Influence of natural smoke vent opening in stairway of multi-storey building

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Abstract. Stairway used as an escape as well as firefighter’s route during evacuation. In addition, stairway connecting different floors of a building and becomes a path for the smoke spread in fire event. In a building, every escape route should be installed with smoke control system to ensure the prevention of dangerous smoke accumulation at those areas. The fire perimeter in terms of heat output and smoke generation is highly depends on building occupancy and the efficacy of smoke confinement may have a great challenge. In this paper, numerical simulations were conducted to study the efficacy of natural smoke vent to confine fire-induced smoke transportation in the stairways of multi-storeys buildings. The simulation used Fire Dynamic Simulator (FDS) was conducted on a full-scale building where the influences of smoke vent opening at different fire size were discussed. When the value of heat release rate (HRR) were kept constant, the different vent’s size opening had a different influence on the efficacy of smoke vent and an appropriate opening size was obtained and proposed for further action. The finding of this study can assist the fire engineer to ensure that the smoke vent installation play a good role in confinement of smoke diffusion.

1. Introduction

In a recent year, urban population and urbanization level increases rapidly in Malaysia. Due to large number of peoples and complex building environment, fires could induce many casualties and property loss. Fire statistics in Malaysia increase from 21,524 fire cases in 2008 to 54,540 fire cases in 2014 with total cost damage nearly RM1 billion and RM3 billion, respectively [1]. Nevertheless, until June 2015, there is 25,978 fire cases with total cost damage more than RM3 billion. This statistic shows the huge increment of property loss to be incurred in 2015 although the fire statistic is lower from year 2013 due to high cost of construction and building furnishing nowadays. Beside property losses, a number of injuries and fatality cases in fires also increase with 88 fatalities and 79 injuries in 2008 to 98 fatalities and 152 injuries in 2012. During fire in a multi-story building, despite being one of the main routes for evacuation and rescue operation, stairways also become the means of smoke spread between floors. Flame can cause to injury and property damage however majority of fire deaths resulted from smoke inhalation during evacuation or trapped in the building [2-5]. A case had been reported recently where a couple had died in stairway of level 31th while escaping from level 38th when their high-rise apartment occurred to fire [6]. This case is similar with fire happened previously in 1998 at Upper West Side apartment tower, New York city which killed four peoples due to smoke inhalation in stairway during
escaping [7]. Smoke generated from combustion depends on type of building occupancy and material used for construction. As a product innovation for fire risk reduction, a future alternative of construction material from natural waste product which has low flame and smoke has been studied and reported by researchers [8-10]. Hence for a building design, it should be constructed based on fire safety design as stated in building code and standards [11].

As stairway is the only measure for egress path during fire, it is worthwhile to study the fire and smoke behaviour in this area for multi-story building. Quantitative tools to analyze the smoke condition in a stairway could assist fire-safety engineer to explore different methods of risk reduction. Most of researchers are generally aware that full-scale fire test are the best way to obtain valuable information about chemistry, engineering, management, human behaviour and psychology which primarily related to fire origin and location, fire spread and growth, smoke propagation, material properties and structural integrity [12]. However, they also learn that full-experiment is expensive, time consuming [13-14] and poor repeatability due to unstable nature of fire. An alternative to study a certain fire phenomena with traditional full- and small-scale experiment is by using a numerical model as reported by Rahman et al., [15].

Fire safety in building is a set of measures designed to reduce the fire risk from its origin and risk of injury towards building occupants as well as fire fighters. Beside fire code regulation and standard, fire risk management is one of the measures for fire safety in building. In general, if a building design is constructed based on corresponding prescriptive codes, the level of fire risk is considered in acceptable risk range (tolerable) [16-17]. According to the current prescriptive code practiced locally, an openable vent outlet at the top of protected stairway without mechanically pressurized may be used as a smoke control system. However, the codes only specified the vent opening size without declared the effectiveness of the opening size in reducing the impacts and venting the smoke outside especially for a different type of building occupancy. As a result, in real fire event, some stairway with natural smoke vent opening cannot effectively vent the smoke to the outside. Currently, there are many researches focused on the smoke venting in road tunnels [18-22] and subway stations [5, 23-25], but there are only a few study reported on the smoke venting in protected stairway [26-28]. Thus, the main objective for this study is to simulate the smoke control in protected stairway with openable vent at the top of stairway where the size and location of smoke vent will be varied. It will provide evidence for the proper design of smoke vent as a smoke control system for protected stairway.

2. Methodology

2.1 Fire Dynamic Simulator (FDS)

The Fire Dynamics Simulator (FDS) is type of fire simulation software develop by the Building and Fire Research Laboratory (BFRL) under the U.S. National Institute of Standards and Technology (NIST). The software resolves numerical equations for low speed fluid flow concentrating on the smoke and radiation from the fire. It is most widely used to model smoke movement and fire scenarios in complicated buildings with many obstructions and complex geometry. The FDS can be used to simulate 3D fire scenarios, and is capable to estimate physical data; such as temperature, pressure, smoke layer height and smoke movement at a fire site [29]. Smoke view is a software that designed for FDS to produce animations and images of the output results [30]. The decision to use FDS was made based on the availability of the software and ease of use [31]. The input files for FDS6 were created in notepad with randomly size of shaft compartments and opening. The model was a protected stairway of multi-story building consisted of two parts: room with dimension of 2 m (W) x 4 m (L) x 3 m (H) and stairway with dimension 2.5 m (W) x 5.5 m (L) x 27 m (H) as shown in Figure 1.
For this study, three parameters were varied in the input files in FDS and smoke temperature as the output quantity was considered as dependent variables. The fire source was located in a center of fire room and HRR value was selected ranging from 300 to 1000 kW. Beside opening size, the efficacy of vent was study on different value of HRR as it produced different amount of smoke according to Shi et al. [32]. The radiation fraction was kept constant at 0.35 in all simulations. Different vent opening values were selected based on the total area of shaft compartment as stated in standards which is not less than 5% of the cross sectional of stairway area and the values for those parameters were given in table 1. The mesh size for the simulation was set according to grid resolution’s result and ran for 600s. The computer used in the analysis was: Intel® Core™ i5-2400 CPU @ 3.10GHz, RAM 4.00 GB. Data from simulation were taken when a stable smoke layer had formed in the stairway shaft.

| Variables                  | Values |
|----------------------------|--------|
| Fire size (kiloWatt)       | 300    |
|                            | 500    |
|                            | 900    |
|                            | 1000   |
| Size of opening, meter (vent) | 1/3.5 |

For the design of fire protection system, the characteristics of design fire such as the value of HRR, CO and CO$_2$ production rates are important [33]. Thus it is important to conduct experiments to measure these three parameters. Nonetheless, full-scale experiments are expensive and resource demanding. Alternatively, computer simulations which also referred as numerical experiment could be used as a research tools to study fire phenomenon in compartment fire and have been applied in different studies in fire science during the last decades [34-39]. Additionally, this type of experimental method had been reviewed by Johansson [40] as a complementary to traditional experiment and is a promising method in fire science research. In his scope to explore it as a research method, the advantages and challenges of numerical experiments were compared to traditional experiments using several examples of previously performed numerical experiments of compartment fires. Less expensive, reduce time; able to control the experiment and fire measurement not affected by the instrument are the main advantages discussed using numerical experiments.
3. Result and Discussion

3.1 Varied Heat Release Rate (HRR)
In order to study the effect of the heat release rate (HRR), four sets of fire test using heptane as fuel with steady HRR of 300 kW, 500 kW, 900 kW and 1000 kW were simulated in a protected stairway with vent opened. According to the experiment, the fire is sharply increased to a stable value of maximum heat release rate (HRR) and was then kept at the maximum value to the end as shown in figure 2. The duration of the four tests was 600 s (10 minutes). In general, when the HRR increases, the increase of the air drawn into the stairway accelerates the spread of the hot smoke. Thus the driving force for the flow in close stairway is the energy input from a fire originated in the lower compartment. Figure 2 shows temperature curves in the top storey of stairway at various HRR.

![Figure 2. Temperature curves at the top storey of stairway at various HRR; 300 kW, 500 kW, 900 kW and 1000 kW.](image)

The heat release rate has huge effect on distributions of smoke temperature. The maximal smoke temperature at top storey of stairway shaft as shown in Figure 2 ranged from 28 °C to 38 °C under HRR from 300 kW to 1000 kW, respectively. However, the smoke temperature curve for 900 kW is nearly similar with 1000 kW due to slightly different of fire size. As these temperatures were measured at the top of stairway with vent opened, the temperature is still remained close to ambient temperature as the smoke was well mixed with air even after 10 minutes of fire ignition.

3.2 Smoke movement in the stairway with and without vent opening
Smoke movement in a stairway with and without vent opening were tested in this study to study the smoke movement from lower level to the top storey. Figure 3 and 4 shows smoke movement in smokeview resulted from numerical simulation using FDS in a stairway produced by fire size, HRR = 500 kW at 10s, 100s, 200s, 300s and 500s after fire ignited.
As shown in Figure 3, it took nearly 100 s for the smoke to enter the first floor of stairway without vent opening. At the same time, for the stairway with vent opening the smoke begin to filled and diffuse in the second and third floor (Figure 4). It shows that for stairway with no vent opening, it takes longer time for the smoke to enter and spread through the stairway. Thus, the lower floor is filled with smoke and after a certain duration the smoke becomes dense as it will reduce visibility during evacuation. After 500 s since the fire break out, the smoke diffused slowly due to turbulent diffusion into the 5th and 6th floor and the whole stairway were filled with smoke after the smoke arrived at the top and flew downward at lower storey of stairway. As a result, the smoke in the stairway accumulated more and more and diffused to the lower space of stairway. The purpose of installing natural vent is to provide fresh air to the stairway [41], however during fire event the air pressure inside the stairway was higher due to smoke diffusing cause by stack effect and as the smoke from fire room entered the stairway accordingly, there was still part of the smoke flowing outside the opened vent. In the situation of stairway with vent opening, the smoke diffused faster into the higher floor at 10 s after fire ignited and spread to the 5th and 6th floor at 300 s which finally flowed to the outside through vent opening figure 4). Consequences, the smoke distribution in each level of stairway could be uniform even though after a few minutes.
3.3 Varied vent opening

Figure 5 shows the influence of vent opening area on the gas temperature rise at different fire size; 300 kW, 700 kW and 900 kW. From previous observation, the smoke temperature measured for fire size 1000 kW is nearly similar with 900 kW, thus for this part of study fire size of 1000 kW is excluded. The fire size has a strong influence on the average rate of smoke temperature rise in the stairway as increasing fire size will increase smoke temperature rise as discovered by previous research [25][42]. Furthermore, compare to all fire sizes; 300 kW, 700 kW and 900 kW in Figure 5 (a), (b), and (c) respectively, smoke temperature decrease when vent opening area increase from 1m x 1m to 2.2m x 2.7m. However, with further increase in vent opening area to 3.5m x 3.5m the smoke temperature reaches a value which same as vent opening area; 2.2m x 2.7m. It indicates that increase vent opening area is helpful to slow down the development of fire as well as reduce smoke entrainment thus resulted in increasing visibility. Therefore, when a fire occurs in a room and smoke diffuse to the adjacent stairway, vent opening at the top storey of stairway is conducive to provide more time for evacuation, firefighting and rescue work.

![Temperature curve in first storey of stairway at various HRR](image)

**Figure 5.** Temperature curve in first storey of stairway at various HRR a) HRR = 300 kW b) HRR = 700 kW c) HRR = 900 kW
4. Conclusion
Vent opening area at the top storey on the smoke temperature rise in stairway was studied in this paper. Three different vent sizes were adopted in FDS simulation with four different fire sizes and the effects of these parameters on smoke temperature rise in stairway were discussed. The fire size has a strong influence on the average rate of smoke temperature rise in the stairway. According to simulation result, natural vent really played a good role in preventing smoke entrainment and different opening size had different influence on the efficacy of smoke venting from stair shaft. The bigger the vent opening, the more smoke could escape from the stairway to the outdoor. It was also revealed that no matter what size of fire, the smoke temperature in the stairway decrease significantly once the vent opening area is increased. In order to support this study using numerical study, physical experiment with full-scale fire experiment could be conducted in future for multi-storey building. The finding of this study could assist the fire engineer to ensure that the smoke vent installation could play a good role in confinement of smoke diffusion.

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References
[1] FRDM 2015 Fire Statistic in Malaysia 2008-2014.
[2] Bennetts I D and Poh K W 2006 Design of Sprinklered Shopping Centre Buildings for Fire Safety OneSteel-Market Mills (Newcastle, Australia) p 42
[3] Thamarajan P 2007 The Essential Aspects of Fire Safety Management in High-Rise Buildings. (Universiti Teknologi Malaysia)
[4] Cebela A 2012 Fire safety education for staff members - case study (Lund University Sweden).
[5] Luo N, Li A, Gao R, Tian Z and Hu Z 2014 Smoke confinement utilizing the USME ventilation mode for subway station fire Saf. Sci. 70 202–10
[6] New York Daily News 2014
[7] The New York Times 1998
[8] Mohammed A A, Bachtiar D, Siregar J P and Rejab M R 2016 Effect of sodium hydroxide on the tensile properties of sugar palm fibre reinforced thermoplastic polyurethane composites J. Mech. Eng. Sci.10(1) 1765–77
[9] Aniza N, Hassan S, and Inayat M 2016 Thermogravimetric kinetic analysis of Malaysian poultry processing waste material under inert and oxidative atmospheres J. Mech. Eng. Sci.10(2) 1943–55
[10] Fajrin J, Zhuge Y, Bullen F and Wang H Flexural behaviour of hybrid sandwich panel with natural fiber composites as the intermediate layer J. Mech. Eng. Sci.10(2) 1968–83
[11] UBBL, Uniform Building By-Laws 1984
[12] Buchanan A H and Abu A K 2017 Structural Design for Fire Safety, 2nd Ed. (United Kingdom: John Wiley & Sons).
[13] Li Y Z and Ingason H 2015 A New Methodology of Design Fires for Train Carriages Based on Exponential Curve Method Fire Technol. p 16
[14] Yang P, Tan X and Xin W 2011 Experimental study and numerical simulation for a storehouse fire accident Build. Environ. 46(7) 1445–59
[15] Rahman M M, Alim M A, Mamun M A H, Chowdhury M K and Islam A K M S 2007 Numerical Study Of Opposing Mixed Convection 2(2) 25–36
[16] Chu G and Sun J 2008 Decision analysis on fire safety design based on evaluating building fire risk to life Saf. Sci.46(7) 1125–36
[17] Ramachandran G and Charters D 2011 Quantitative Risk Assessment in Fire Safety (London, United Kingdom: Taylor & Francis LTD)
[18] Ji J, Gao Z H, Fan C G and Sun J H 2013 Large Eddy Simulation of stack effect on natural smoke exhausting effect in urban road tunnel fires Int. J. Heat Mass Transf. 66 531–42
[19] H. Bjelland 2013 Engineering Safety with application to fire safety design of buildings and road
tunnels (University of Stavanger)

[20] Horváth I, van Beeck J and Merci B 2013 Full-scale and reduced-scale tests on smoke movement in case of car park fire Fire Saf. J. 57 35–43

[21] Chen J, Fang Z and Yuan J 2013 Numerical Simulation about Smoke Vent Arrangement Influence on Smoke Control in Double-decked Tunnel Procedia Eng. 52 48–55

[22] Meng N, et al. 2014 Numerical study on the optimization of smoke ventilation mode at the conjunction area between tunnel track and platform in emergency of a train fire at subway station Tunn. Undergr. Sp. Technol. 40 151–59

[23] Bartlett N 2012 Optimization of Smoke Control Systems in Underground Subway Stations (Ghent University)

[24] Luo N, Li A, Gao R, Song T, Zhang W and Hu Z Performance of smoke elimination and confinement with modified hybrid ventilation for subway station Tunn. Undergr. Sp. Technol. 43 140–47

[25] Qu L and Chow W K 2013 Common practices in fire hazard assessment for underground transport stations Tunn. Undergr. Sp. Technol. 38 377–84.

[26] Lambert K and Merci B 2014 Experimental Study on the Use of Positive Pressure Ventilation for Fire Service Interventions in Buildings with Staircases Fire Technol. 50(6) 1517–34.

[27] Mokhtarzadeh-Dehghan M R 2011 Numerical simulation and comparison with experiment of natural convection between two floors of a building model via a stairwell Int. J. Heat Mass Transf. 54(1–3) 19–33

[28] Ji J, Wan H, Li Y, Li K and Sun J 2015 Influence of relative location of two openings on fire and smoke behaviors in stairwell with a compartment Int. J. Therm. Sci. 89 23–33

[29] Khairul Zaimy, Anika Zafiah M, Najibah A and NurulSaadatulsyida A 2013 Mechanical And Thermal Properties Of Waste Bio-Polymer Compound By Hot Compression Molding Technique J. Mech. Eng. Sci. 5 582–591

[30] Mcgrattan K, Peacock R and Overholt K 2016 Validation of Fire Models Applied to Nuclear Power Plant Safety Fire Technol. 52 5–24

[31] Audouin L, Rigollet L, Prétrel H, Le Saux W and Röwekamp M 2013 OECD PRISME project: Fires in confined and ventilated nuclear-type multi-compartments - Overview and main experimental results Fire Saf. J. 62 80–101

[32] Shi C L, Li Y Z, Huo R, Yao B, Chow W K and Feng N K 2005 Mechanical smoke exhaust for small retail shop fires Int. J. Therm. Sci. 44(5) 477–90

[33] Fauzi F A, Ghazalli Z and Siregar J P 2016 Effect of various kenaf fiber content on the mechanical properties of composites J. Mech. Eng. Sci. 10(3) 2226–33

[34] Phillips W G B 1994 Simulation models for fire risk assessment Fire Saf. J. 23(2) 159–69

[35] Novozhilov V, Harvie D J E, Kent J H, Apte V B and Pearson D 1997 A computational fluid dynamics study of wood fire extinguishment by water sprinkler Fire Saf. J. 29(4) 259–82

[36] Prasad K, Patnaik G and Kailasanath K 2002 A numerical study of water-mist suppression of large scale compartment fires Fire Saf. J. 37(6) 569–89

[37] Bittern A 2004 Analysis of FDS Predicted Sprinkler Activation Times with Experiments (University of Canterbury)

[38] Huang H, Ooka R, Chen H and Kato S 2009 Optimum design for smoke-control system in buildings considering robustness using CFD and Genetic Algorithms Build. Environ. 44(11) 2218–27

[39] Johansson N 2015 Fire Dynamics of Multi-Room Compartment Fires (Lund University)

[40] Johansson N 2014 Numerical experiments and compartment fires Fire Sci. Rev. 3(2) 1–12

[41] Zhang J, Lu S, Li C and Yuen R K K 2014 Vent Location Impacts on Building Compartment Fire under Natural Roof Ventilation APCBEE Procedia. 9 360–64.

[42] Harish R and Venkatasubbaiah K 2014 Effects of buoyancy induced roof ventilation systems for smoke removal in tunnel fires Tunn. Undergr. Sp. Technol. 42 195–205