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# 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 31st 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.

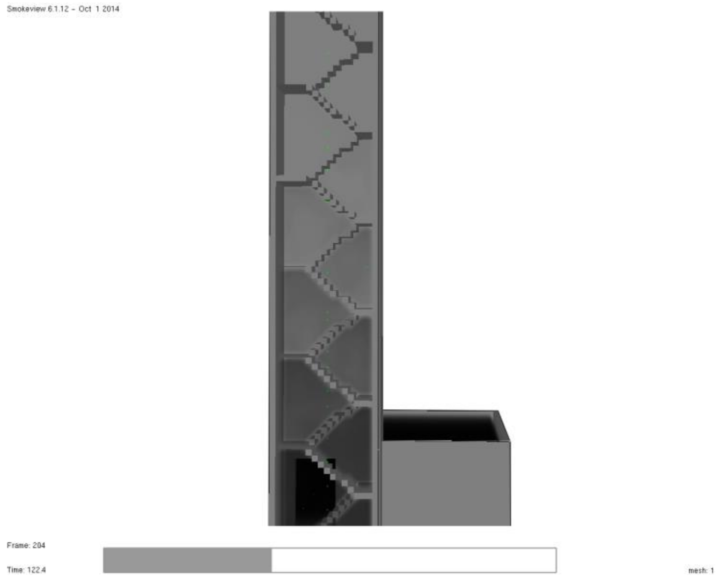


**Figure 1.** Room and stairway model

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$^{TM}$ 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.

**Table 1.** Parameters that were varied in all simulations

| 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 300kW, 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.

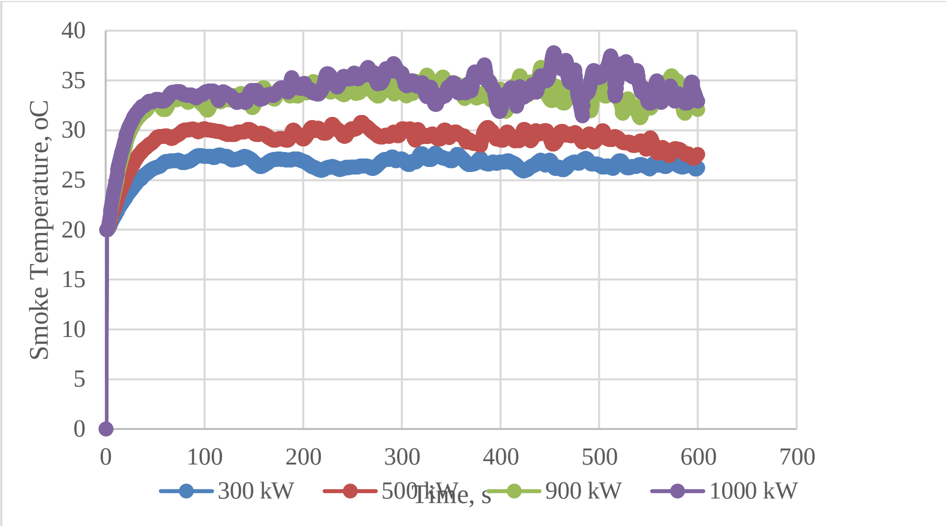



**Figure 2.** Temperature curves at the top storey of stairway at various HRR; 300 kW, 500 kW, 900 kW and 1000 kW.

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 $^{o}$C to 38 $^{o}$C under HRR from 300kW to 1000kW, 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.

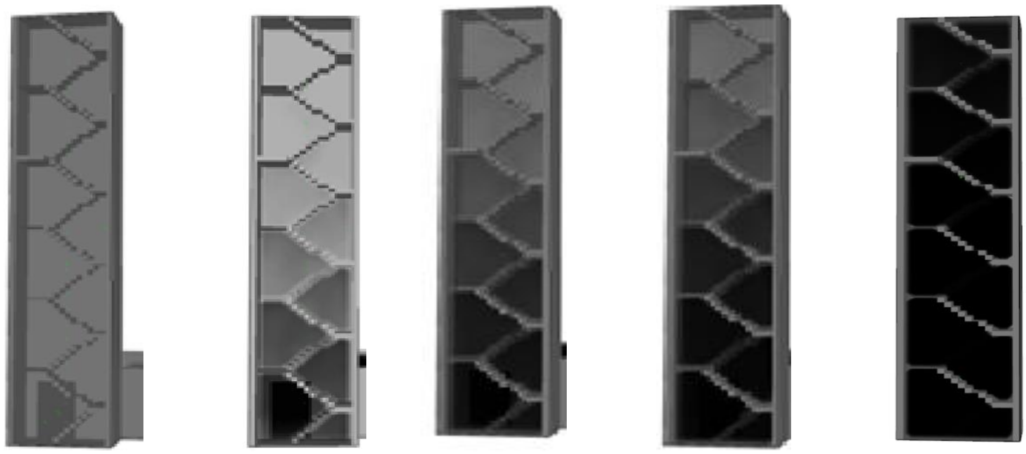



**Figure 3.** Smoke movement in the stairway without vent opening

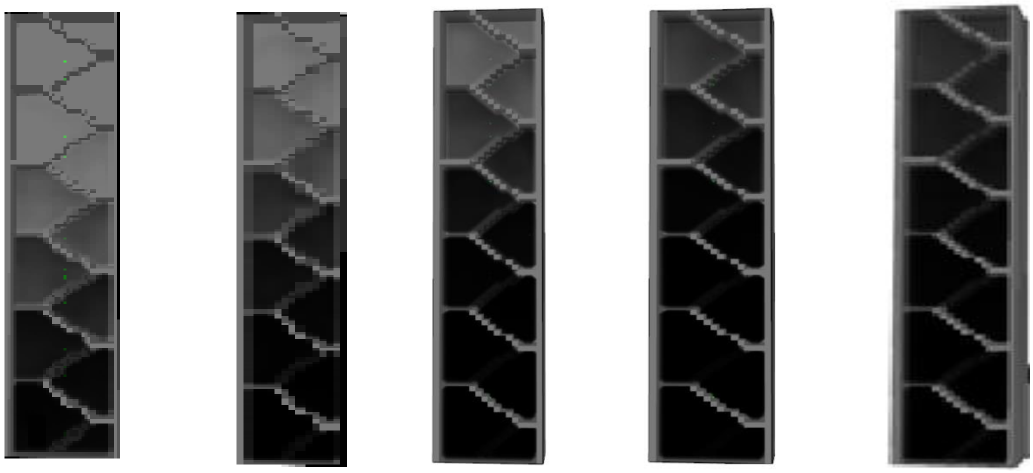
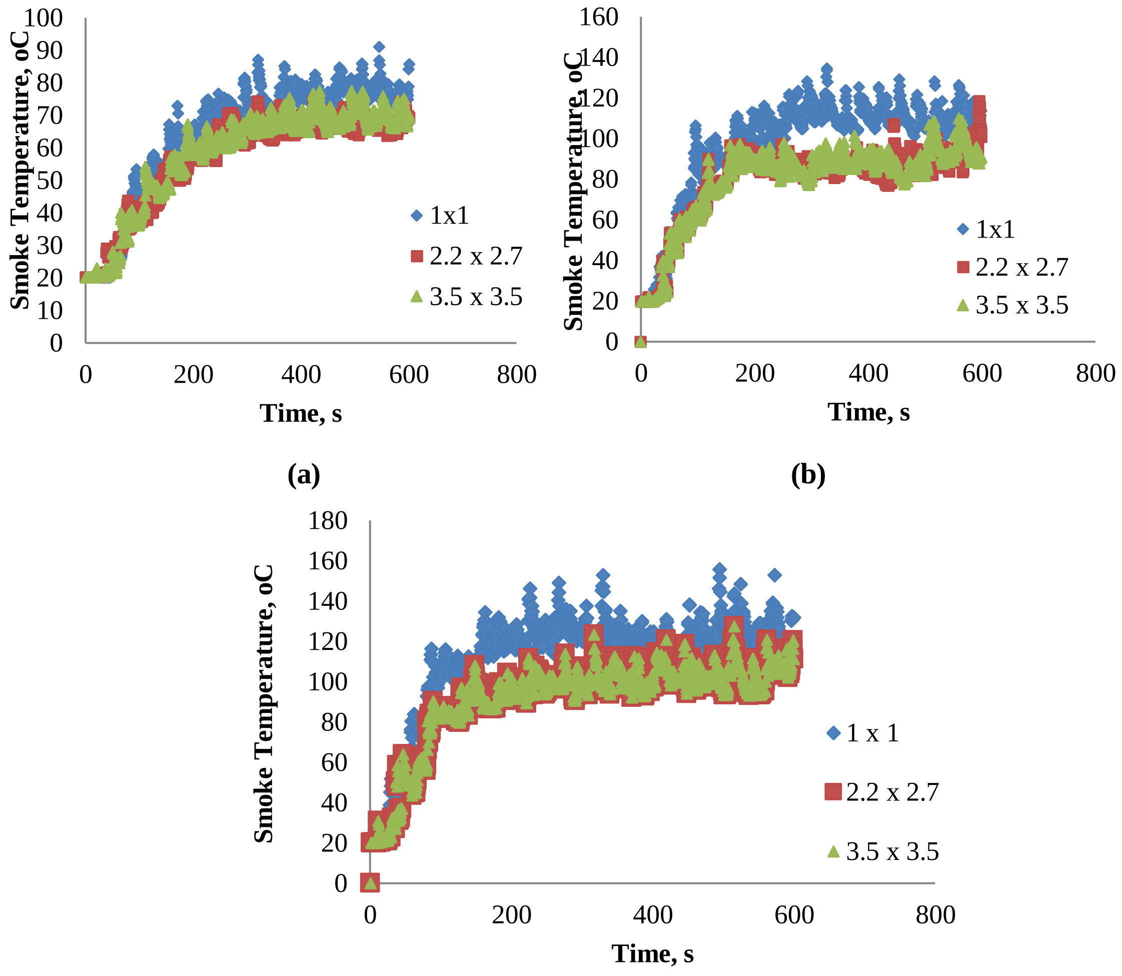



**Figure 4.** Smoke movement in the stairway with vent opening

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 5$^{th}$ and 6$^{th}$ 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 5$^{th}$ and 6$^{th}$ 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; 300kw, 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.




**(c)**

**Figure 5.** Temperature curve in first storey of stairway at various HRR a) HRR = 300 kW b) HRR -= 700 kW c) HRR = 900 kW

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## 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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