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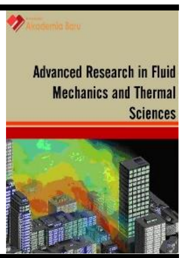

Reversible Longitudinal Smoke Extraction System in Enclosed Underground Parking Structure

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Kong Kok Haw[1], Chong Wen Tong[1,*], Koh Voon Li[2]

[1] Department of Mechanical Engineering, Faculty of Engineering, University of Malaya, Malaysia, 50603 Kuala Lumpur, Malaysia
[2] Leong Poon & Assoc (M) Sdn Bhd, A-3A-5, Block A Setiawalk, Persiaran Wawasan, Pusat Bandar Puchong,47160 Puchong, Selangor, Malaysia

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ABSTRACT

City urbanization induces many mega mixed development projects. Expansion and utilization of the underground space is an alternative to overcome the cost of super-high-rise buildings. Storing and managing vehicles in underground space predispose these buildings to fire hazards. Some passive requirements stated in Uniform Building By-Law Malaysia 1984 are difficult to comply with. Limitations in allocating fan rooms and large duct work design are some of the major drawbacks in the design of a large enclosed underground parking structure. Because the reversible longitudinal smoke extraction systems are well applicable to trains and road tunnels, this paper investigated the performance of this smoke extraction system in a confined long and flat underground parking structure and enlarging the fire compartmentation by four times. In this reversible scheme, fan shafts installed at fire zones are operated as extraction shafts, whereas fan shafts positioned in adjacent areas are running as make-up air. Results showed that the reversible longitudinal smoke extraction system is applicable to retain the smoke within the fire zone in the underground parking structure.

Keywords:
Performance-based approach, fire safety engineering, reversible smoke management system, CFD simulation, underground parking structure

1. Introduction

The quick pace of urbanisation exerts increasing pressure on the limited land space of cities. To circumvent the shortage of land mass, super-high-rise skyscrapers are becoming the go-to solution to meet the population demand. Often, these buildings also extend downwards to include the underground spaces [1]. Because the ownership of private cars is on the rise in major metropolis, such as Kuala Lumpur [2], many underground spaces are used as parking facilities. The increasing prevalence of underground parking structures in modern cities requires intense study and modern engineering to minimize hazards and increase safety of residents.

* *Corresponding author.*
E-mail address: chong_wentong@um.edu.my (Chong Wen Tong)

The confined nature of underground parking structures predisposes them to fire hazards [3]. Whenever a fire breaks out in an underground parking facility, a large amount of smoke is trapped in the building along with rising ambient temperature, leading to difficulty in evacuating the public and providing access for firefighters [4]. Nowadays, the fire risk potential can be assessed through fire modelling analysis/practice/procedure/method, which is generally divided into three categories [4]. The first category is the empirical method, which involves costly and risky experimentations. The second category is the zonal method, which is based on the characteristics of the fire, such as its stratification. The final method is the computational fluid dynamics (CFD) analysis, which can be based on finite difference, finite element or finite volume methods.

Conventional ventilation systems are known to have poor performance in clearing out large volume of smoke that causes the difficulties in evacuation and firefighting due to low visibility [6]. Due to the emergence of many large and mega mixed development projects, many prescriptive fire safety requirements are difficult to comply with. For example, the dead-end travel distance limit, travel distance to exits, and fire rating compartmentation on the passive protection requirement. In Malaysia, fire safety requirement for underground parking structures is stated in the Malaysia Uniform Building By-Law (UBBL) 1984 [7][8]. Table 1 and Table 2 show the maximum travel distance and the fire compartmentation allowed by the UBBL.

Table 1
Part of seventh schedule of UBBL 1984: maximum travel distance [8]

Purpose Group	Limit when alternative exits are available (m)		
	Dead-End Limit	Unsprinklered	Sprinklered
Storage and general			
Low and Ordinary hazard	15	30	60
High Hazard	10	20	35
Parking Garages	15	45	60
Aircraft Hangars (Ground Floor)	15	30+	45+
Aircraft Hangars (Mezzanine Floor)	15	20	20

Table 2
Part of ninth schedule of UBBL 1984: limits of compartments and minimum periods of fire resistance for elements of structure [8]

Purpose Group	Maximum dimensions			Minimum period of fire resistance (in hour) for elements of structure forming part of:	
	Height (m)	Floor area (m^2)	Cubical extent (m^3)	Ground storey or upper storey	Basement storey
Storage and general	7.5	150	NL	1/2	1
	7.5	300	NL	1/2	1
	15	NL	1700	1	1
	15	NL	3500	1	2
	28	NL	7000	2	4
	28	NL	21000	4	4
	over 28	1000	NL	4	4

'NL' means no limit

The escape staircases are normally located at the perimeter of the parking structure where the discharge is directly to the exterior of the building. In a large enclosed underground parking structure, the dead-end limit and travel distance from middle to the escape staircases are difficult to be met. On the fire compartmentation requirement, a large parking structure is divided into few smaller pocket fire compartments. When fire occurs, fire shutters will be activated and closed up the space into smaller compartments. A smaller compartment will be filled up with smoke in shorter period and reduces the visibility for escape.

Confined fire compartment creates confusion and causes panic to the occupants during fire emergency escape. Furthermore, occupants from adjacent fire compartments have less perception on the actual fire location and may run toward to the fire zone instead of away. Occupants in their vehicle would prefer to escape by driving to the exit of the parking structure. Shutting down the exit way by fire shutters will cause confusion and panic to the drivers.

1.1 Performance-Based Approach (PBA)

Other than the prescriptive codes, fire safety engineering research introduces the performance-based approach (PBA) within the regulation, which allows more flexibility and cost-efficiency in design [9]. A PBA of fire safety needs to comply with the fundamental objective that prescriptive measures adhere to [10]. The PBA in designs is gaining acceptance internationally as countries such as New Zealand, United Kingdom and Hong Kong have already implemented the performance-based code for fire safety [11]. The codes are more flexible, innovative, more functional, less complex, and easier to apply in achieving code objectives and safety criteria [12]. Many designers propose or implement the PBA in their designs. In Sweden, a group of researchers proposed a framework of road tunnel fire safety based on the PBA design derived from Swedish and European regulation [13]. The overall purpose of the framework is to protect life, health, property, environment, and key societal functions from fire while fulfilling the prescriptive requirements. Similarly, Zhou *et al.,* studied the implementation of a PBA fire protection design of ruins protection pavilion based on air-supported membrane structure in China [14]. By means of combustion experiment and numerical simulation, they carried out fire risk analysis of air-supported membrane structure, smoke spread process, and safe evacuation analysis in fire scenes. They showed that, personnel evacuation can be achieved before the untenable condition. Therefore, the PBA fire safety is a better alternative to the conventional approach as long as the prescriptive objective is satisfied.

1.2 Smoke Extraction Systems in Tunnels

Longitudinal smoke extraction systems are widely used in trains and road tunnel designs. Carvel reported on the influence of forced longitudinal ventilation on car fires [15]. Wu [15] and Modic [16] studied and simulated the critical velocity of forced ventilation in preventing back layering of smoke in road tunnels. Many ventilation strategies such as longitudinal, semi-transverse, transverse, partial transverse and combined longitudinal and semi-transverse ventilation systems were studied by Jojo Li [17]. A numerical 3D simulation and the full-scale tests, which use reversible longitudinal ventilation system, were carried out by Vega on the Memorial Tunnel [19]. Results showed that the simulation is in compliance with the full-scale tests.

1.3 Smoke Extraction System in Parking Structure

The challenge for a large underground parking structure is the positioning of the exhaust fan shafts, which the inlet is limited to the perimeter of the basement, and the outlet of the fan shafts should be positioned above ground level and to the external of the building. To effectively discharge the large volume of smoke during a fire incident, large exhaust air ducts are required in the basement. Higher headroom space is required to house the exhaust large air duct and deeper underground space increases the construction cost. In the absence of such setup/system, smoke takes a longer period to travel from one end to the other end of the exhaust system, and the cooling of smoke front layer reduces the smoke clearance height.

A normal mode reversible ventilation system in a parking facility was studied by Chen [20]. He demonstrated that the reversible longitudinal effect is able to remove the contaminated air more effectively than the conventional uni-directional method. Faiz carried out an evaluation of large eddy simulation in underground parking structure, compared between constant and adiabatic wall thermal boundary conditions [21]. He demonstrated via Fire Dynamics Simulator (FDS) that the constant temperature thermal boundary produced the maximum heat transfer and recommended to be adopted for subsequent analysis.

The longitudinal smoke extraction system in tunnel is very effective due to a confined tube structure. This paper investigated the application of the reversible longitudinal smoke extraction system for a large enclosed underground parking structure without fire compartmentation. This proposal deviates from the UBBL and provide a flexibility solution of smoke management system and fire safety in a large underground parking structure.

2. Methodology

2.1 Details of Case Study

A case study was carried out for an enclosed underground parking structure encompassing 130,734 m^3 in volume. The floor height was 3 m. The length and width were approximately 560 m and 80 m, respectively. It was shaped like a long flat tunnel. Figure 1 shows the plan view of the enclosed underground parking structure. The area was provided with an automatic water sprinkler system. This parking structure is originally provided with 4 compartments. The fire compartment walls were removed and merged into single large compartment as indicated in Table 3.

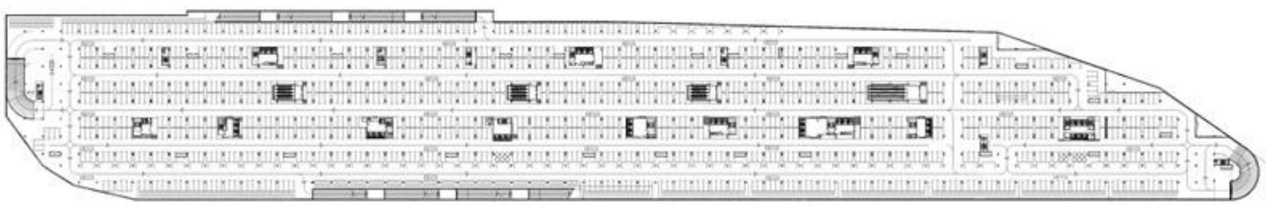

Fig. 1. An enclosed underground parking structure with a volume of 130,734 m^3

Table 3
Tabulation of fire compartmentation volume for compliance to UBBL and performance base approach

Compartment	Effective Volume (m^3)	
	Compliance to UBBL	PBA
Compartment 1	36,447	130,734
Compartment 2	37,704	(all for compartments are combined into single compartment)
Compartment 3	35,541	
Compartment 4	21,042	

Possible fire scenarios for a parking structure in the basement could include either a car catching fire, or fire erupted from one of the storerooms, plant rooms, switch rooms or bulk fuel storage rooms in the parking facility. However, the latter scenarios are usually compartmentalized, and the fire is restricted to the room where it originated. Therefore, fire originating from vehicles is considered as the greatest risk to the occupants in an underground parking structure.

An automatic sprinkler system is provided in areas/zones and corresponded to the active smoke management systems. Activation of the sprinkler system will automatically initiate the occupant warning system and the smoke management systems.

2.2 Design Principles of a Reversible Longitudinal Smoke Extraction System

The smoke extraction system was operated in the longitudinal direction based on zoning. The long underground space is divided into 5 segments. There was a total of 23 fan shafts scattered throughout the parking structure. Each fan shaft was equipped with smoke spill fans up to 21 m^3/s flow rates, but the reverse direction was de-rated to 70%. These fans were reversible. The floor was divided into five virtual smoke zones based on the fire scenario. Fan shaft operations were programmed to the virtual smoke zones demarcation and activated by the sprinkler system in response to zonal sprinkler flow switch. There were six fan shafts working in exhaust mode within the fire zone, whereas the rest of the fan shafts were in make-up air mode (maximum of up to 8 fan shafts).

Each fan shaft was extended on both sides through ducts to delocalise the extraction points (i.e. to provide a better spread of extraction points). Each point served as an extraction or supply point. The smoke zone demarcation and numbering of fans shafts for the underground parking structure are shown in Figure 2, and Table 4 shows the fan operating scheme in the event of fire.

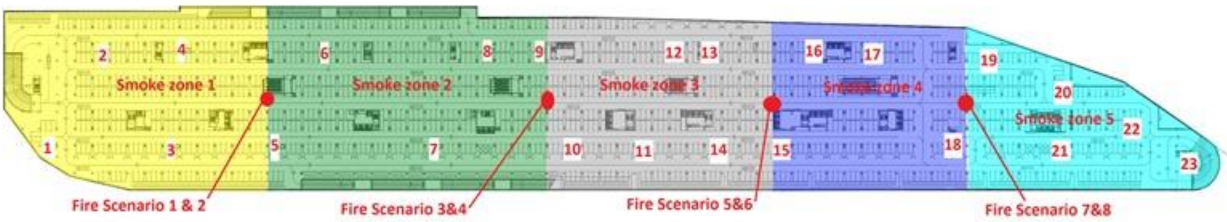

Fig. 2. Smoke zone demarcation and fan shaft numbering

Table 4
Smoke spill fan shaft operation schedule during fire mode

Smoke zone on fire	Fan shaft 1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23
1	E	E	E	E	E	E	S	S	S	S	S	S	S	S	X	X	X	X	X	X	X	X	X
2	S	S	S	S	E	E	E	E	E	E	S	S	S	S	X	X	X	X	X	X	X	X	X
3	X	X	X	X	X	X	S	S	S	E	E	E	E	E	E	S	S	S	S	X	X	X	X
4	X	X	X	X	X	X	X	X	X	S	S	S	S	E	E	E	E	E	S	S	S	S	S
5	X	X	X	X	X	X	X	X	X	S	S	S	S	S	S	S	S	E	E	E	E	E	E

'E' represents exhaust fan, 'S' represents supply fan and 'X' represents non-operation fan

2.3 Evaluation and Analysis

Quantitative analyses, which included computer simulation of fire development and smoke spread, were undertaken for the parking structure. For the assessment of the underground parking structure, the Fire Dynamics Simulator (Version 5) was used to model the fire scenarios [22]. The NIST field model Fire Dynamics Simulator (FDS) is a computational fluid dynamics (CFD) model of fire-driven fluid flow. The FDS software is appropriate for low-speed, thermally-driven flow with the emphasis on smoke and heat transport from fires. The FDS model used is a deterministic 'fire model', which is commonly used to predict the spread of heat and smoke in an enclosure or multiple enclosures. Visual presentation of the FDS simulation modelling results was provided using the 'smoke view' program [22].

For the fire modelling, all assumptions were based on practices nominated in the International Fire Engineering Guidelines and practical simplifications were incorporated to maintain a conservative element to the fire safety engineering assessment [23].

For the purpose of this assessment, a conservative 4.5 MW car fire was adopted as the worst-case scenario. Fire growth rates were predicted according to the BHP car fire (shown in Figure 3) [24]. The summary of simulation parameters is tabulated in Table 5.

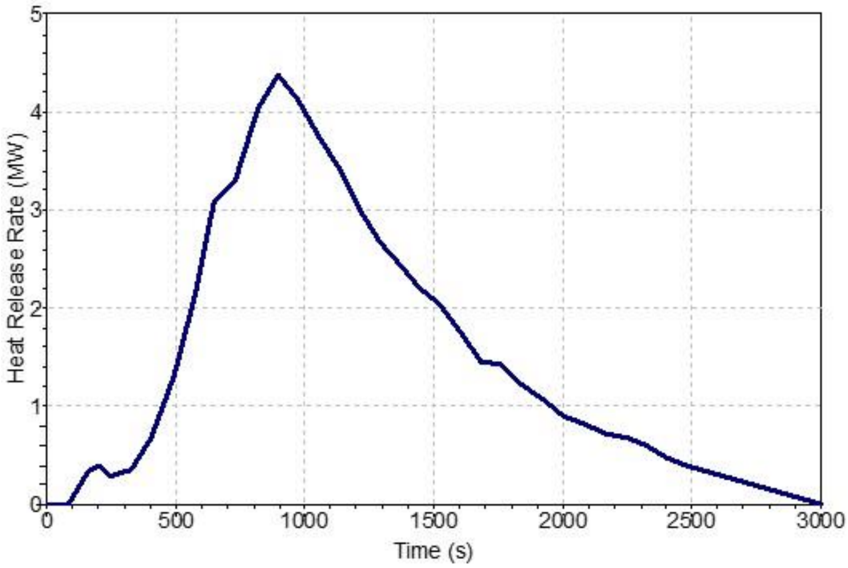

Fig. 3. Heat release rate of car fire

Table 5
FDS simulation parameters

Description	Design Parameter
Simulation Software	FDS Version 5
Design Fire Size	4.5 MW
Fire Growth Rate/Curve	NFPA T^2 fire curve - fast fire growth rate
Soot Yield	0.1 kg/kg
Fire Location	Remote location to exhaust points
Fixed Extinguishing System	Automatic Sprinkler System
Smoke Exhaust Scheme	Mechanical Ventilation
Smoke Exhaust Rate	Up to 6 numbers of fan shafts to 126 m^3/s for underground parking structure
Occupants walking speed	1 m/s
Rate of escape of staircase	1 person/s

2.4 Acceptance Criteria and Factors of Safety

The acceptance criteria was based on the British Standard PD7974:2003 [24] and Society of Fire Protection Engineers (SFPE) handbook [26], where the performance levels are determined for a limiting height of 2.1 m from the floor. These criteria are summarized in Table 6.

Table 6
Summary of acceptance criteria

Description	Acceptance Criteria
Soot visibility	Minimum 10 m for occupant/fire fighter
Air Temperature	• Less than 60°C for occupants • Less than 200°C for close proximity fire fighting
Smoke Layer Height	2.1 m
Radiant Heat Exposure	Shall not exceed 2.5 kW/m^2 (corresponds to a hot layer temperature of 180-200°C)

The safety factor is defined as the ratio of available safe egress time (ASET) to required egress time (RSET). For this study, a safety factor of 2 was used, as recommended by the National Fire Protection Association (NFPA) 101 Fire Safety Code for use in life safety assessment in large and complex public buildings [27].

3. Results and Discussion

3.1 Evacuation Simulation

The population density for the underground parking level was based on 10 m²/person for Car Park/Storage categories [7]. Thus, for the area of 43,578 m^2, the occupancy population was calculated as approximately 4,358 persons. The rate of discharge was assumed as 1 person per second for each of the staircase. With 18 m width of exit from the basement floor (excluding staircase), the movement time from the evacuation simulation was 252 seconds.

The alarm detection time for the underground parking structure was based on the activation of the sprinkler system. The sprinkler activation time was conducted based on the ceiling height of 3 m. The alarm time as determined by the ceiling jet temperature was 321 seconds based on medium t^2 fire growth rate [28]. The results of the evacuation analysis are presented in Table 7.

Table 7
Summary of evacuation analysis

Parameter	Time (s)
Detection time	321
Pre-movement time	180
Movement time	252
Total Required Egress Time	753

3.2 Fire and Smoke Simulation

The spread of the smoke has been modeled within the underground parking structure by FDS. Various scenarios were simulated and studied. Fire scenario 1 and 2 represent the same point of fire with different shaft operations during the fire mode. The same conditions were presented in fire scenario 3 and 4, fire scenario 5 and 6, and fire scenario 7 and 8. The arrangements of fan shaft operation are tabulated in Table 4. The results and discussion for these scenarios are discussed in the following sub-sections.

3.2.1 Temperature

The temperature distribution at the center of the fire for all scenarios is plotted in Figure 4. The peak temperature for all scenarios occurred at approximately 900 s, which was consistent with the heat release rate (Figure 3) adopted in the simulation. It was observed that for fire scenario 1, the temperature distribution was significantly lower than others. This is because the fire location is in close proximity to the exhaust point.

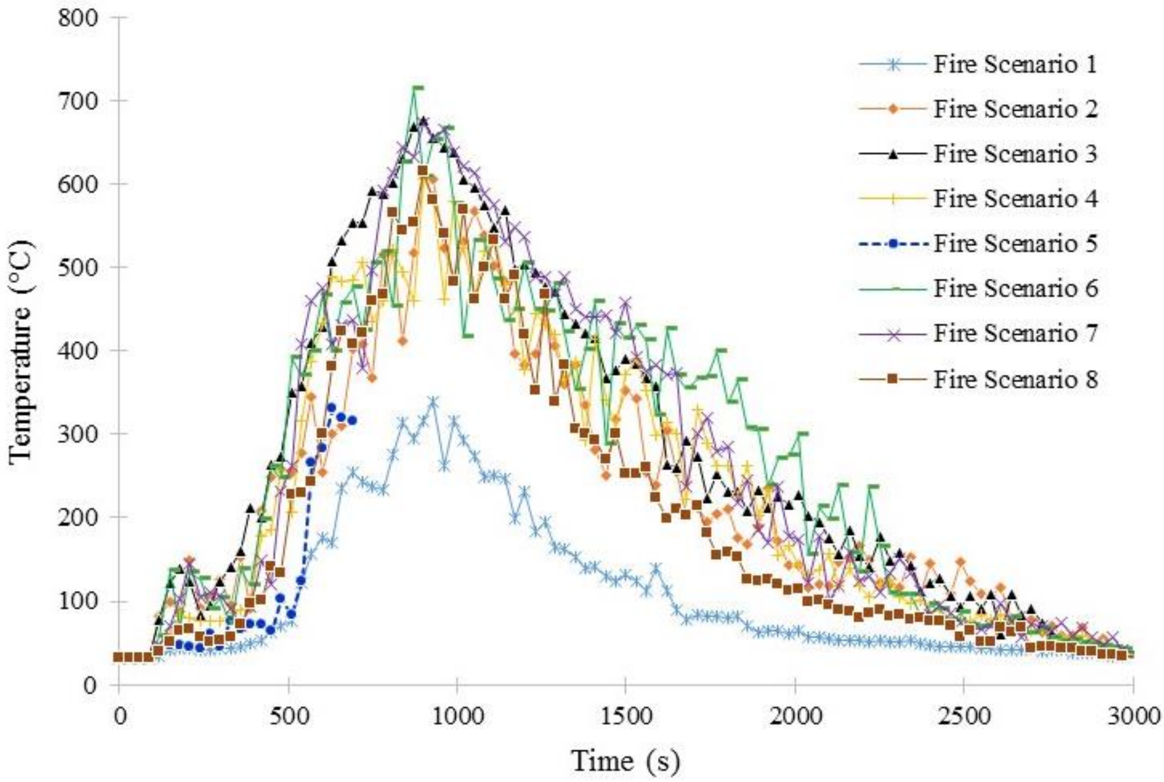

Fig. 4. Temperature distribution at the centre of fire for fire scenarios 1 – 8 at the underground parking structure

Figure 5 illustrates the temperature distribution visualizations at the height of 2.1 m and 750 s for all fire scenarios. During the initial 750 s, the temperature was kept at 60 °C before increasing rapidly at 900 s. This condition was deemed acceptable because a period of 13 min of the initial stage was considered as a safe time frame for evacuation from an underground parking structure [6].

3.2.2 Soot visibility

The production of soot is one of the most important factors in the study of underground fire. Heavy smoke is known as the major cause of deaths during a fire incident, where victims fail to escape due to bad visibility caused by soot particles [6,29]. Figure 6 to 13 depict the soot visibility visualization for scenarios 1 to 8, respectively. Generally, visibility for all scenarios was at the lowest level in the period between 750 s to 2000 s. Results showed that the spread of soot particle could be controlled with dedicated fan operations at different zones. During the heaviest smoke period (750 s to 2000 s), soot particles were retained in the designated fire zone. For example, fire scenario 1, the smoke was retained and exhausted at fire zone 1 throughout the period, and only minimal amount of smoke spread to adjacent fire zones. Similar results were observed for other scenarios.

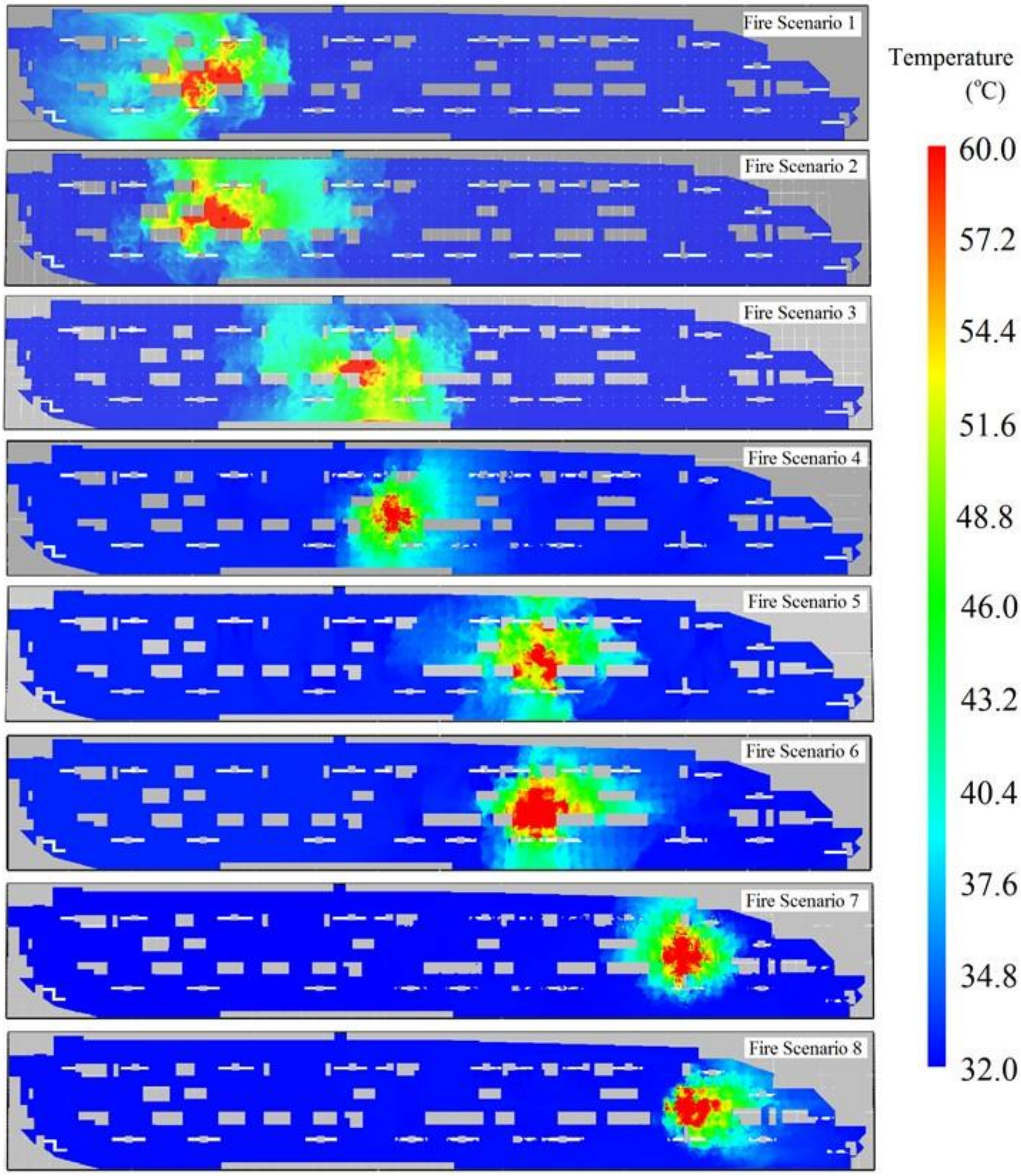

Fig. 5. Temperature distribution visualizations at the height of 2.1 m and 750 s

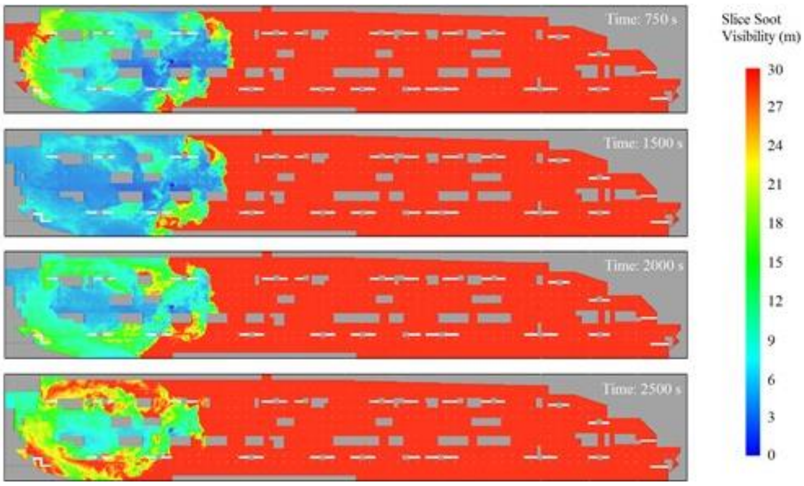

Fig. 6. Soot visibility simulation results slice cut at 2.1 m from floor level at time 750 s, 1500 s, 2000 s and 2500 s for fire scenario 1

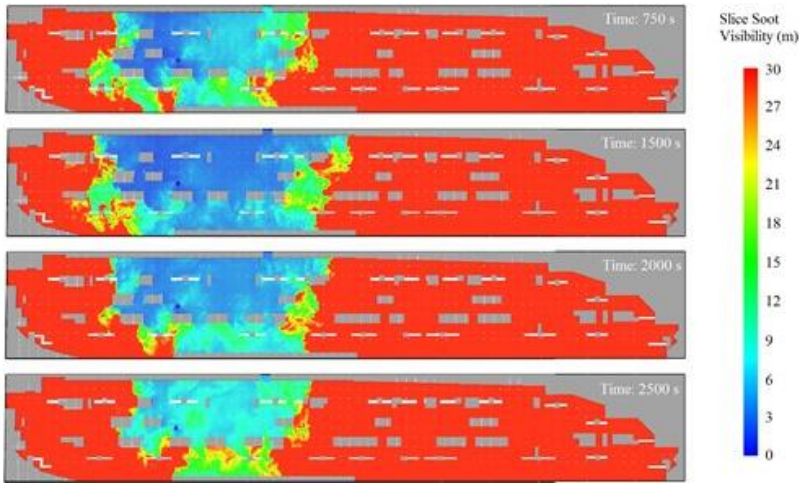

Fig. 7. Soot visibility simulation results slice cut at 2.1 m from floor level at time 750 s, 1500 s, 2000 s and 2500 s for fire scenario 2

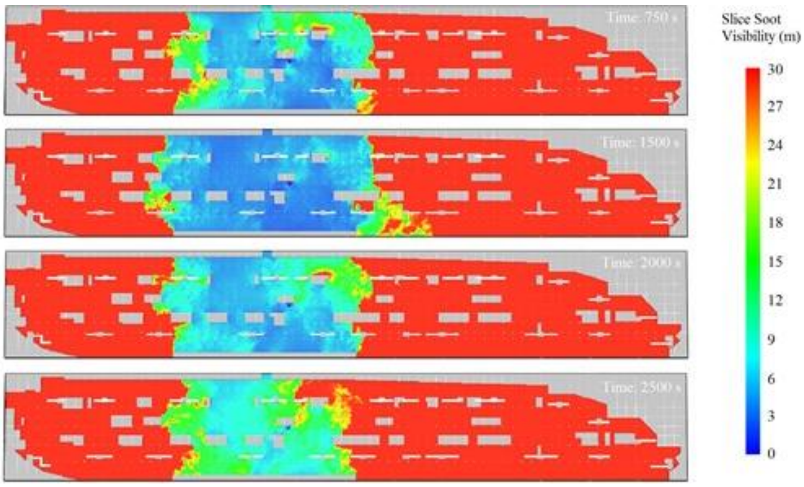

Fig. 8. Soot visibility simulation results slice cut at 2.1 m from floor level at time 750 s, 1500 s, 2000 s and 2500 s for fire scenario 3

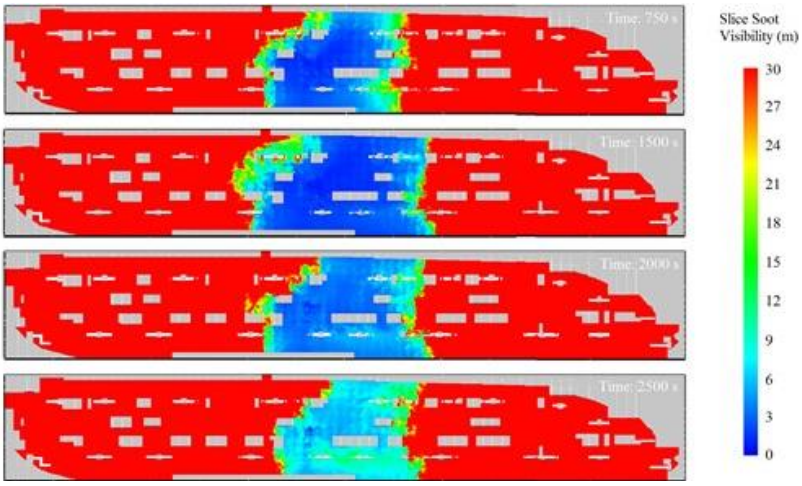

Fig. 9. Soot visibility simulation results slice cut at 2.1 m from floor level at time 750 s, 1500 s, 2000 s and 2500 s for fire scenario 4

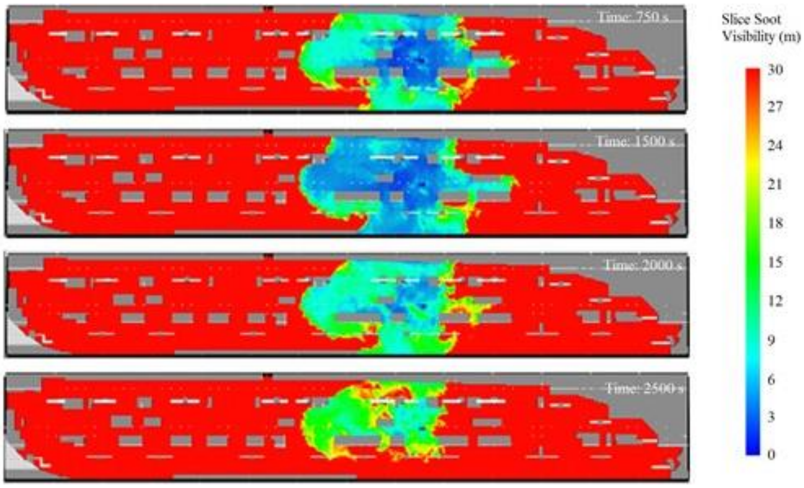

Fig. 10. Soot visibility simulation results slice cut at 2.1 m from floor level at time 750 s, 1500 s, 2000 s and 2500 s for fire scenario 5

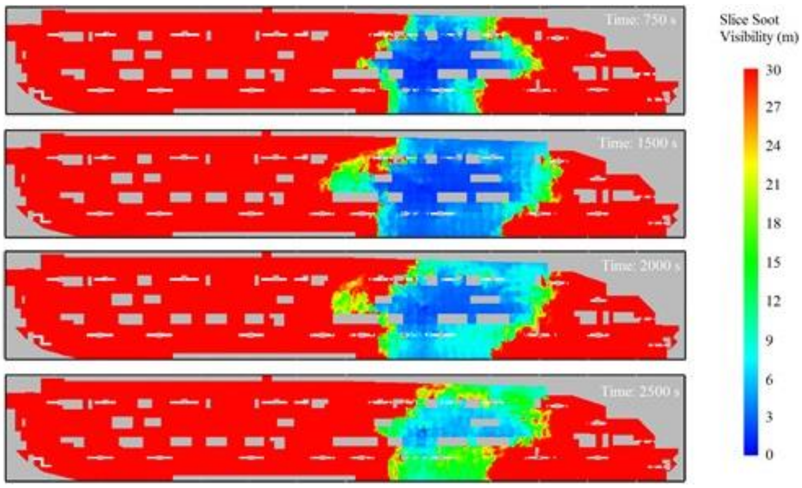

Fig. 11. Soot visibility simulation results slice cut at 2.1 m from floor level at time 750 s, 1500 s, 2000 s and 2500 s for fire scenario 6

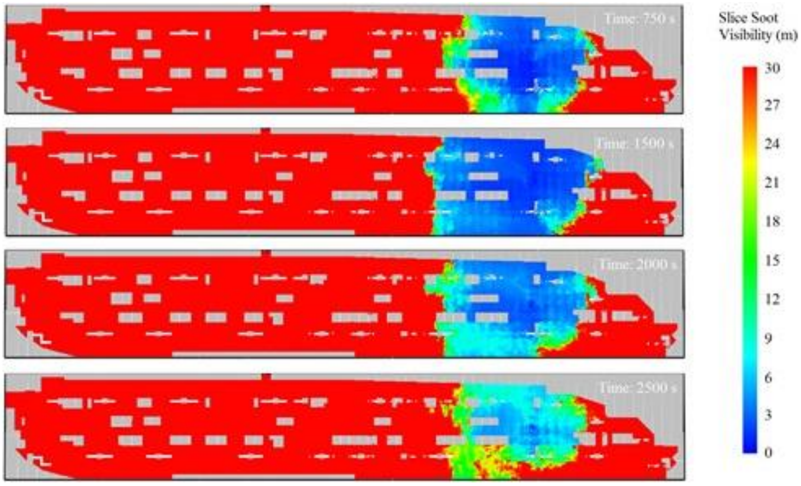

Fig. 12. Soot visibility simulation results slice cut at 2.1 m from floor level at time 750 s, 1500 s, 2000 s and 2500 s for fire scenario 7

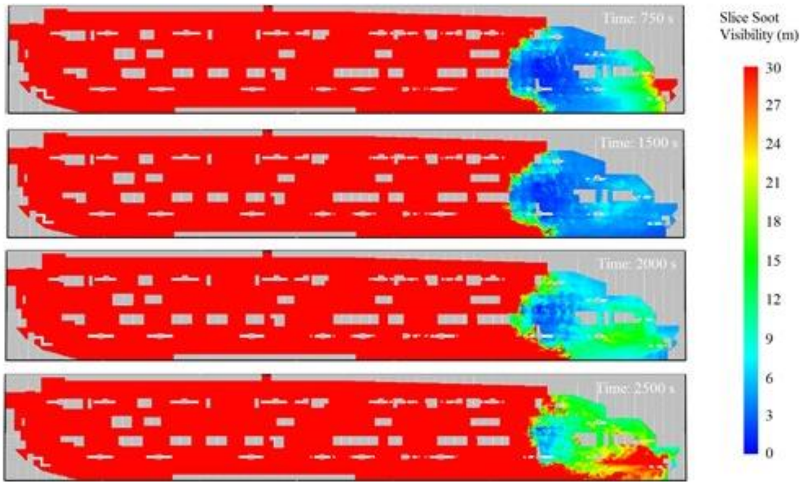

Fig. 13. Soot visibility simulation results slice cut at 2.1 m from floor level at time 750 s, 1500 s, 2000 s and 2500 s for fire scenario 8

4. Conclusions

The evacuation simulation showed that the total egress time was 753 s and the safety factor of 2 was met. The CFD results showed that the spread of smoke from the car fire were controlled by the proposed smoke control scheme. Generally, the results indicated that

i) The reversible longitudinal smoke extraction system retained the smoke within the dedicated zone.
ii) The visibility pattern was such that the accessibility to the fire for fire-fighting was at least within 10 m of the seat of the fire from the leeward side of the fire (i.e. from the side of the makeup air points).
iii) The temperature only exceeded 200°C near the seat of the fire where the plume was located, and thus, allowing the accessibility for firefighters.
iv) Much of the area within the underground compartment was within tenability limits (i.e. ≥ 50% of area) and the non-fire zones were relatively unaffected.

Based on the results of the CFD study, it was concluded that the design proposed for the smoke extraction scheme satisfactorily met the general objectives. This large enclosed underground parking structure meets the fire life safety requirement even though the fire compartment is enlarged four times. The reversible smoke management scheme reduces the large exhaust air duct and thus, cost savings is achieved.

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