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Full Length Research Paper

Simulation research on natural smoke ventilation and external airflow in large space: Case study of the improvement project of Taoyuan International Airport, terminal 1

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The paper analyzed the influence of external airflow on natural smoke ventilation in large space by means of computational fluid dynamics (CFD) and engineering calculation. The purpose of the paper is Terminal 1 of Taiwan Taoyuan International Airport after renovation. In the renovation project, the separate departure and arrival halls will be connected to create a large atrium; natural smoke ventilation will be adopted as the smoke control strategy for the new space. As external airflow may directly impact natural smoke ventilation, the study means to investigate the extent to which external airflow influences natural smoke ventilation by analyzing scales of fire and presence of external airflow. Conclusions of the study are as follows: 1) when directly affected by headwind, entrances and exits on the first floor pose danger to the safety of certain parts of the floor; 2) when directly affected by headwind, natural smoke ventilation becomes weaker than when unaffected; 3) in the case study, natural smoke ventilation proves effective under the premise that the scale of fire is less than 2000 kW.

Key words: Airport terminal, natural smoke ventilation, external airflow, evacuation safety, FDS.

INTRODUCTION

The fire safety is very important in implementing the engineering design for airport terminals. Since the crowd gathered, the fire safety equipments in buildings should be defined and stated clearly in order to provide a safe, cost-effective, and sustainable building (Beever, 1991; Klote, 1993; Aik, 2011). Fire safety strategies are divided into four parts including passive building construction strategy and fire services installation strategy (Chow and Ng, 2008; Su and Chiang, 2011a). Chow and Ng (2003) and Huang et al. (2010) have discussed the special features of an airport terminal and the utilization of the cabin design in engineering-performance-based fire safety in Hong Kong.

Thirty years has passed since terminal 1 of Taiwan Taoyuan International Airport was inaugurated in 1979. Recently a renovation subproject, project of important national gateways for the terminal, will be modified to be curved glass roofs and walls that extend from the fourth to the first floor, which will cover the current platforms of the third floor, making the terminal hall a large atrium. Facilities will be enhanced to provide passengers with more convenience and better services. Natural smoke ventilation is to be adopted as the smoke control strategy of this large space. However, as airport buildings are often situated in open, obstacle-free areas that are usually affected by visible and constant external airflow, it is yet to be investigated whether the prospect of natural smoke ventilation is significantly affected by external airflow.

The current study focuses on the influence of external airflow on natural smoke ventilation of the large space in

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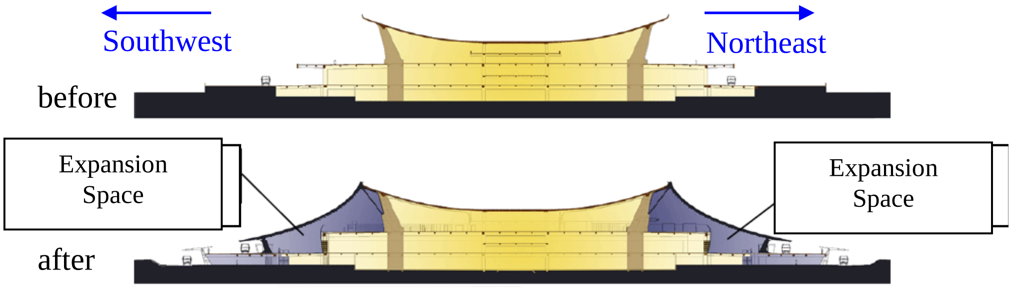

Figure 1. Sectional drawings of Terminal 1, Taoyuan International Airport (Before and After renovation).

question. Several simulations are analyzed by means of CFD and calculation of necessary time for evacuation to identify users' evacuation safety as well as the extent to which external airflow affects smoke ventilation.

LITERATURE REVIEW

Characteristics of airport terminal fire

To suit various purposes of an airport, large-scale atriums are widely used in the architecture of terminals. The downside to this feature is that during a fire, the upward flow of smoke in the atrium is almost uninterrupted, causing the smoke to spread rapidly in the building (Xiang, 2008). Meanwhile, as the interior space of a terminal is comparable to an outdoor space in the sense that air supply is sufficient, the fire is more similar to "fuel-dominated combustion," which spreads to other parts at a rather face speed, than to "ventilation-dominated combustion," which is characteristic to most cases of building fire (Xiang, 2008).

Cases of terminal fire in history

An airport terminal is a large multi-purpose construction; hence, the cause, type and location of fire are highly varied. In Taiwan's previous cases of terminal fire (Liu, 1996; Schultz et al., 2006; Xiang, 2008), most are caused by construction failure (4 out of 11); other causes include electrical short circuit (2 out of 11), fire in the trash can (2 out of 11) and fire in a restaurant (1 out of 11); none of the aforementioned fire caused casualty. As for cases of fire in airport terminals overseas (Lu, 2009), the case of Airport Orly of Paris, France, in 1973, was caused by electrical short circuit in Transformer Room B2, which fortunately did not result in any casualty. The case in Düsseldorf, Germany in 1996 was much less fortunate: the fire was due to a construction failure at a flower shop in the arrival area between the first and second floors; the smoke spread to all parts of the arrival hall through air ducts, and the accident caused 16 deaths and 62 injuries. In 2009, the waiting area of Perth Airport, Australia, was because of a cigarette butt that ignited wastes disposed in the drainage pipe, causing the hall to be filled with smoke; without consequent casualties, the airport was closed for 5 h as a result of the incident.

OVERVIEW OF THE STUDY SUBJECT

Overview of the construction

The subject for simulation in this study is the large space connecting the arrival and departure halls on the first and third floors of terminal 1, Taoyuan International Airport (Figures 1, 2, 3 and 4). The surface of the first floor (mainly used as departure hall) is 28,640 m^2, while average ceiling height is 8.31 m; the surface of the third floor (mainly used as arrival hall) is 24,460 m^2, while ceiling height is from 4.2 m to 15.7 m (average: 9.97 m). Neighboring spaces are separate from this particular area in that they belong to different fire evacuation sections. In addition, four main entrances and exits can be found on the first floor.

Overview of external airflow

According to statistics in the aerodrome climatological annual sumaries (Civil Aeronautics Administration Annual Report, 2008) in 2007, the prevailing wind direction and average wind speed of Taoyuan International Airport are shown in Table 1.

Moreover, wind speed increases with the elevation of altitude and is related to the type of terrain. The correlation may derive the following equation (1) (National Construction and Planning Agency, 2006):

$$\frac{V_z}{V10} = \left(\frac{z}{10}\right)^{\alpha} \quad 0 \le Z \le Z_g \tag{1}$$

Herein,

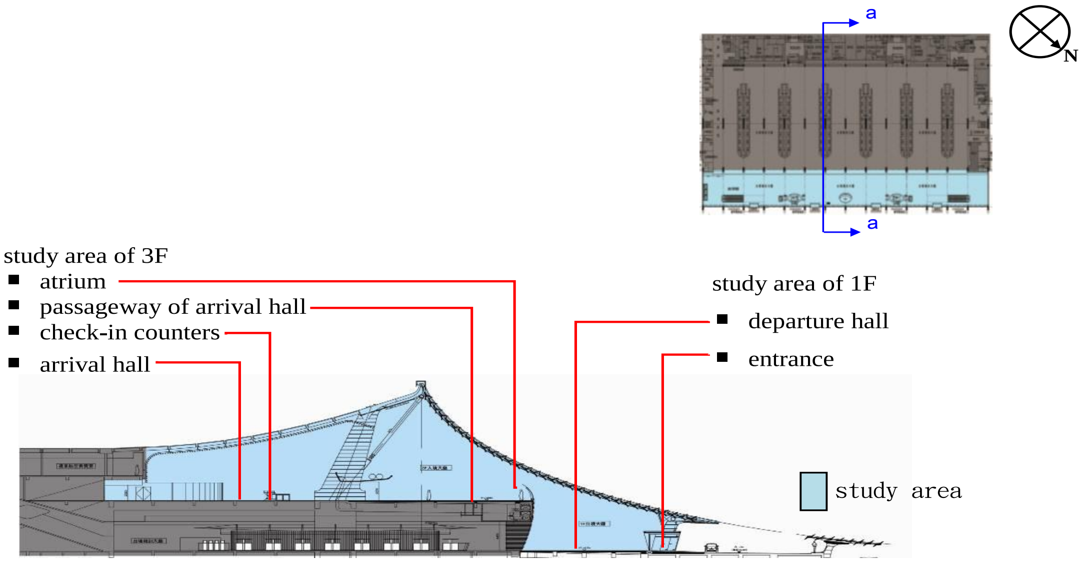

Figure 2. Profile of the study subject.

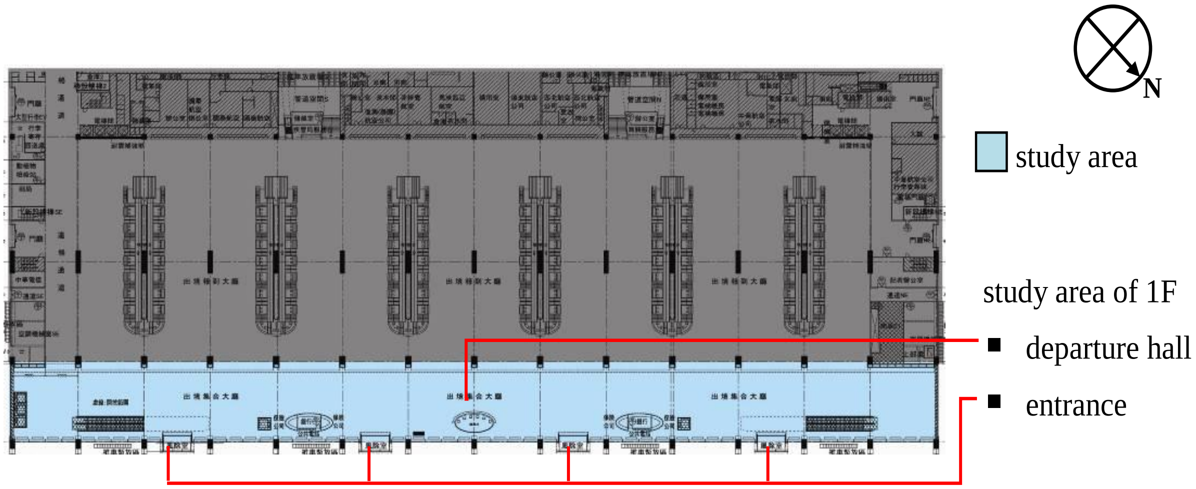

Figure 3. The first floor plan.

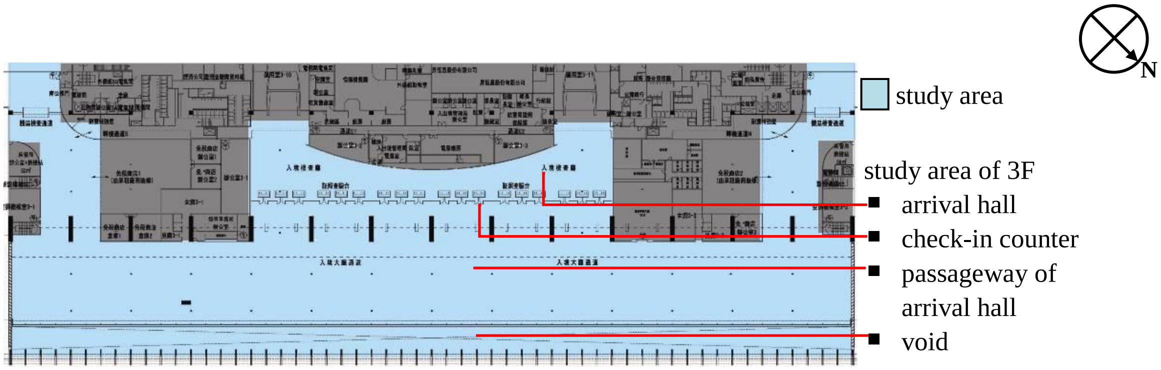

Figure 4. The third floor plan.

Table 1. Prevailing wind direction and average wind speed of Taoyuan International Airport.

Item	**Year**			
	2005	**2006**	**2007**	**Average**
Prevailing wind direction	NE	NE	NE	NE
Average wind speed (mph)	5.21	5.87	6.18	5.7

Table 2. Relation between ground wind speed and type of terrain.

Type of terrain	**α**	**Gradient Z_g (m)**
Metropolises and urban areas	0.32	500
Suburbs and towns	0.25	400
Open plains	0.15	300

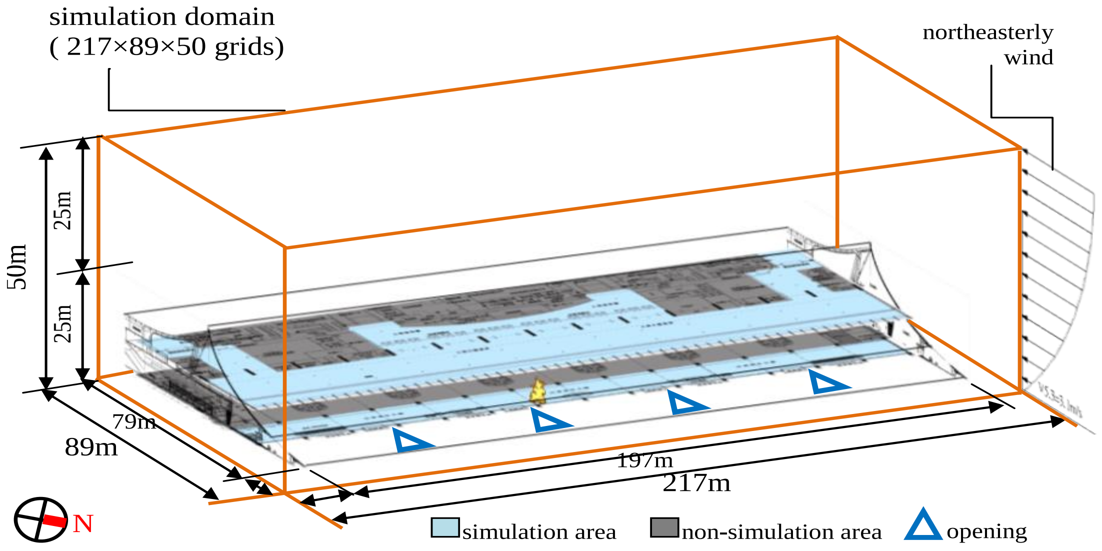

Figure 5. Simulation model.

V_z = wind speed at the height of z (m/s)
V_{10} = wind speed at the height of 10 m (m/s)
Z_g = δ gradient (related to type of terrain), the values are shown in Table 2.
α = exponent or index (related to type of terrain), the values are shown in Table 2.

SIMULATION

Method and model of simulation

Software program

Modelling and simulation applications are useful at pre-planning, predicting possible damage, training responders, raising public awareness, and performance evaluation for reconstruction. Sagun et al. (2011) simulated the contribution of crowd modelling to improving the design of the built environment. Chow (1997) adopted a simulation modelling method to simulate smoke generated in the cabin would flow out from the door left opened for human egress. The effectiveness of natural smoke systems in large spaces have been studied by computational simulations and experiments and the results indicated wind was an important factor (Chow et al., 2001; Yang, 2004; Huoa et al., 2005; Su et al. 2011b).

The CFD software employed in the study is version 4 of the fire dynamics simulator (FDS) developed by National Institute of Standards and Technology, US (NIST). FDS simulates situations of fire accidents by solving Navier-Stokes numerical equations to estimate the flow of smoke and heat in a case of fire.

Geometry and parameters

Model of simulation is displayed in Figure 5. Computational

Table 3. Simulation settings of scale of fire and corresponding descriptions.

Item	Scale kW	Description
Minimal fire origin in a large space where flammable objects are limited in number	2,000	Fire originates from the lounges in the hall; the incident is caused either by human or by other agents.
Minimal fire origin in a large space where the flammable objects are abundant	5,000	Fire originates from the lounges in the hall and spreads to neighboring seats or the carry-on luggage of passengers waiting in the area.
Large fire origin	25,000	In the design of the subject of study, facilities with a heavier fire load or is more vulnerable to fire (i.e. shops and restaurants) are separated from the space in question and sectioned into different fire protection zones. However, subsequent to such terrorist attacks as 911, it is urgent to take deliberate arson into consideration when formulating fire protection strategies. Likewise, the study simulates a fire caused by crashes of cars or trucks carrying flammable substances. The maximal scale of fire origin under this simulation is 25,000 kW.

Table 4. Time to reach maximal scale of fire.

Formula: $Q=\alpha t^2$			
Group	**Max. HHR Q (kW)**	**Fire development rate α (kW/s^2)**	**Time to maximal HHR t (s)**
1	2,000		274.72
2	5,000		434.37
3	10,000	0.0265	614.29
4	20,000		868.74
5	50,000		971.28

dimensions of the model are 217 m (L), 89 m (W) and 50 m (H); to conduct simulation, the space is divided to 965,650 grids of 1 m^3. Except for the ground (represented by the lower boundary), all boundaries of the model are specified as open boundaries. As for surface material of the construction, the setting is airtight concrete. Environmental temperature is initially set at 25ºC; air conditioning is switched off before simulation starts. External airflow is initially set at 30ºC; in cases where external airflow is present, the wind direction and speed at each of the various heights is set according to the data and equation stated in 3.2. Considering the upper limit on required evacuation time, the time allowed in a simulation is set at 30 min.

Setting of fire source

Location of fire origin, maximum scale, speed of development and types of post-combustion yields are set according to the material, quantity, geometric form and possibility of inflammation of flammable substances in the space. In the study, simulation is set at such scales of fire origin as 2,000, 5,000 and 25,000 kW corresponding to different simulation settings (Table 3); the size of fire origin is set at 2.0 m (L) × 0.8 m (W) × 0.9 m (H).

In addition, to ensure the simulation is as close to real combustion as possible in the beginning of the development of fire, the authors adopted the commonly known T2 (Architecture and Building Research Institute, 2006) to estimate the relation between heat-release rate (HRR) and required time. Fire development rate α (Novozhilov et al., 1997), on the other hand, is estimated by considering such parameters as use of space, arrangement of flammable objects, and condition of interior maintenance. The relations between HHR of fire origin and required time of simulation are indicated in Table 4 and Figure 6. The fire origin in the simulation is set in the arrival hall on the first floor (Figure 7). Table 5 indicates the simulation groups of the study, which differ from one another in such parameters as scale of fire origin and presence of external airflow.

Estimating method of evacuation time

Among the several methods to estimate evacuation time, the theory proposed by the English researcher Marchant is the most widely adopted one. Marchant theorizes (Ho and Chiang, 1999) that evacuation time is affected by three factors: 1) changes in surroundings; 2) changes in evacuator's physiological, mental and behavioral state; 3) evacuation facilities, including the design of exits, passages and stairs. In Taiwan and Japan, the most frequently adopted method to estimate evacuation time is Route B (Architecture and Building Research Institute, 2006), which resembles Marchant's theory in the fact that it considers the geometric shape of space, state of evacuator, network of evacuation

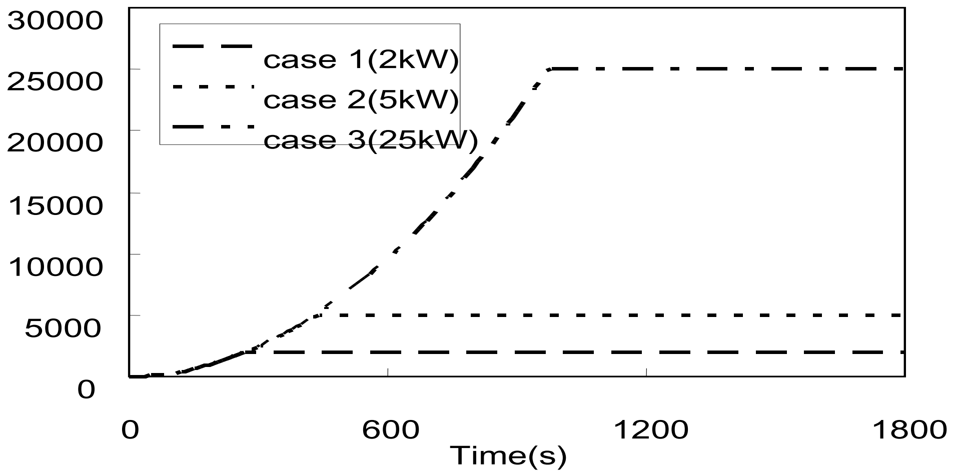

Figure 6. HHR growth curve in fire.

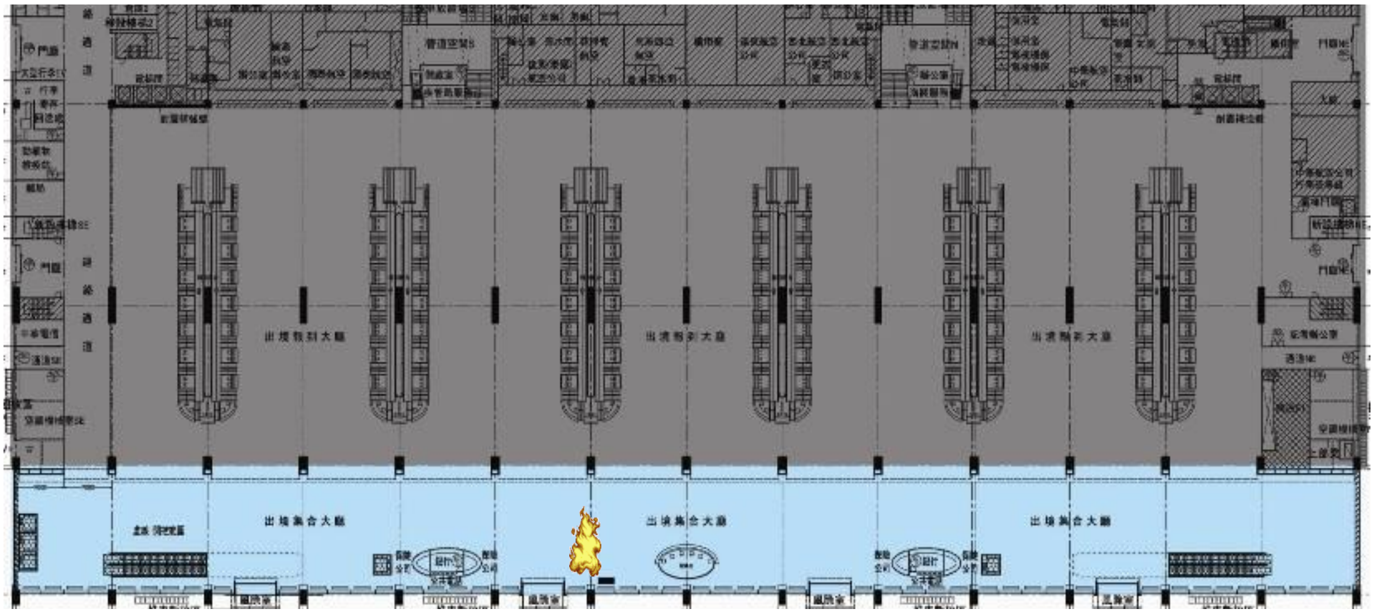

Figure 7. Location of fire source - the 1st floor plan.

Table 5. Simulation settings and grouping.

External airflow	Scale of fire (kW)		
	2,000	5,000	25,000
Absent	A1	A2	A3
Present	B1	B2	B3

routes, and installation of facilities. The current study adopts Route B to calculate required evacuation time to provide reference for assessment of fire safety in the design of the subject.

The equation (2) of Route B is:

$$tescape = tstart + ttravel + tqueue \tag{2}$$

Herein

tescape: time required to escape to safe areas
tstart: time between the onset of fire and the initiation of evacuator's attempt to escape
ttravel: time for evacuator to travel to safe areas
tqueue: time for evacuator to escape through the exit

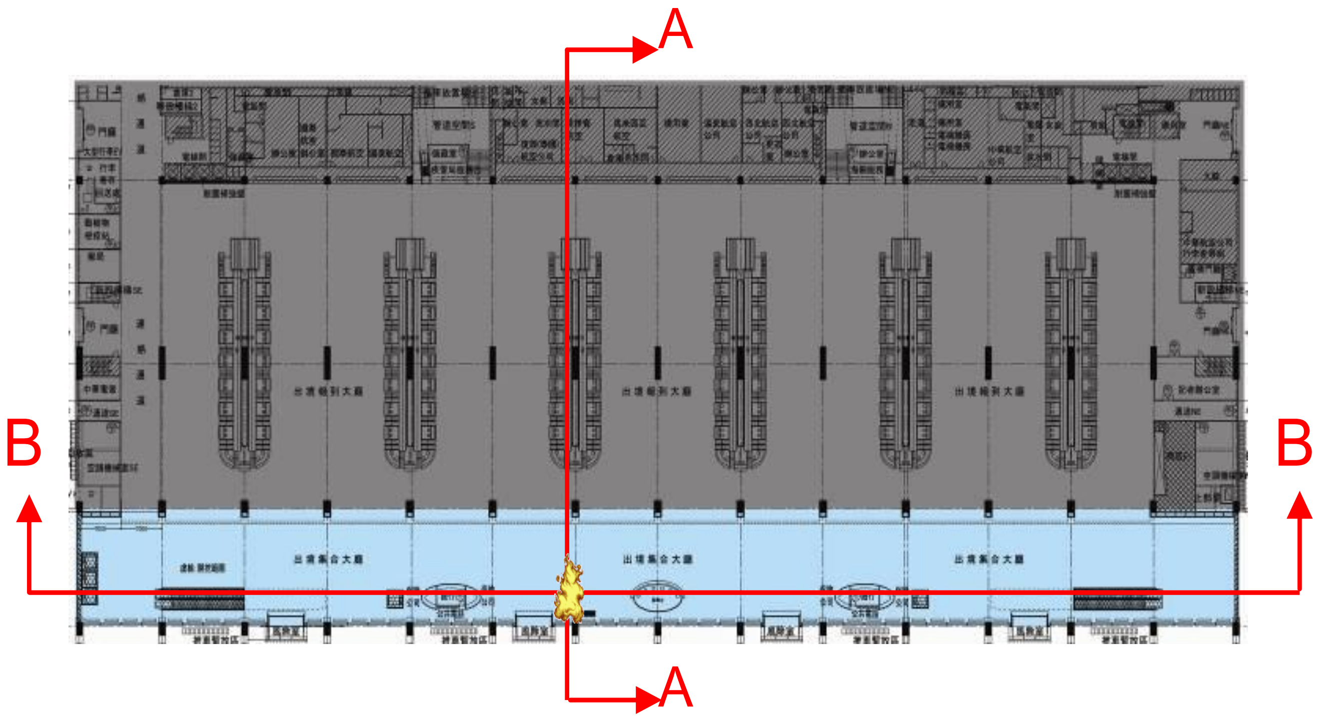

Figure 8. Position of visibility section.

RESULTS AND DISCUSSION

Simulation results of smoke control strategies

Results of simulation are shown in cross sections of visibility. The position of cross sections is shown in Figure 8. On the other hand, danger of smoke is shown in visibility-time curve. Taking reference from the SFPE Handbook (Jin, 2002), which suggests that evacuator may not clearly identify the route when visibility is lower than 10 m in a large space (or lower than 5 m in a small space).

1) Group A1
As shown in Figure 9, smoke accumulates in the upper area of the space by the influence of thermal buoyancy. Figure 10 further indicates that within the 30 min of simulation, visibility in all parts of the space has never been lower than 10 m (Jin, 2002).
2) Group A2
From Figure 11 and 12, one may notice that an obvious decrease in visibility takes place from 5.00’, which implies that at this point certain amount of smoke has spread to the third floor. At 16.05’, the visibility in a part of the third floor (hall) decreases to lower than the benchmark of 10 m.
3) Group A3
One may confirm in Figures 13 and 14 that in Group A3, the scale of fire is larger than in Groups A1 and 2, and the rate of smoke accumulation and descending is also the fastest. At 12.15’, low visibility (that is, below 10 m) occurs in a part of the third floor (hall), and subsequently (after 16.00’) in other parts of the floor. As for the first floor, certain amount of smoke descends at around 15.00’.
4) Group B1
Results of the simulation (Figures 15 and 16) of Group B1 indicates that visibility of the entire space has not decreased to below 10 m when the scale of fire is set at 2000 kW with the influence of external airflow. Furthermore, a comparison between results of Group B1 and those of Group A1 (that is, Figures 9 and 16) indicates that visibility at different parts of the space changes at an earlier time.
5) Group B2
Results of the simulation (Figures 17 and 18) of Group B2 indicates that visibility in the left passage and the hall on the third floor, as well as in the hall of the first floor, decreases to below 10 m at 11.13’. In contrast to the situation of Grouup A2, the first floor of Group B1 is more heavily influenced by smoke; on the third floor, visibility decreases to below 10 m at an earlier time.
6) Group B3Group B3 is the simulation of the largest scale of fire in the study influenced by external airflow. Figures 19 and 20 indicate that low visibility (that is, below 10 m) on the third floor occurs at 9.06’. A comparison among Groups B1, B2 and B3 may point to the fact that the most critical factor to influence the safety time limit (that is, time for the visibility to decrease to below 10 m) is the scale of fire.

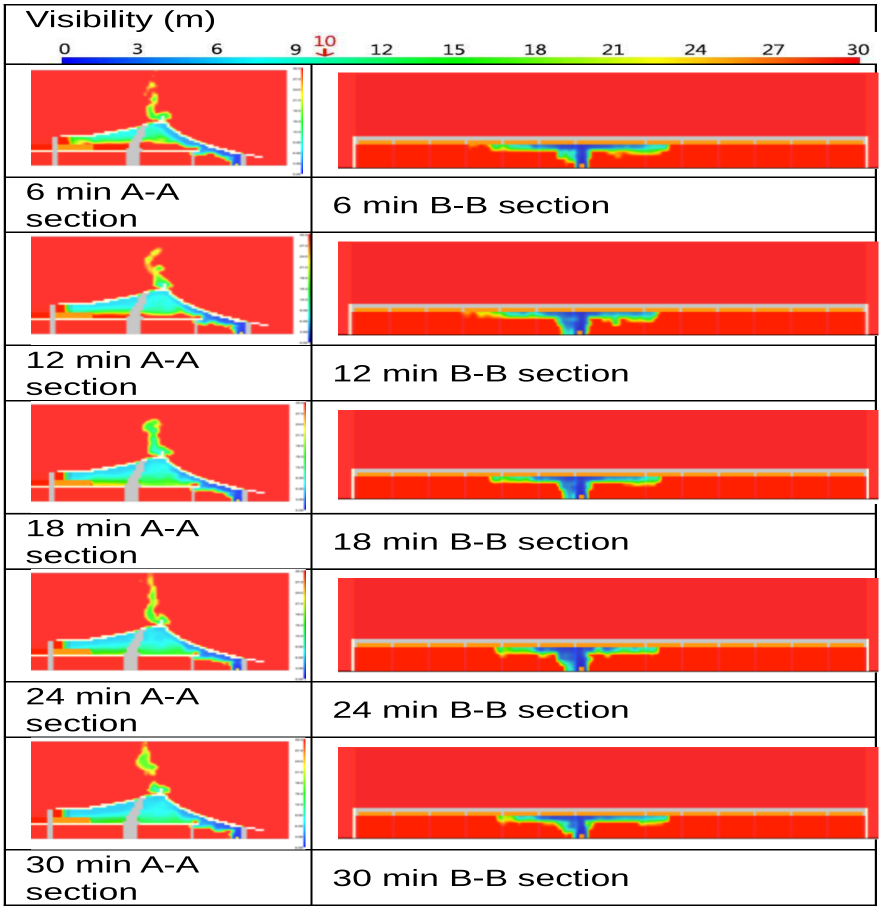

Figure 9. Relation between visibility and time – Group A1.

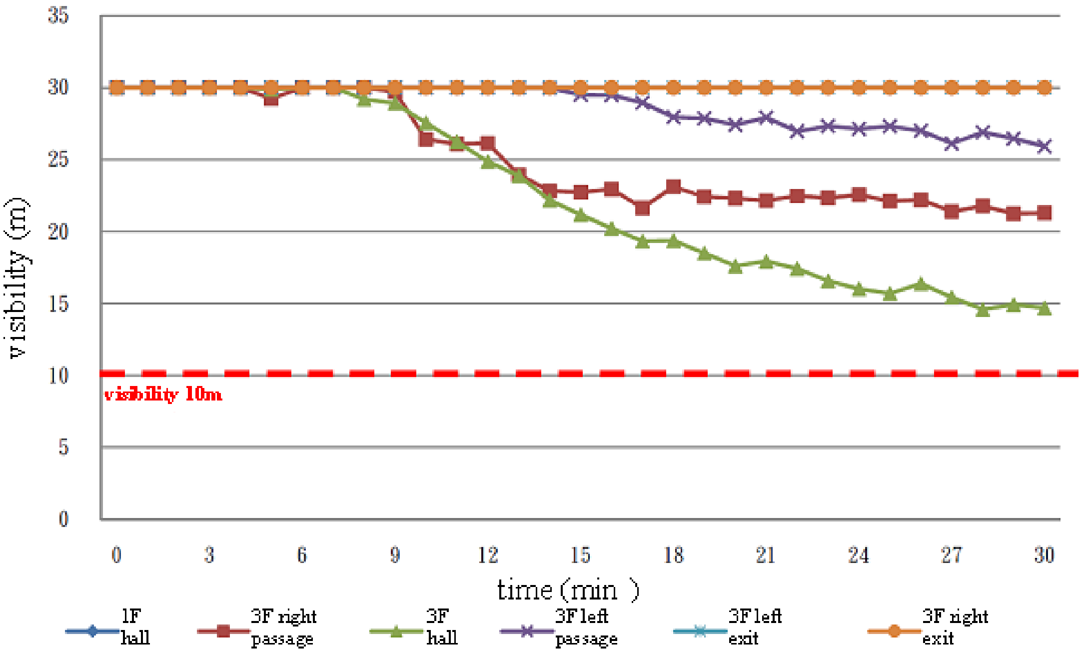

Figure 10. Visibility-time curve – Group A1.

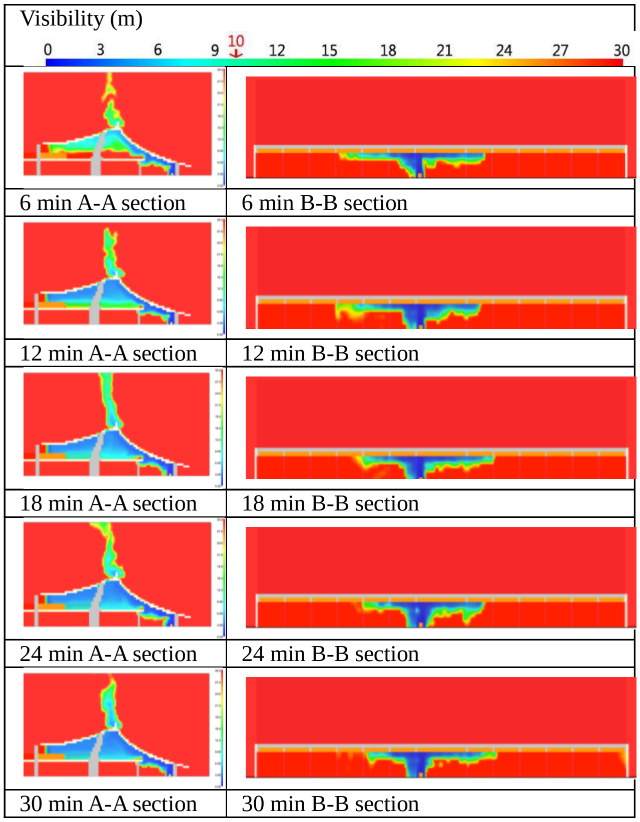

Figure 11. Relation between visibility and time – Group A2.

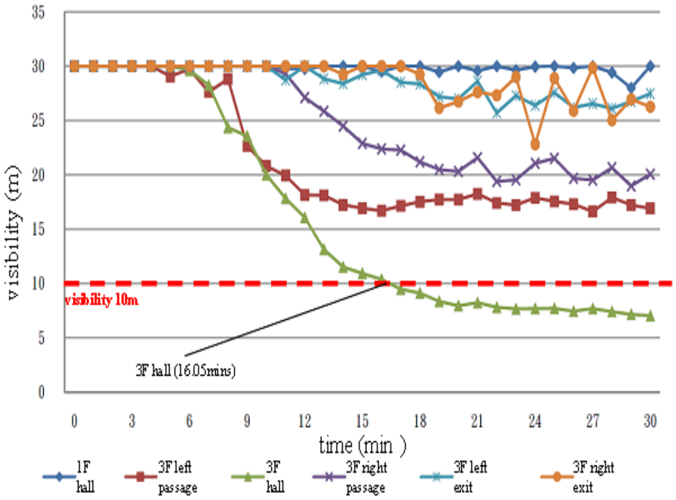

Figure 12. Visibility-time curve – Group A2.

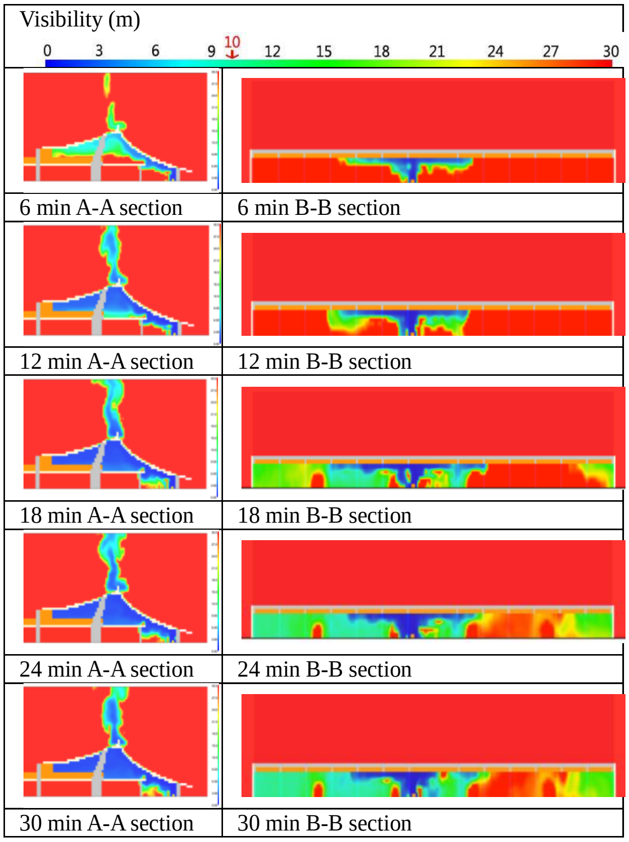

Figure 13. Relation between visibility and time – Group A3.

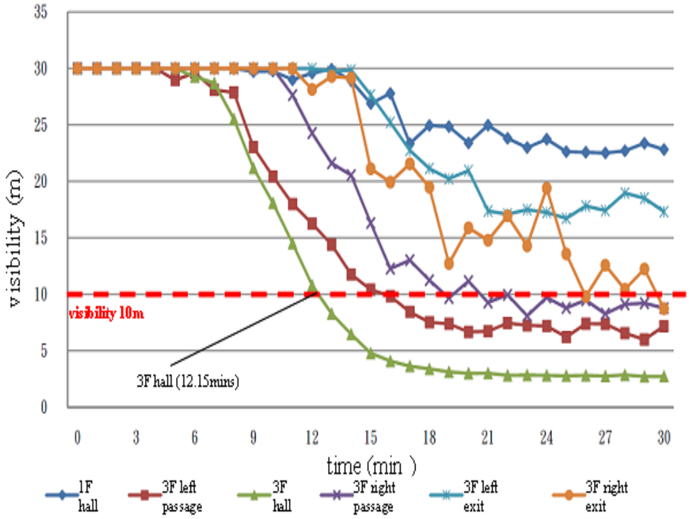

Figure 14. Visibility-time curve - Group A3.

Calculation of evacuation time

As the large space includes the departure hall on the first floor and the arrival hall on the third floor, all persons on both floors have to evacuate in cases of fire. Given that the space is vast and the actual fire origin is thus more uncertain than in usual situations. Considering these findings, the estimation of evacuation time is considered in two different settings: 1) to regard the first and third floors as the same space, and 2) to regard the first and

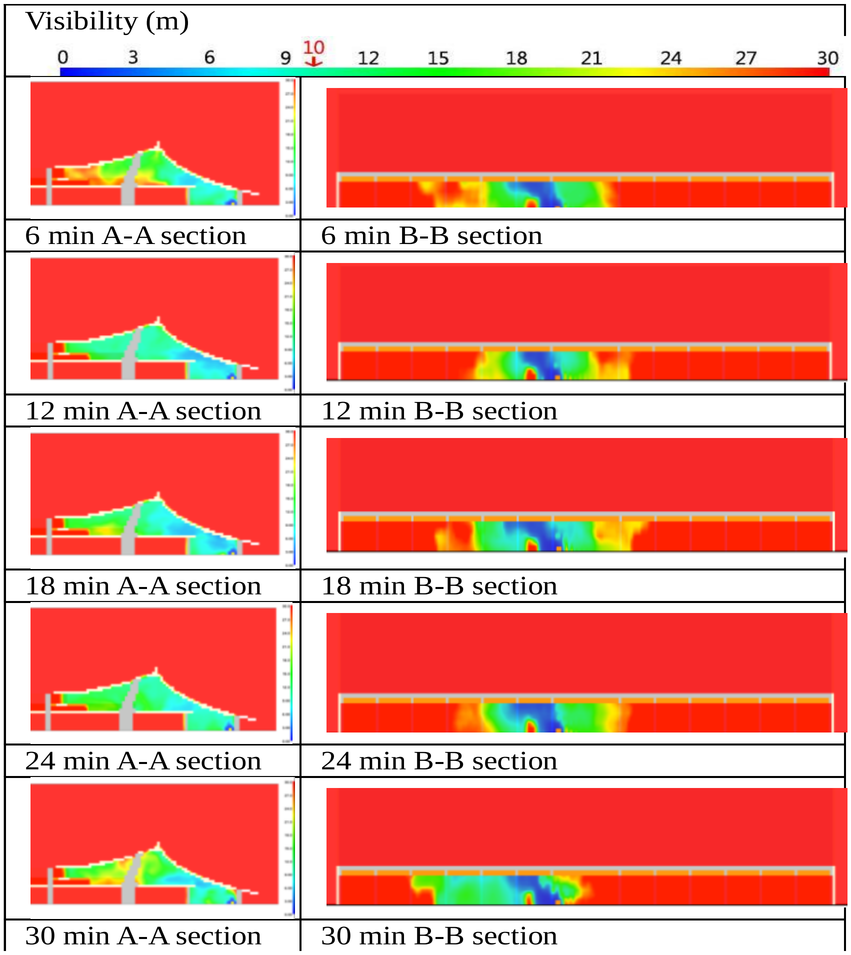

Figure 15. Relation between visibility and time – Group B1.

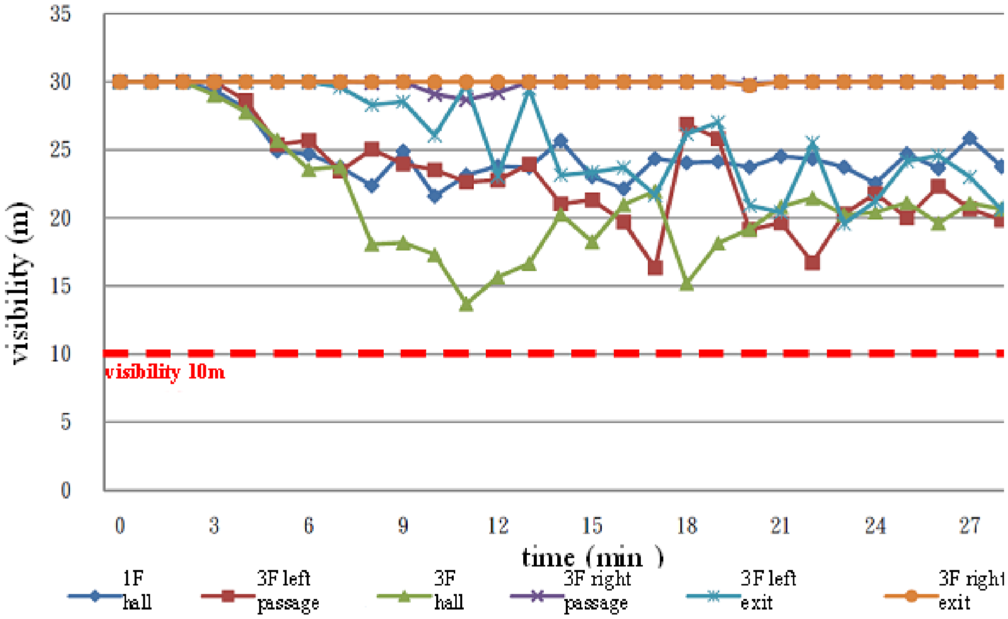

Figure 16. Visibility-time curve – Group B1.

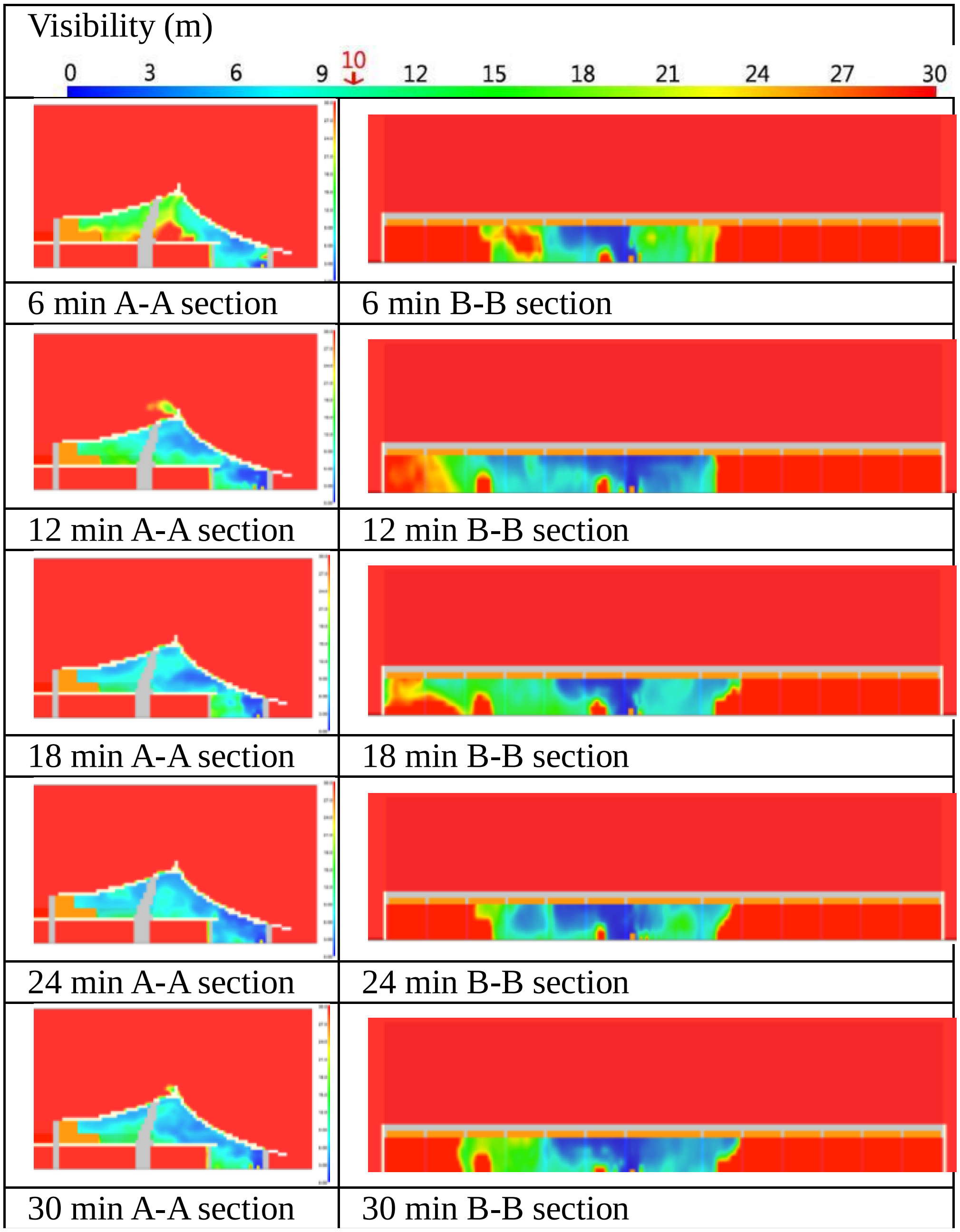

Figure 17. Relation between visibility and time - Group B2.

third floors as two separate spaces. Subsequent to calculation, the estimated evacuation time is indicated in Table 6; the longest evacuation time (that is, 29.6 min) serves as the time limit of simulation.

Conclusion

Furthermore, if one cross-matches simulation results of the six groups of fire scenario and required time of the two evacuation modes, one may conclude that in Groups A1 and B1, where the scale of fire is 2,000 kW, the visibility at any part of the space is never lower than 10 m in the entire course of simulation, hence no difficulty of finding evacuation route.

By comparing the visibility-time curves of Groups A and B in 5.1, one may conclude that the presence of external airflow significantly influences natural smoke ventilation. On the first floor, the flow of headwind comes in directly through entrances and exits, causing the flow of smoke in certain parts to be disturbed and hence an early decrease in visibility. On the third floor, the upper ventilation

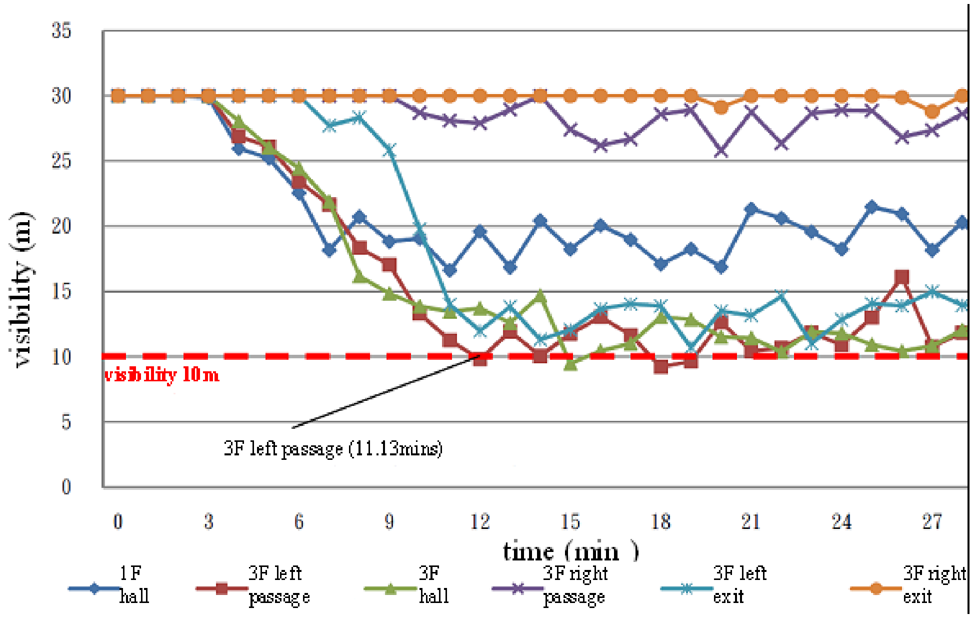

Figure 18. Visibility-time curve - Group B2.

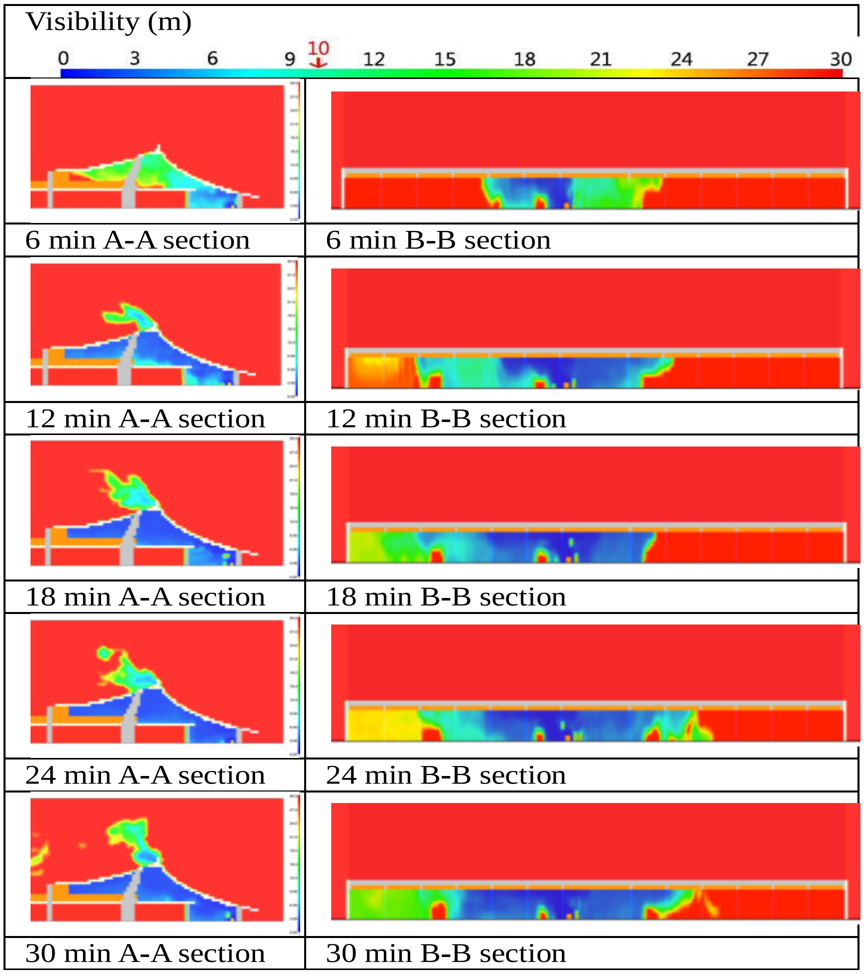

Figure 19. Relation between visibility and time - Group B3.

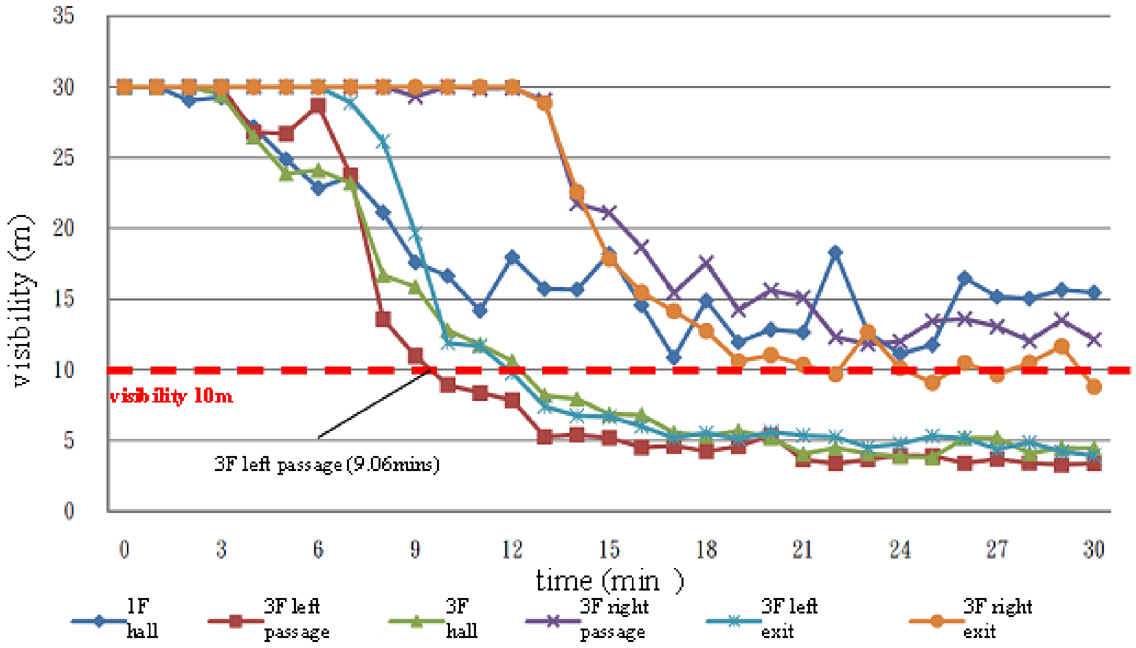

Figure 20. Visibility-time curve - Group B3.

Table 6. Calculation of evacuation time.

Evacuation time	As one combined space	As two separate spaces	
	1F+3F	1F	3F
Initiation of evacuator's attempt to escape	6.12	4.76	5.57
Time to travel to safe areas	1.58	0.81	1.58
Time for evacuator to escape through the exit	21.9	6.00	11.23
Time required to escape to safe areas	29.6	11.58	18.38

Unit: minute.

vents function less effectively with less pressure difference when influenced by headwind, resulting in slower ventilation and faster accumulation and descending of smoke.

As for Groups A2 and B2 (5,000 kW) and Groups A3 and B3 (25,000 kW), natural ventilation facilities fail to ventilate the amount of smoke and to meet the goal of evacuation safety within the simulated evacuation time. Considering results and analysis of the aforementioned simulations, the result are concluded that:

1) When directly affected by headwind, entrances and exits on the first floor pose danger to the safety of certain parts of the floor;
2) When directly affected by headwind, natural smoke ventilation becomes weaker than when unaffected;
3) In the case study, natural smoke ventilation proves effective under the premise that the scale of fire is less than 2,000 kilowatts; in case that the scale of fire is larger, it is suggested that smoke control strategies be bettered to meet the objective of evacuation safety.

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