [40]. The specific requirements were:

- Complete building sprinkler protection;
- Pressurized elevator shafts;
- Elevator lobby enclosures on all floors;
- Pressurized elevator lobbies;
- Air intakes for pressurization systems located in a smoke free area;
- Smoke detectors in elevator lobbies, water resistive elevator systems;
- Elevator recall when power fails;
- Dedicated emergency power for all elevators;
- Pressurized stairways for all elevator lobbies;
- A means of two-way voice communication between all elevator cars and fire command location;
- A means of two-way voice communication between all elevator lobbies and fire command location;
- A program for the priority response of elevators during fire emergencies.

Among these issues, Klote and Braun pointed out that water infiltration was determined to be the area requiring additional research. It is pointed out that protection of the elevator system against water damage is necessary [41]. They suggested preliminary methods to conduct laboratory tests and developed some recommendations for protection of elevator system from water. In another paper, Klote and Fowell indicated that water damage to elevator components was the most significant factor affecting elevator usage [42]. They suggested that elevators could be designed using wet resistant components and located to minimize water infiltration.

Discussion on preplanning for elevator use during major fires was conducted by Cook [43]. Based on analytic studies, he concluded that it is possible to improve safety, evacuation and fire operations in high-rise buildings by using new technology and ideas, developing multi-agency contingency plans, cross training firefighters and elevator mechanics, and training building occupants.

A research agenda to measure the efficacy of such a procedure is proposed by Proulx [44] This paper was not aimed at discussing the technical issues but proposing an occupant interface to ensure the successful use of elevators by occupants during an emergency. Assuming that all technical issues are solved, it was pointed out that developing an elevator evacuation procedure is critically important.

Work focused on evacuation studies and human behavior was also conducted in Japan by Sekizawa [45]. A simplified model was developed to evaluate evacuation time by elevators, and some case studies were conducted in order to examine the feasibility and issues of elevator use for evacuation. However, the result of case studies suggested that it would be effective to use elevator in evacuation only for a small portion of the occupants such as the disabled people, while for the other people, it would be better to use stairs for evacuation in most cases.

Performance criteria based on practical objectives are suggested by Bukowski [46,47]. Some suggestions based on a more appropriate performance metric were provided, for reasonable revisions to design practice along with a more holistic philosophy that takes better account of human behaviour. But these suggested that regulatory thresholds need to be vetted through the existing consensus process of model code development and regulatory adoption followed in the adopting jurisdiction. While there are currently no regulations that generally permit egress lifts, there are a growing number of systems being approved worldwide under performance-based or alternative solutions provisions [48]. However, there is a lack of in-depth research on fire safety provisions for these elevator systems. Therefore, studies on how to achieve safe elevator system usage under a big fire in supertall buildings should be carried out urgently.

4. STUDIES ON FDS SIMULATIONS

CFD techniques have been used in engineering analysis of the ventilation system in the fire scenario for many years. Computer modelling for smoke control in buildings was proposed in 1980s [49], and then took centre stage in fire safety design with the fast development of computer science. FDS is a powerful CFD model of fire driven fluid flow developed by NIST, which has been applied widely in solving practical fire problems in fire protection engineering. It solves numerically a form of the Navier-Stokes equations appropriate for low-speed, thermally-driven flow with an emphasis on smoke and heat transport from fires [50]. FDS provides a more rigorous, three-dimensional treatment where the underlying conservation equations are solved in a numerical grid containing typically tens or hundreds of thousands of points. Incorporating with a simplified pyrolysis model, large eddy simulation turbulence model, mixture-fraction combustion model, and finite-volume radiative heat transfer model, FDS can describe fires in complex geometries, and the incorporation of a wide variety of physical phenomena. The advanced model interface, a solution 'picture' comprising temperatures, smoke concentrations, air velocities, etc. at each grid point, allows the engineer or designer to assess in detail the interaction of fire and smoke with building designs and smoke control systems of arbitrary complexity, and to study the implications for means of escape. It is a valuable tool that can be very useful in designing and analyzing smoke management systems.

Throughout its development, FDS has continuously undergone various forms of evaluation, both at NIST and beyond [51]. FDS Technical Reference Guide [51] provides a thorough summary of the validation work carried out for the program. The validation work described by the developers of FDS can be divided into the following categories:

- Comparison with full-scale tests conducted specifically for the code evaluation.
- Comparison with engineering correlations.
- Comparison with previously published full-scale test data.
- Comparison with standard test.
- Comparison with documented fire experience.

Other researchers and institutes also did a lot of evaluation work on FDS for different types of applications. Zou and Chow [52] used FDS version 3.01 to simulate a series of full-scale gasoline pool fire tests. Numerical results were compared in the light of some experimental data from experiments carried out in a compartment similar in size to the ISO-9705 room calorimeter. Taking the curve of heat release rates from the experiment as the input function, FDS gave good predictions for temperature and radioactive heat flux of a post-flashover fire which agreed well with experimental results. Deviations from the measured data are acceptable for most engineering applications.

Simulations on a set of unconfined fires of different sizes using FDS were conducted by Ma and Quintiere [53]. The aim of their work was to determine the accuracy and limitations of FDS. Pool fire with propane was applied as the typical fuel. All simulations were based on constant radiative loss fraction and specified the mass flow rate of propane with uniform velocity. The simulation results reveal that the temperature near the burner is over-predicted, while the centerline temperature and velocity in the non-combusting region is well predicted. The simulations also indicate that the optimum resolution of a pool fire simulation on the flame height is around 0.05, when using the characteristic length as the scaling factor.

5. SCALE MODELING TECHNIQUE

Full-scale fire experiments are necessary to fully understand the fire behavior in a building. As for supertall buildings, it may not be practical to apply the necessary fire loads to a full-scale experiment target which could be too large to reproduce at realistic scales. Scaled experiments offer an economical and simple alternative for laboratory study. In a scale model study, the most relevant significant dimensionless groups can usually be preserved, while the other unimportant variables cannot be completely scaled since too many dimensionless groups appear [54].

Thermal induced motion for scale models of an atrium immersed in water and air were studied by Chow [55]. Two groups of atrium models, which represented an actual shopping mall and three typical types of atria in Hong Kong respectively, were used for analyzing the smoke movement pattern induced by a thermal source. Very clear flow patterns inside the models were observed using aluminum powder as tracer in water.

Scale-modelling on atrium smoke movement was presented by Chow [56,57]. A 1/25 scale model and a 1/26.5 scale model were constructed respectively for assessing the scaling law with experimental data on natural smoke filling process with diesel pool fires in a full-scale atrium. Experimental studies with scaling parameters preserved were carried out, and results were compared with 50 hot smoke tests performed in the full-size model. Froude modelling for studying smoke movement and expression for temperature proposed in the literature were evaluated.

Using scaled model, Chow [58] investigated the smoke movement pattern in a tilted tunnel model. A 1/50 tunnel model was employed to observe smoke movement patterns with different tunnel angles varying up to 30° to the horizontal.

A series of experiments in a 1/10 scale model of typical vertical shafts were conducted by Zhu et al. [59] to study smoke movement induced by buoyancy. Six scenarios were set up by varying the ventilation conditions by opening different side wall and top vents at the shaft. The smoke temperature and concentrations of carbon monoxide in the shaft model were measured to justify the reduction of buoyancy in the vertical shaft.

A scale model shaft was used to study air pressure difference distributions due to stack effect at constant temperature by Zhao and Chow [60]. Air temperature inside the model was kept at different constant values above that of outdoor by wounding hot electric wires. Experimental scale modelling studies and numerical simulation with CFD were carried out to justify hydrostatic equations. For constant inside and outside air temperatures, air pressure difference varied linearly with height as estimated by hydrostatic equations. Both experimental data with scale models and CFD-FDS simulation results support estimation of air pressure by the hydrostatic model.

Overall, three scale modelling techniques have been successfully used in fire problem research [61]:

Froude modelling

In this form, the scaling is primarily based on representing transient inviscid flows characteristic of large Reynolds number in order to model the momentum and buoyancy effects. Thus, solid boundary effects are assumed to be of nonexistence or unimportance. Certain techniques should be applied to compensate for the neglect of Reynolds number effects at solid boundaries. It will not be possible to preserve all of the radiation and conduction groups and various approximations have been made to attempt their partial accommodation. It is important to maintain a sufficiently high Reynolds number to ensure that flow regimes that should be turbulent are turbulent.

Analogy modelling

In this approach, the fire flow effects are modelled by using different fluids, such as helium in air or salt-water system, to simulate the buoyancy effects. For a common salt-water system, water can be employed as the medium in the reduced-scale system when applying Froude modelling to fire induced flows. Compared to air, the smaller kinematic viscosity of water is a compensation for assuring high Re conditions. The heat source in the fire system can also be simulated by another fluid or a solute such as salt in the water system. In that case, the mass, momentum and specie equations in the water system correspond to the mass, momentum and energy (and specie) equations of the fire system.

Pressure modelling

In this approach, Reynolds number can be accomplished by changing the pressure of the ambient in the model, in the meantime the dimensionless coefficients group in Froude modelling can be preserved as well.

6. PRELIMINARY WORKS

6.1 Case Studies on Evacuation for Tall and Supertall Commercial Buildings

Long evacuation time for tall and supertall commercial buildings is a deep concern during emergency. Evacuation times in tall offices were studied by empirical expressions [62]. Offices in five tall buildings including a community building, a university campus, a commercial building, a bank and a residential building were selected. Different evacuation codes are reviewed first. Field studies on the geometry of buildings, evacuation strategies through staircases under different occupant loadings were carried out. The estimated evacuation times were justified with reference to the local codes on means of escape. Evacuation software in a fire engineering tool was also applied to justify the evacuation time estimated for offices at different heights. A long travel time of 24.2 min was estimated in the bank office. This value is much longer than those for offices in the other four example cases. As the evacuation time for a tall commercial building can be very long when the occupant loading is high, evacuation by elevator is recommended.

According to the Council on Tall Buildings and Urban Habitat, a supertall building is any of that which exceeds a height of 984 feet (300 m). Predictions of the required total evacuation time for selected offices in supertall buildings by different empirical expressions were studied [63]. The evacuation times for a supertall commercial building with high occupant loading are much longer than the expected 5 min for buildings with sprinkler. Even if the evacuation design was based on specification in local regulations or codes such as the MoE code in Hong Kong, the evacuation time would be very long. This point should be watched for future design on evacuation routes for supertall buildings. Evacuation strategy for supertall buildings should be watched carefully. Evacuation by elevator is recommended.

6.2 Fire Safety Requirements on Lifts System for Evacuation in Supertall Buildings

Lifts are not yet designed to be used by most of the occupants in fire. Two major safety concerns are identified on the hazards due to smoke spread to the lift shafts and lobby; and the fire resisting construction required under big fires. Literature review on designs for fire and smoke protection for lift systems for evacuation was carried out. Lift used for evacuation, smoke movement in the lift shafts and lobbies, and reduction in fire resistant rating of construction elements under big fire were discussed. Fire safety protection for evacuation is not demonstrated to be adequate for supertall buildings. Little progress for the evacuation in supertall buildings was made in the following years. Applying all works to normal tall buildings to supertall buildings over 300 m should be justified. Key issues and problems need to be addressed are discussed. Full-scale fire experiments are necessary to fully understand the fire behavior impact on the lift shafts and lobbies. Mathematical models with CFD, such as the FDS developed by NIST and full-scale burning tests on scale models and part of the lift shafts and lobbies should be carried out to study the fire environment in the supertall buildings. Further works should be carried out to investigate appropriate evacuation strategy.

6.3 Numerical Studies on Heat Release Rate in Room Fire under Different Ventilation Factors

Fire behavior involves complex dynamics driven by critical events, such as the ignition of secondary items, flashover and window breakage. All phenomena are difficult to predict. In fire safety design, the most important parameter is the heat release rate (HRR) which gives information on the fire size, fire growth rate, available egress time, and suppression system impact. Very limited value on HRR under real fires is available for local products. It is difficult to estimate from large-scale tests even with a cone calorimeter. Consequently, HRR in a room fire were studied by CFD. This leads to many arguments. A systematic grid sensitivity study was carried out using FDS version 5 to require grid independent results of an ISO 9705 room pool fire compared with experiment results. The predictions with the coarse grid were found to have the largest discrepancies with the experimental data. The predictions with the finer grid were closest to the data while the predictions with the medium grid were found to agree with that of the experiment data well enough. Hence the medium grid was chosen for this study. With the proper grid file, five fire scenarios based on different ventilation conditions were investigated. The effects of ventilation factor on HRR and mass flow rate through door opening were analyzed.

7. FURTHER RESEARCH WORK

Key issues and problems that need to be addressed in developing safe lift system for emergency evacuation in supertall buildings are:

- A better understanding of the fire environment in lift shafts and adjacent lobbies in supertall buildings, such as the main driving forces for smoke movement in supertall buildings which will be very different from that in a normal tall building, and smoke movement and fire spread into the vertical lift shafts and lobbies under big fires, etc. Identification of the safety requirements for lift systems used for evacuation means should be developed.

- Pressurization of lift shafts and lobbies in supertall buildings should be thoroughly studied. Issues related to opening doors upon pressurization of lift shaft and lobbies should be studied carefully.

- As studied in evaluating fire shutters under big fires [64], both thermal radiation and gas temperature have to be considered in fire hazard assessment. Full-scale burning test with big fires should be carried out to better understand the radiation effect. Requirements of fire resistance and heat protection for the lift system for supertall buildings under a big fire will be evaluated.

Full-scale burning tests on scale models and part of the lift shafts and lobbies should be carried out to study the fire environment in the supertall buildings. Experimental data in terms of HRR, temperature, pressure distribution and so on, will be compared with the FDS results to evaluate FDS model. The validated FDS model will be used to calculate fire scenarios within a typical design of lift shaft and adjacent lobbies in a supertall building. The smoke movement and fire spread into the lift shafts and lobbies under big fires should be studied carefully. Further works should be carried out to investigate appropriate evacuation strategy.

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