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Enhancing Fire Safety in Multiple-Level Basements: Utilizing Computational Tools for Smoke Management

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The process of ensuring basement airflow and explosion safety is currently a critical concern. Designing a smoke management system for a multi-story basement poses a significant challenge for engineers because the basement is located underground, making natural ventilation through openings nearly impossible. Furthermore, the placement of stacking vehicles in the basement increases the risk of fire and smoke spread due to the high density of vehicles in a limited area. To address these challenges, Fire Dynamics Simulation (FDS), a Computational Fluid Dynamics (CFD) tool, was chosen to provide solutions for the combustion process and to predict risks. FDS enables the visualization and prediction of fire scenarios on a large scale without compromising safety or requiring substantial investment. This research aims to predict the efficiency of smoke management in a level-2 basement containing two car stackers in an actual office building in Melbourne, Australia. The model incorporates Very-Large Eddy Simulation (V-LES) for turbulence, with fire modeled using the Heat Release Rate (HRR) of 15 MW and an ultrafast T-square fire growth. The study examines the performance of the smoke management system by considering different criteria relating to temperature, visibility and toxic gas level with an exhaust fan capacity of 4 m^3/s under two scenarios: successful activation of the sprinkler system and failure to activate the sprinkler system. The obtained results show a requirement of better smoke management system in the structure due to the risks to human life in both scenarios.

1. Introduction

According to a report conducted by USFA's National Fire Incident Reporting System (NFIRS), there were 108,500 non-residential building fires annually from 2017 to 2019 in the US (U.S. Fire Administration's National Fire Incident Reporting System, 2010). Building fires are highly destructive disasters, causing human casualties, economic losses, and environmental damage. The risk of fire in multi-story basements poses significant challenges due to limited space, narrow escape routes, and complex ventilation systems. These conditions increase the risk of rapid fire spread and intense smoke accumulation, endangering occupants and reducing the chances of successful firefighting which results in, complicating firefighting efforts. A notable example is the underground garage fire in the Netherlands, which damaged 50 cars and rendered more than 20 apartments uninhabitable, demonstrating the severity of such fires.

The presence of vehicle stackers increasingly used in urban environments pose an additional fire risk due to quick spread and hindrance to emergency response efforts. Notably, the fire at London Luton Airport's multi-story car park, which destroyed around 1,500 vehicles and caused structural collapse, highlights the catastrophic potential of vehicle-related fires (Jomaas, 2024). To mitigate these risks, many fire detection technologies have improved their ability to assess and detect fires. Some fire alarm systems use image-based surveillance technology to detect fires or fire hazards by employing artificial intelligence to analyze the shape and color of smoke and flames such as integration of machine learning algorithms (Li et al., 2021), or logistic regression and temporal smoothing (Kong et al., 2016), helping to reduce false alarm rates (Wu et al., 2022). In addition, oxygen (O_2), carbon dioxide (CO_2), carbon monoxide (CO), and smoke sensor models have been developed and studied by many scientists (Liu et al., 2023), to improve response times and reduce sensor fatigue in high-risk environments (Jana and Shome, 2023). The primary purpose of these studies is to enhance

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fire detection within buildings, improving the intelligence and accuracy of sensors. This allows for more precise identification of fire characteristics without extensive experiments. These systems still face challenges, such as limited visibility due to complex construction layouts, numerous blind spots, or obstructions by objects, leading to missed detections or false alarms. Despite these advancements, gaps remain in fire safety measures for multi-level basements. Current ventilation systems often fall short in managing the rapid spread of smoke and heat, while fire detection systems can struggle with the unique conditions of underground parking structures. Additionally, the regulatory framework requires more detailed guidelines specifically addressing the complexities of multi-level basements with vehicle stackers. Addressing these challenges requires further research and development in fire safety technology, along with the establishment of comprehensive regulatory standards. Conducting fire tests in basement parking areas or buildings is challenging due to space and cost limitations, making it difficult to perform experiments and collect data. With the introduction of Computational Fluid Dynamics (CFD), dangerous situations can be accurately predicted without real-scale experiments (Le et al., 2023) and avoid dealing with the complexities of fire behavior (Duong et al., 2023). To effectively address these complex fire scenarios, the application of CFD modeling is critical. CFD enables detailed simulation of fire dynamics, including heat and smoke propagation, in complex environments such as multi-story basements and vehicle stackers. This advanced modeling approach provides key insights into the implementation of fire protection measures and evacuation strategies, supporting the development of more effective fire safety designs.

This study uses FDS to predict the performance of smoke management systems in a two-story underground car park with vehicle stackers under various fire scenarios. The novelty of this research lies in its application of advanced CFD modeling to simulate fire dynamics, specifically focusing on the unique challenges posed by the presence of vehicle stackers in underground parking basements while existing research on fire safety has largely focused on conventional car parks, with limited studies addressing the additional hazards introduced by vehicle stackers. This research aims to provide critical insights into fire protection measures and evacuation strategies, supporting the development of more effective fire safety designs in such environment.

2. Research Methodology

2.1 Scenario description

The building used in this research is an eight-story mixed-use structure with a two-story basement car park, located in Melbourne, Victoria. Car stackers are installed in two areas of this car park, spanning two stories, as illustrated in Figure 1a. The scope of this model is confined to the basement and a portion of the ground floor, with dimensions provided in Table 1. The model also includes a smoke exhaust system with a capacity of 4 m^3/s and two natural openings through the car lift doors. These mechanical systems are connected to the smoke detection system; hence, the activation of the smoke detector leads to the activation of mechanical ventilation. The sprinkler system is provided throughout the car stacker areas in accordance with AS2118.1 (Standards Australia Limited, 2017). This research evaluates two fire scenarios: the failure of the sprinkler system to activate and the successful activation of the sprinkler system.

Table 1: The dimensions of the building (only the selected part of the simulation)

	Floor area (m^2)	Slab thickness (m)	Elevation (m)	Wall height (m)
Basement 2	700	0.2	- 7.6	3
Basement 1	700	0.2	- 4.6	4.6

2.2 Mathematical representations

2.2.1 Geometry and meshing

The mesh of this model accounts for Basement 2, Basement 1, and the opening on the Ground Floor. The mesh consists of 4,998,874 hexahedral cells with dimensions of 0.1 m x 0.1 m x 0.1 m. The resolution index of this mesh was calculated to be 28.3, as confirmed by a previous study (Vinay et al., 2023), which is significantly greater than 4. Based on this, the cell size was deemed reasonable.

2.2.2 Flow models

The flow in this simulation, which includes air flow from the ventilation system, fire flow, smoke and gas generated from the fire, is solved numerically using the Navier-Stokes equations tailored for low-speed, thermally-driven flow, focusing on smoke and heat transport from fires (Smardz, 2006).

Fires in the parking lots often involve combustible materials such as gasoline, plastics, and upholstery. These materials generate high heat release rates forming the buoyant plumes and rapid expansion of gases, thereby contributing to turbulent mixing. To capture the highly turbulent and unsteady flows found in fires accurately, the

Large Eddy Simulation (LES) model was applied to solve the large-scale flow (Baalisampang et al., 2021). In LES, large turbulent eddies are directly simulated, while smaller ones, which are below the grid resolution (sub-grid scales), need to be modeled. To address this, the sub-grid scale (SGS) model of Smagorinsky was used to solve the smallest scales of the solution numerically (Abdel-Gawad and Ghulman, 2013).

2.2.3 Combustion model and radiative transport

The combustion and fire models for the car were numerically investigated using the mixture fraction model, a conserved scalar quantity that represents the fraction of gas originating as fuel at any point in the flow field. The mixture fraction indicates the proportion of gas that originated as fuel at any point in the flow field. The model includes radiative heat transfer by solving the radiation transport equation for a non-scattering grey gas, occasionally employing a wide-band model. This equation is solved using a method similar to finite-volume techniques for convective transport, known as the Finite-Volume Method (FVM) (Wong et al., 2023).

2.2.4 Devices setup and boundary condition

The model included a car fire, a smoke detector, a sprinkler system installed throughout the car stacker, two supply fans, and two exhaust fans, as described in Figure 2. The operation conditions of the smoke detector and sprinkler system, as well as boundary conditions, are provided in Table 2.

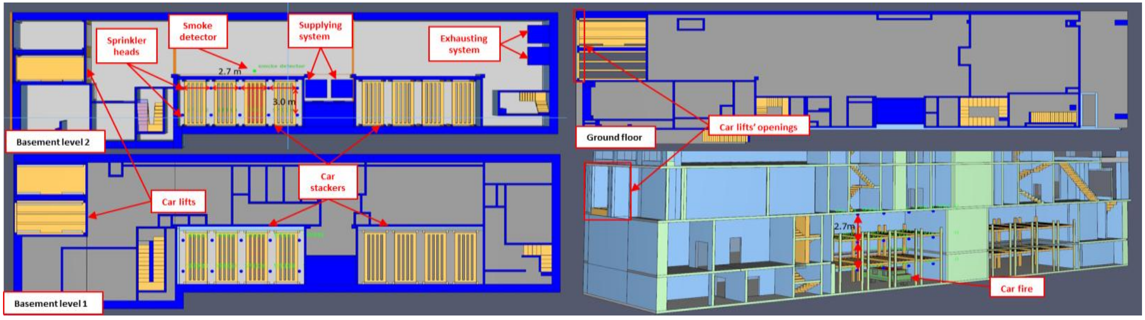

Figure 1: The devices and ventilation system

Table 2: Operating conditions

Operation condition	Model
Solver	3D simulation
	Explicit predictor-corrector scheme
	Second-order accuracy in space and time
Heat Transfer	Radiation transport solver
Viscous model	Very Large Eddy Simulator
	SGS model
Combustion model	Mixture fraction model
	Specified Heat Release Rate
Sprinkler	Generic commercial spray
Smoke detector	Cleary photoelectric P1

Table 3: Boundary conditions

Boundary conditions	Materials	Parameters	Value
Car fire	CO_2	Peak Heat Release Rate (HRR)	15MW
	CO	Fire Growth	
	H_2O		Ultra-fast t^2
	Soot		
Supply fan	Air	Volume Flow Rate	4 m^3/s
		Temperature	20 °C
Exhaust fan	Air	Volume Flow Rate	4 m^3/s
		Temperature	20 °C
Car lift's opening	Air	Pressure	1 atm
		Temperature	20 °C

3. Results and discussion

3.1 Effectiveness of the sprinkler in controlling fire

Figure 3 illustrates how temperature changes in the car stacker in two scenarios over the first 500 s. As shown, the temperature of both cases was similar during the first 130 s. Subsequently, the temperature in the sprinkler-protected case witnessed a significant drop compared to the case where the sprinkler failed to activate. This phenomenon resulted from the extinguishing effect of the water droplets from the sprinkler. These results align with the activation times of the sprinkler system, where the first sprinkler head was activated at approximately 100 s, and all sprinkler heads were activated by around 380 s.

The effectiveness of the sprinkler system is further illustrated in Figure 4, which shows the temperature distribution within the car stacker from both a right-side view. In the first 100 s, the temperature distribution in both cases was similar, with the highest temperature reaching around 600 °C. After this period, a significant temperature difference was recorded between the two scenarios. In the case without sprinkler protection, the highest temperature reached around 870 °C, with the temperature above the car exceeding 300 °C over time. Conversely, in the sprinkler-protected case, the highest temperature reached nearly 670 °C at the fire's origin, after which the temperature decreased to near-ambient levels over most of the car stacker area.

Based on these findings, it can be concluded that the sprinkler-protected scenario shows better performance in controlling the fire at its origin.

Table 4: The temperature within the car stacker

Time (s)	Average temperature in car stacker without sprinklers (°C)	Average temperature in car stacker with sprinklers (°C)
0	20	20
100	69.63	69.7
200	236.92	95.92
234	373.86	107.69 (peak temperature)
314	379.2 (peak temperature)	81.64
400	357.67	88.3
500	350.82	88.3

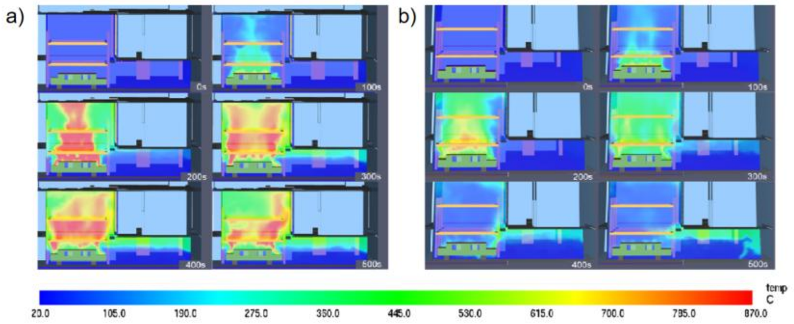

Figure 2: The temperature within the car stacker of (a) without sprinkler protection; (b) with sprinkler protection

3.2 Visibility and Species Concentration

In a fire incident, visibility threats can pose significant risks to individuals' safety and exacerbate the overall emergency situation. Smoke is one of the primary visibility threats in a fire because it can quickly fill enclosed spaces, reducing visibility to zero and making it difficult for people to see and navigate their surroundings. Hence, visibility less than 10 m was chosen as a tenability criterion for this construction based on previous research (Yamada and Akizuki, 2012). Figure 5 shows the visibility of the occupants at the plane z = 2.1 m, where they are expected to see the exit signs. In both cases, the distribution of smoke was similar, with visibility less than 10 m appearing after about 100 s and then quickly covering the entire floor. This occurred because, in the first 100 s, the sprinkler system had not yet activated. After the activation of the sprinkler, smoke still filled the floor area because the small volume of the basement and the capacity of the smoke exhaust fans were not sufficient to control the smoke. It can be concluded that the basement's smoke management strategy needs improvement during the first 100 s of a car fire to ensure better visibility and safer evacuation.

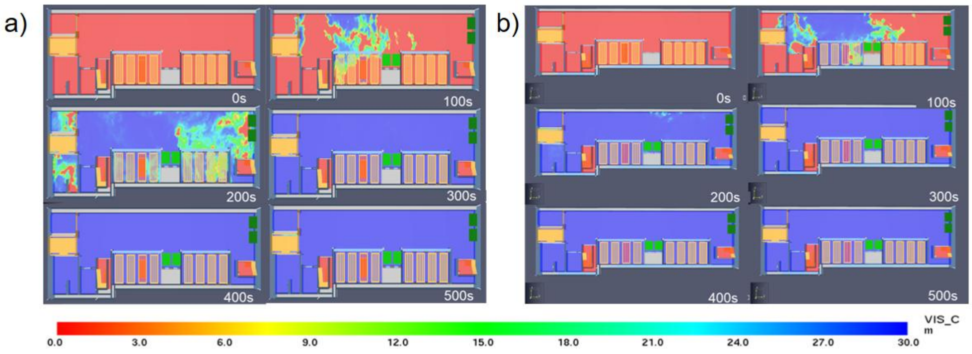

Figure 3: Visibility at plane z = 2.1m of (a) without sprinkler protection; (b) with sprinkler protection

Investigating gas species and soot in a fire incident is crucial for understanding the fire's behavior, assessing risks, and determining mitigation measures. Key gases to monitor included O_2, CO, and CO_2, as the latter two are toxic and pose severe health hazards, while O_2 levels help assess fire severity, ventilation effectiveness, and the risk of asphyxiation. Figure 6 provides the concentrations of O_2, CO, and CO_2 within the basement. In terms of O_2, CO, and CO_2 gases, a similar trend was observed in both cases during the first 200 s While O_2 levels gradually decreased, the concentrations of CO and CO_2 increased due to the fire consuming O_2 to sustain the flame, resulting in the production of CO and CO_2. After this initial period, these gases continued to follow their respective trends in the sprinkler-protected case. The mole fraction of O_2 continued to drop to 0.165, while the fractions of CO and CO_2 increased to over $9.5x10^{-4}$ and 0.0225, respectively. However, in the sprinkler-protected case, the car fire required more O_2 from the basement space to sustain the flame, leading to a significant drop in O_2 concentration and an increase in CO and CO_2 compared to the case without sprinkler protection. The fraction of O_2 rapidly decreased to about 0.15, while CO and CO_2 peaked at about 0.001 and 0.023, respectively. After that, the concentration of O_2 slightly increased, likely because the O_2 consumption rate of the fire decreased as the fire was minimized due to the activation of the sprinkler. In terms of soot concentration, both cases showed similar upward trends in the first 400 s. Subsequently, the soot concentration significantly decreased in the sprinkler-protected case, while the non-sprinkler-protected case continued to show an increase. This phenomenon can be explained by the successful extinguishment of the fire by the sprinkler system, which significantly reduced the soot generation.

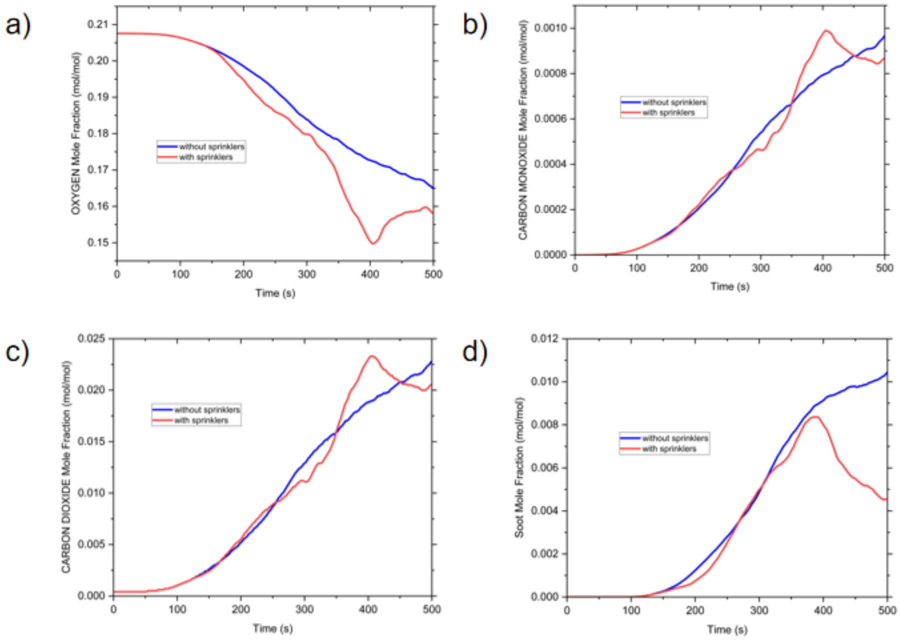

Figure 4: (a) O_2, (b) CO, (c) CO_2, (d) soot concentration within the basement

4. Conclusion

This research employs a detailed numerical investigation of fire safety in a multi-level basement car park using advanced computational tools, including the FDS, the mixture fraction model for combustion, and the V-LES model. Results demonstrate the effectiveness of the sprinkler system, with a significant drop in HRR, and the temperature distribution in the sprinkler-protected case reaching nearly 670 °C, lower than the 870 °C observed in the non-protected scenario. Visibility less than 10 m appeared after about 100 s in both cases, underscoring the need for better smoke management strategies. Further, sprinklers effectively reduced O_2 consumption, limited the increase of toxic gases like CO and CO_2, and significantly decreased soot levels compared to the non-sprinkler case, demonstrating their efficacy in fire suppression and risk mitigation. Although the study confirms the effectiveness of combined fire suppression and smoke management systems in mitigating the impact of fires in multi-level basements, further research should expand on different fire scenarios and alternative safety measures to enhance the robustness of fire safety strategies in basement car parks with car stackers.

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