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Smoke Management of Underground Car Park using CFD Simulations

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ABSTRACT

Underground car parks present a substantial safety challenge due to the swift spread of smoke during fire incidents, often posing more significant risks than the fire itself, necessitating effective smoke management systems. Addressing this concern, this study undertakes thorough numerical investigation utilizing Computational Fluid Dynamics (CFD) to refine Smoke Management Systems (SMS) in such enclosed spaces. Various parameters impact the underground car parks including air change per hour (ACH), car park height, exhaust air opening locations, fresh air inlet positions, transfer beams, and jet fans. In this study, air change per hour (ACH) is invistigated aiming to comprehend the complex dynamics of smoke movement and evacuation challenges. In particular, this study focuses on the impact of air changes per hour (ACH) to comprehend the intricate dynamics of smoke movement and evacuation challenges within underground car parks. The results highlight the significant impact of Air Changes per Hour (ACH) on enclosed systems, underscoring the importance of fan quantity and their locations. While valuable, further experimental validations are recommended to enhance practical applicability, contributing to improved safety measures in underground car parks.

KEYWORDS: Smoke management, Underground car park, Park air change, Computational Fluid Dynamics.

إدارة وسحب الدخان في مواقف السيارات تحت الأرض باستخدام محاكاة ديناميكا الموائع الحسابية (CFD)

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الملخص

تمثل مواقف السيارات تحت الأرض تحديًا أمنيًا كبيرًا بسبب الانتشار السريع للدخان أثناء حوادث الحريق، وغالبًا ما تشكل مخاطر أكبر من الحريق نفسه، مما يستلزم أنظمة فعالة لإدارة الدخان. ومعالجةً لهذا القلق، تقوم هذه الدراسة بإجراء دراسة نظرية باستخدام ديناميكا الموائع الحسابية (CFD) لتطوير أنظمة إدارة الدخان في مثل هذه المساحات المغلقة. تؤثر عوامل مختلفة على مواقف السيارات تحت الأرض بما في ذلك تغير في الساعة (ACH)، وارتفاع موقف السيارات، ومواقع فتحات تهوية الهواء الخارجي، ومواضع مدخل الهواء النقي، و الكمرات العرضية، والمراوح النفاثة. وفي هذه الدراسة، يتم دراسة تغير الهواء في الساعة (ACH) بهدف فهم ديناميكيات حركة الدخان المعقدة وتحديات الإخلاء. وعلى وجه الخصوص، تركز هذه الدراسة على تأثير تغير الهواء في الساعة (ACH) وكذا اعداد واماكن المراوح داخل مواقف السيارات تحت الأرض.وتؤكد النتائج على التأثير الكبير لـتغير الهواء في الساعة على منظومة سحب الدخان وكذا عدد المراوح واماكنها. وعلى الرغم من نتائجها، يُوصى بمزيد من التجارب العملية لتعزيز التطبيق العملي، مما يساهم في تحسين إجراءات السلامة في مواقف السيارات تحت الأرض.

الكلمات المفتاحية : ادارة الدخان، مواقف السيارات تحت الارض، تغير الهواء

1. INTRODUCTION

The rise in urban populations has expanded the demand for parking solutions, prompting the construction of both aboveground and underground facilities. Underground carparks, chosen for their space efficiency, necessitate a thorough focus on indoor air quality due to emissions such as Carbon Monoxide. Ensuring a robust ventilation system, whether through natural means or employing mechanical alternatives such as ductless systems with jet fans, becomes paramount for maintaining indoor air quality and implementing effective smoke management [1], [2]. The controlling patrameters of smoke management system are classified as geometrical (number of cars) and oprerating parameters (Air Change per Hour (ACH), number of fans and their locations) [1], [3]. More sophisticated approach is indispensable for creating underground carparks that not only enhance accessibility but also prioritize safety by effectively addressing both indoor air quality and smoke management concerns.

Traditional calculations may lead to errors due to factors affecting smoke flow. Visualizing fluid flow and utilizing Computational Fluid Dynamics (CFD) simulations can be practical, offering in-depth analysis and control [4], [5]. CFD simulations compared two fire ventilation system alternatives, highlighting the critical influence of design and element placement on system functionality [4], [6].

Additionally, a comparative study [4] on the impact of a jet fan system on smoke clearance in underground car parks used CFD simulations with ANSYS FLUENT to addresses the critical safety issue of fire propagation and control. Results recommended dividing the car park into zones for effective smoke management, emphasizing the importance of further investigation [7], [8].

A full-scale experiment and numerical simulations [9] studied natural ventilation design parameters for the fire lane in an underground car park. Findings emphasized the effectiveness of natural ventilation in discharging flue gas, providing valuable references for future fire protection designs [9].

Furthuremore, temperature measurements from an experimental campaign on closed car park fires [8] emphasized the impact of a Smoke and Heat Control (SHC) system on smoke patterns. Lower fire HRR and higher smoke extraction rates reduced smoke back-layering, with flow patterns playing a substantial role. Jet fans primarily induced local cooling, with effectiveness contingent on their position relative to smoke-filled regions [8].

On the other hand, the introduction of Impulse Ventilation is a significant advancement in car park ventilation, offering an alternative to traditional systems. A study in Riyadh, Saudi Arabia, compared two jet fan smoke ventilation systems, favoring the one with 11 jet fans for improved evacuation and reduced CO concentration [10]. Morover, CFD was crucial in predicting air movement, temperature, and smoke density throughout the car park with precision [10], [11].

Nonetheless, based on our current knowledge, that smoke management in underground spaces is challenging and with uncertainties remaining, and a more in-depth understanding is necessary. Consequently, this study aims to fill this gap by focusing on Air Changes per Hour (ACH) impact on the impulse ventilation system throuugh Computational Fluid Dynamics (CFD) exploration. It aims to provide a preliminary guide for designing experimental studies to facilitate further investigation and streamline the process for additional inquiries.

2. Materials and Methods

2.1. Mathematical modeling

The mathematical foundation for simulating smoke management in underground parking structures involves solving the fundamental equations governing fluid dynamics, heat transfer, and smoke dispersion. Computational Fluid Dynamics (CFD) simulations serve as a valuable tool for analyzing systems involving mass and heat transfer, offering a more comprehensive and sophisticated understanding of related phenomena through computer models. The Fire Dynamics Simulator (FDS) has gained popularity as a CFD tool for describing fire evolution [4], [12], [13], [14] employing a large eddy simulation form of the Navier–Stokes equations tailored for low-speed, thermally-driven flow [4]. PyroSim, a graphical user interface for the Fire Dynamics Simulator (FDS), facilitates this mathematical modeling process [4], [15], [16, 18].

Governing Equations :
The incompressible form of continuity and momentum equations (Navier-Stockes equations), representing mass conservation and fluid movement, respectively, forms the core of the mathematical model [7], [13], [16], [20]. The unsteady 3D continuity equation can be represented as:

$$\frac{\partial \rho}{\partial t}+\frac{\partial(\rho u)}{\partial x}+\frac{\partial(\rho v)}{\partial y}+\frac{\partial(\rho w)}{\partial z}=0 \tag{1}$$

While the 3D momentum quations are presented as fellow:

$$\frac{\partial(\rho u)}{\partial t}+\frac{\partial(\rho u^2)}{\partial x}+\frac{\partial(\rho uv)}{\partial y}+\frac{\partial(\rho uw)}{\partial z}=-\frac{\partial p}{\partial x}+m\left(\frac{\partial^2 u^2}{\partial x^2}+\frac{\partial^2 u^2}{\partial y^2}+\frac{\partial^2 u^2}{\partial z^2}\right)+\rho g_x \tag{2}$$

$$\frac{\partial(\rho v)}{\partial t}+\frac{\partial(\rho vu)}{\partial x}+\frac{\partial(\rho v^2)}{\partial y}+\frac{\partial(\rho vw)}{\partial z}=-\frac{\partial p}{\partial y}+m\left(\frac{\partial^2 v^2}{\partial x^2}+\frac{\partial^2 v^2}{\partial y^2}+\frac{\partial^2 v^2}{\partial z^2}\right)+\rho g_y \tag{3}$$

$$\frac{\partial(\rho w)}{\partial t}+\frac{\partial(\rho wu)}{\partial x}+\frac{\partial(\rho wv)}{\partial y}+\frac{\partial(\rho w^2)}{\partial z}=-\frac{\partial p}{\partial z}+m\left(\frac{\partial^2 w^2}{\partial x^2}+\frac{\partial^2 w^2}{\partial y^2}+\frac{\partial^2 w^2}{\partial z^2}\right)+\rho g_z \tag{4}$$

Where, ρ represents density, u, v, w are velocity components in the *x, y, z* directions, p is pressure, m is dynamic viscosity, and g_x, g_y, g_z are gravitational accelerations.

Discrete Phase Model (DPM): To simulate the movement of respiratory particles and smoke under the influence of jet fans, the Discrete Phase Model (DPM) is employed [4], [12], [16]. The DPM tracks the trajectory of particles using the following equation:

$$\frac{du_p}{dt}=F_D\left(u-u_p\right)+g\left(\rho_p-\rho\right)+F_{Brownin}+F_{Saffman} \tag{5}$$

Where, u_p is the particle velocity, F_D is the drag force, g is the gravitational acceleration, and $F_{Brownin}+F_{Saffman}$ account for Brownian motion and Saffman lift, respectively.

The simulation assumptions include the constant size of respiratory particles and the exclusion of particle generation during the simulation. The study focuses on understanding the impact of Air Changes per Hour (ACH) on the impulse ventilation system and aims to guide the design of experimental studies for further investigation. PyroSim functions as a graphical user interface designed for FDS (Fire Dynamics Simulator)[11], [17], [18-20]. Its purpose is to facilitate the construction, exploration, and modification of FDS input files. To aid in the development of 3D building models, similar to obstruction blocks in FDS, a 2D image of the building layout is overlaid on the graphics editor screen. This overlay allows for the manual placement of three-dimensional wall elements by tracing over the lines of the image.

2.2. Model description

This investigation centers on an underground car park dedicated to a building in Cairo, featuring a total of 57 parking spaces. The dimensions of this facility are 60 meters in length, 40 meters in width, and 3 meters in height, as represented in Fig. 1. The total floor area of the parking facility is approximately 2,400 m². Access to and from the upper levels is facilitated by four ramps, with two designated for vehicle entrance and two for vehicle exit, strategically positioned along the 40 m walls of the car park.

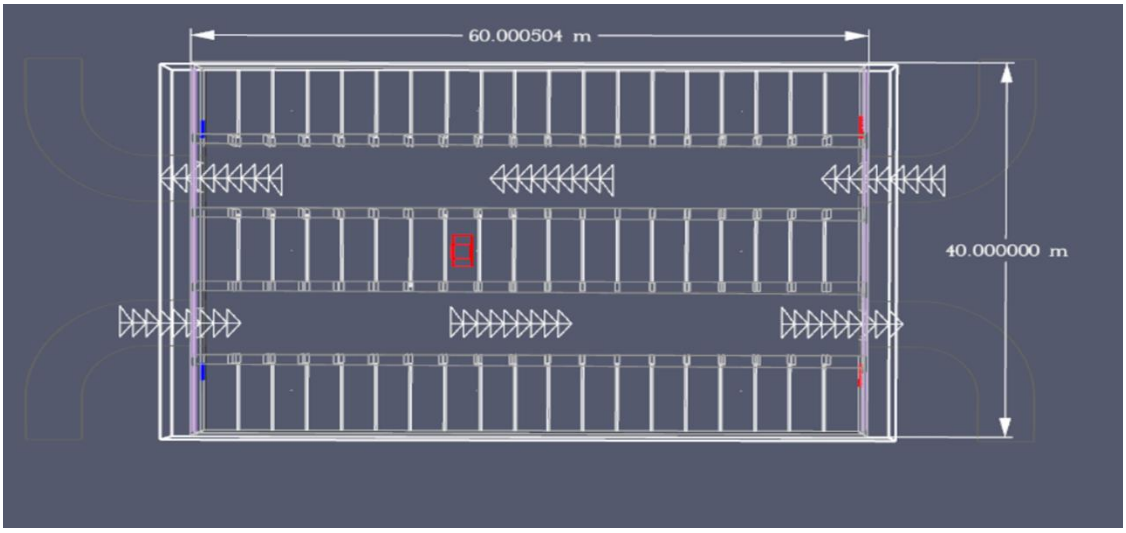

Figure.1: The total floor area of the studied parking facility

In this investigation, three distinct ventilation approaches are introduced and thoroughly examined:

(a) First approach:

Two mechanical supply fans (SF), each with a capacity of 8 m³/s, are employed to introduce a substantial volume of fresh air into the basement. Three extract fans, each capable of handling 10 m³/s, work in tandem with nine jet fans, each with a capacity of 2.8 m³/s, to channel and control air contaminants towards designated extraction points. Refer to Fig. 2 for an illustration of the first model.

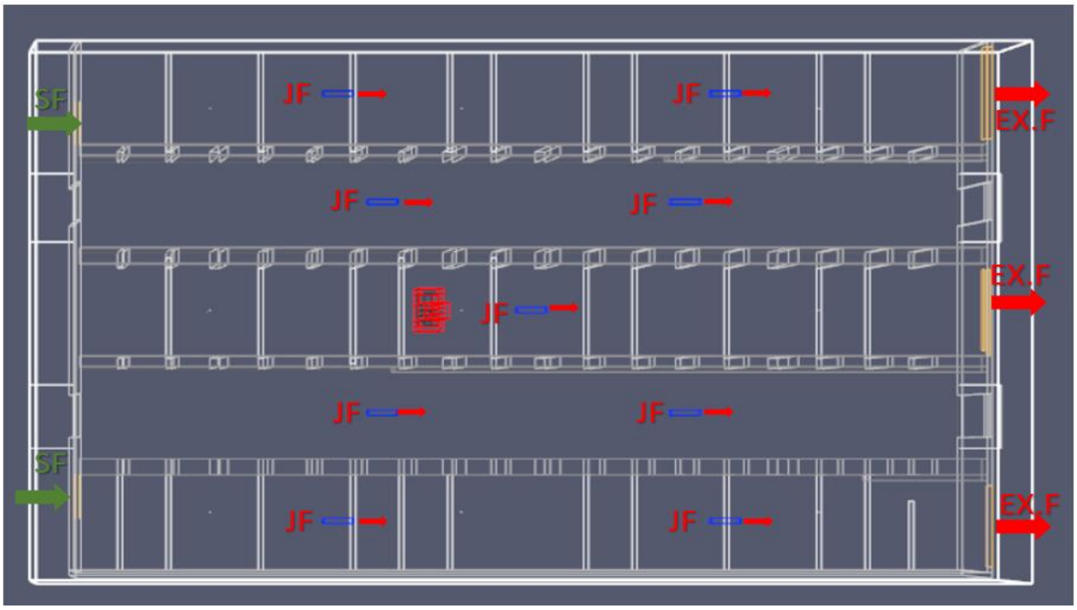

Figure.2: First approach with two supply fans

(b) Second approach:

Three mechanical supply fans (SF), each providing 5.3 m³/s, are utilized for delivering a bulk of fresh air to the basement. A single extract fan (EX.F), with a capacity of 30 m³/s, collaborates with twelve jet fans (JF), each boasting a capacity of 2.8 m³/s, to efficiently pump and guide air contaminants towards extraction points, as seen in Fig. 3 for a visual representation of the second model.

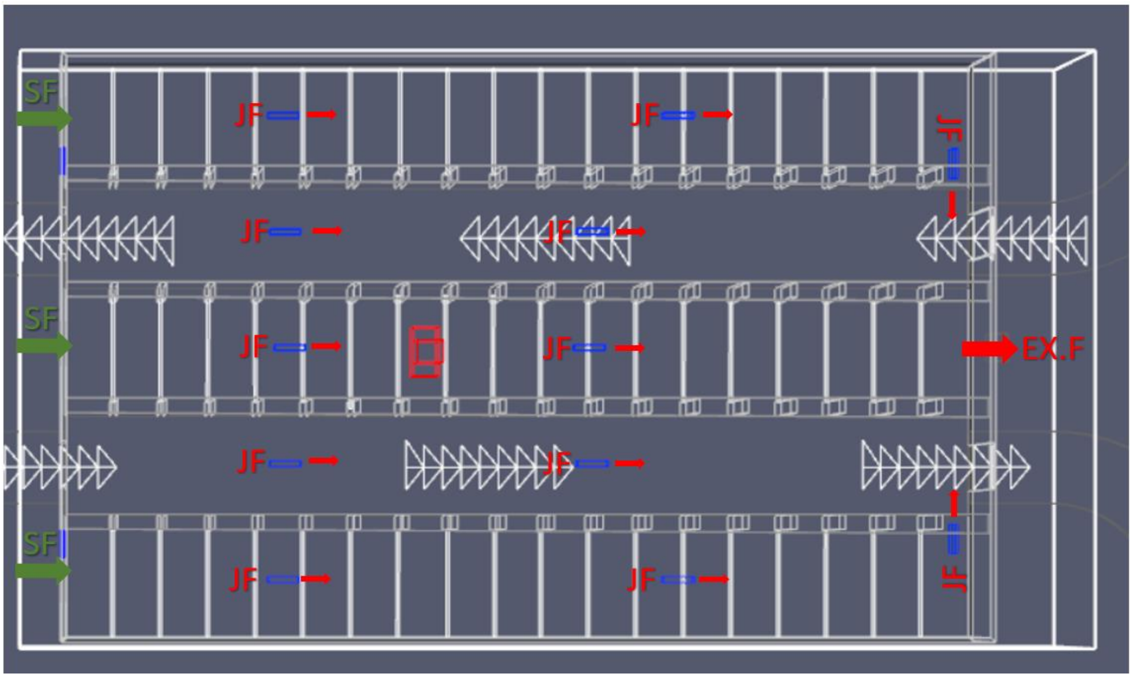

Figure.3: Second approach with three supply fans

(c) Third approach:

Five mechanical supply fans (SF), each delivering 3.2 m³/s, are implemented to supply a substantial volume of fresh air to the basement. Five extract fans (EX.F), each capable of handling 6 m³/s, team up with fifteen jet fans (JF), each with a capacity of 2.8 m³/s, to effectively pump and direct air contaminants towards extraction points. Refer to Fig. 4 for an illustration of the third model. These approaches represent different ventilation strategies aimed at optimizing air quality and contaminant control within the underground car park.

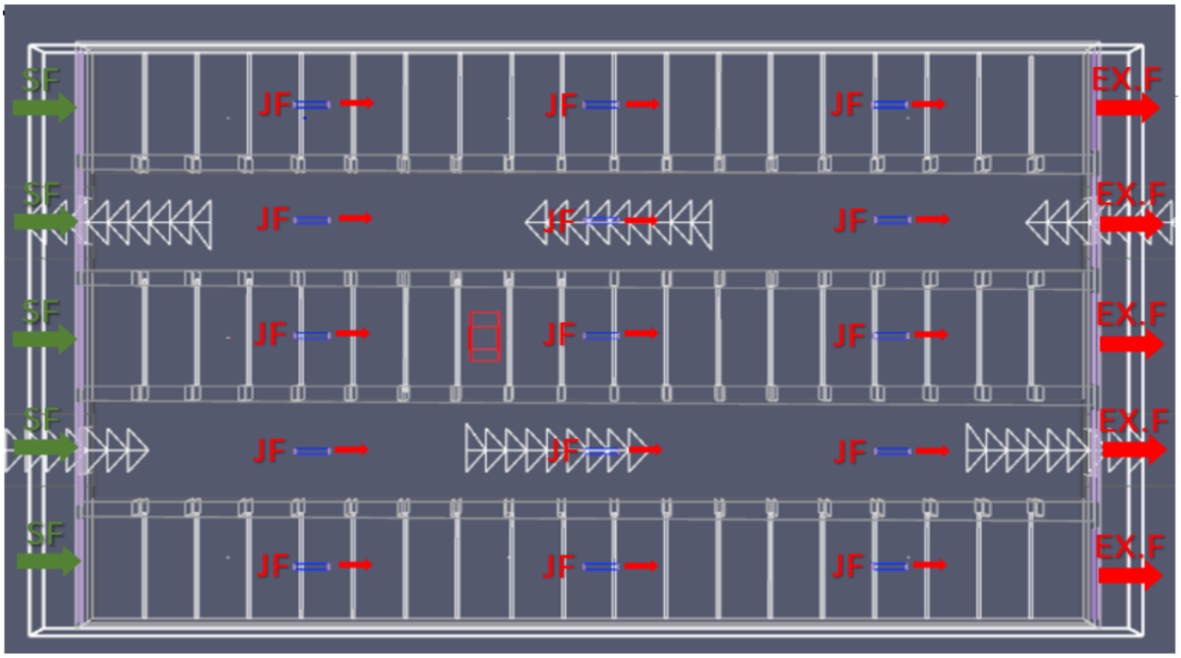

Figure.4: Third approach with five supply fans

In all the examined approaches, the configuration of the supply airflow has been meticulously set to account for 80% of the necessary exhaust air volume. This strategic design approach ensures optimal ventilation efficiency and adherence to specified air quality standards. Table.1 shows how simulations performed at different approaches. It can be noticed that three approachs were performed firstly while the air change per hour (ACH) kept constant. Moreover, two additional cases were tested by changing the ACH for approach 2 which ended up with five approaches as seen in Table.1.

Table.1: Simualtaion settings and approachs parameters

Approach No.	Case No.	ACH	No of Jet Fans (JF)	No. of supply fans (SF)	No of exhaust fans (EX.F)
1	A	10	9	2	3
2	B	10	12	3	1
3	C	10	15	5	5
2	D	12	12	3	1
2	E	14	12	3	1

3. RESULTS AND DISCUSSION

To assess the effectiveness of the Impulse Ventilation System (IVS) in clearing smoke from evacuation routes and ensuring firefighter safety, the evaluation focused on specific criteria for all analyzed fire approaches at the occupant's head level. The established requirements include maintaining visibility above 2 meters in the car park, ensuring the predicted temperature remains below 77 degrees Celsius, sustaining a velocity exceeding 0.1 m/s to prevent air stagnation, and keeping it below 5 m/s to secure safe evacuation routes, as outlined in the British standard [14].

Following the execution of simulations utilizing Pyrosim software based on the hypothesized scenarios, the software facilitates a comprehensive analysis of each scenario's impact on visibility. It allows for the interpretation of stagnation velocity points, enabling an exploration of temperature distribution around the ignition source or smoke point within the designated parking area. The simulation outcomes provide valuable insights into the effects on visibility, stagnation points, and temperature dynamics associated with the identified fire scenarios in the chosen parking location.

3.1. Impact of Fan Numbers and Locations on Smoke Control

The assessment of the Impulse Ventilation System's (IVS) efficacy in smoke control necessitates a thorough examination of how the number and placement of fans influence its performance. This evaluation contains a comparative analysis of three distinct approaches: Case-A, Case-B, and Case-C. Figure 5 provides a visual representation of the visibility contours for these cases in both plan and elevation views. Notably, Case-A stands out as the most advantageous when considering the horizontal perspective exclusively. However, upon considering both plan and elevation views, it becomes evident that Case-B represents the optimal configuration, demonstrating visibility exceeding 7 meters across most elevations. This analysis contributes to a comprehensive understanding of how variations in fan numbers and locations impact the overall smoke control capabilities of the IVS.

Furthurmore, Case-B, depicted in Fig.6, is identified as the optimal configuration, maintaining desired temperatures within the parking area, while effectively addressing stagnation points as in seen on Fig.7. It ensures a balanced airflow, mitigating the risk of air stagnation areas. This configuration, aligned with Table 1 design, proves to be a comprehensive and efficient solution for the Impulse Ventilation System (IVS) in the studied parking area.

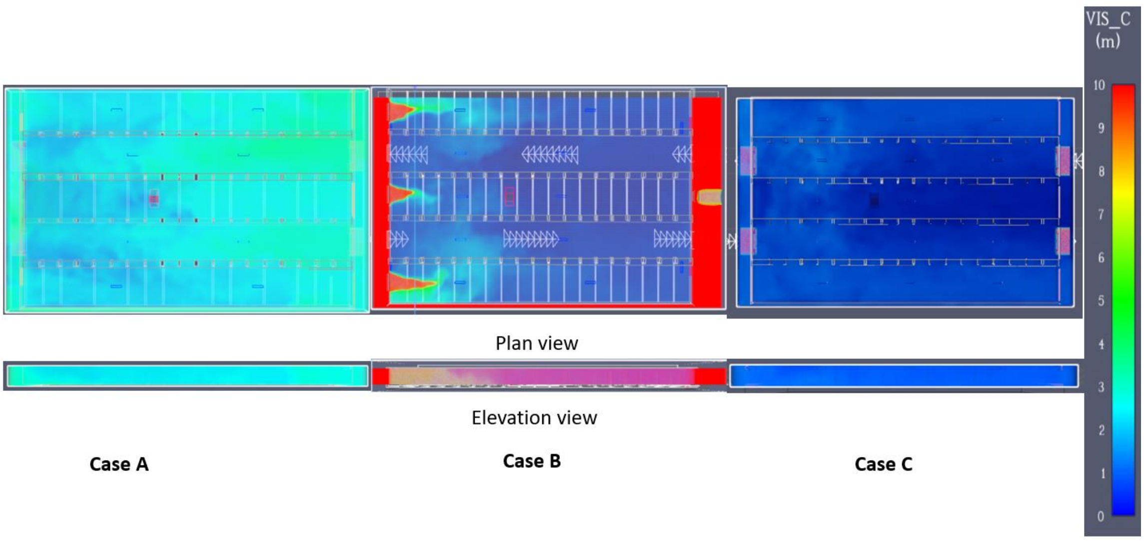

Figure.5: Visibility contours for cases A-C

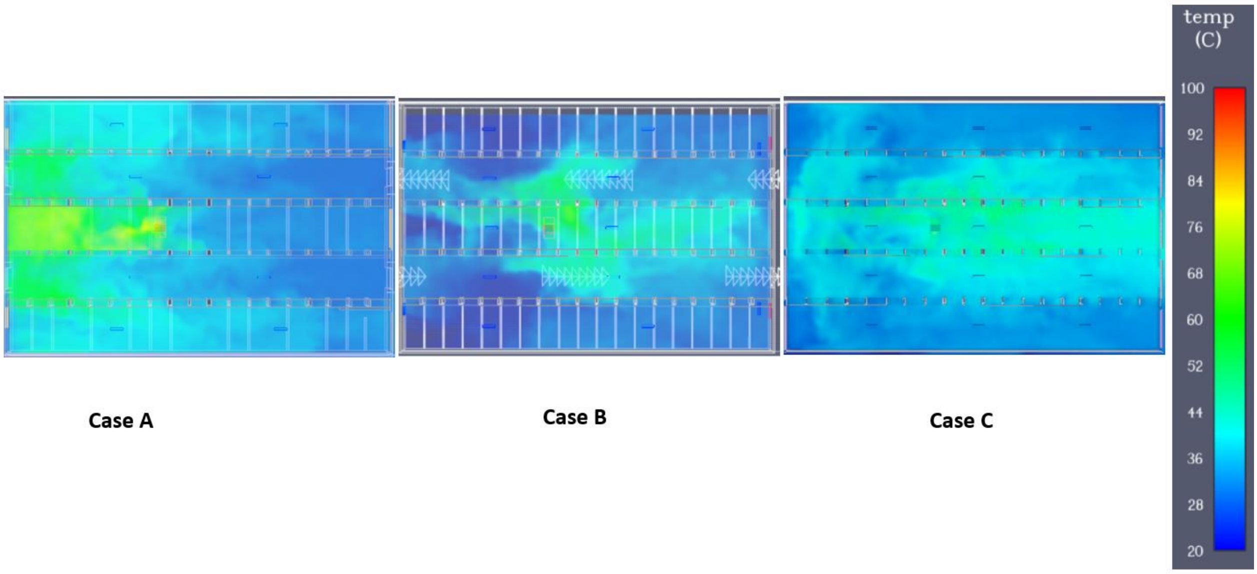

Figure.6: Temperature contours for cases A-C

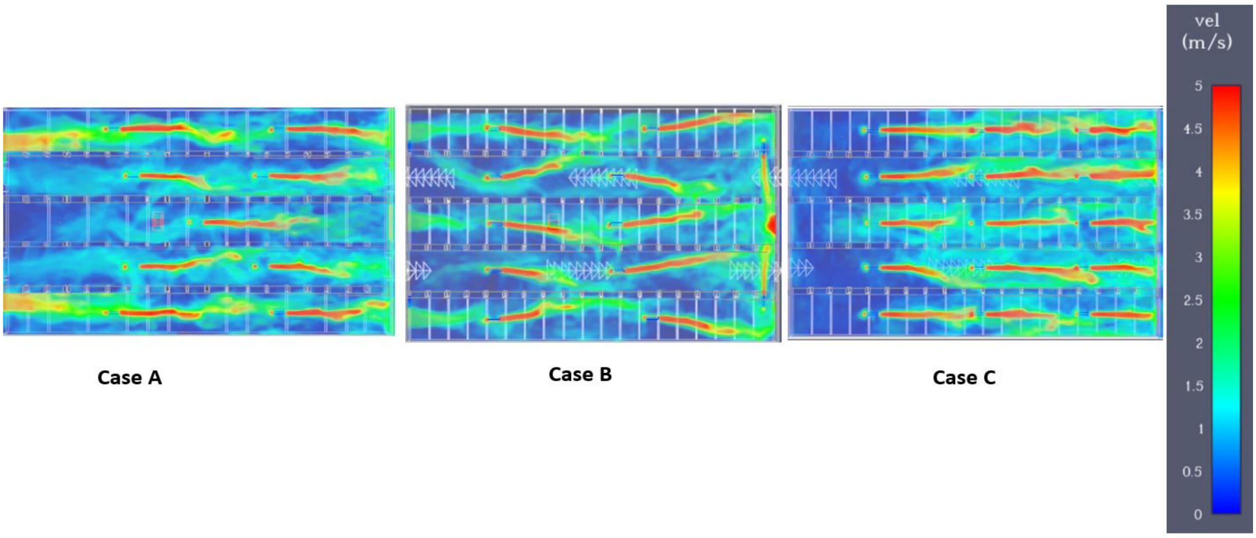

Figure.8: Velocity contours and stagnation points for cases A-C

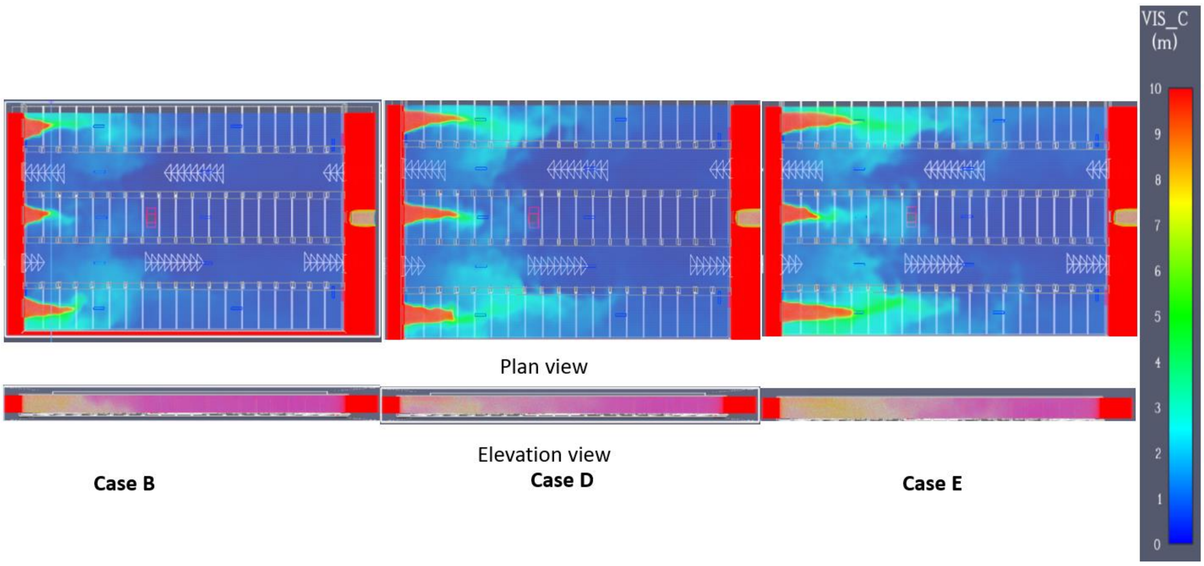

Figure.9: Visibility contours for cases B and D-E

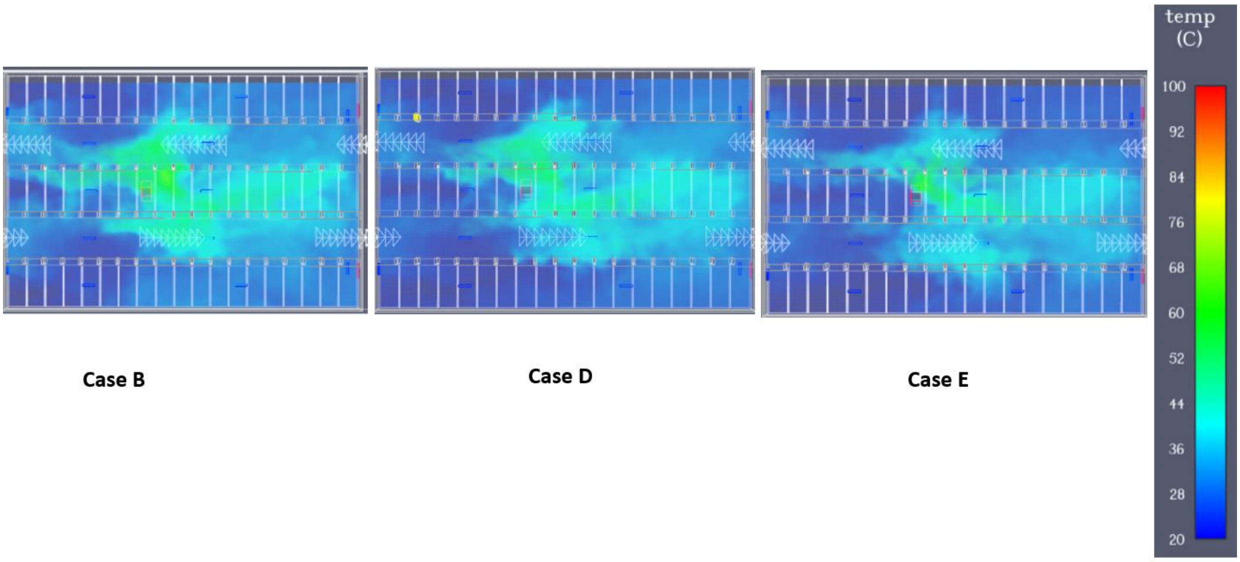

Figure.10: Temperature contours for cases B and D-E

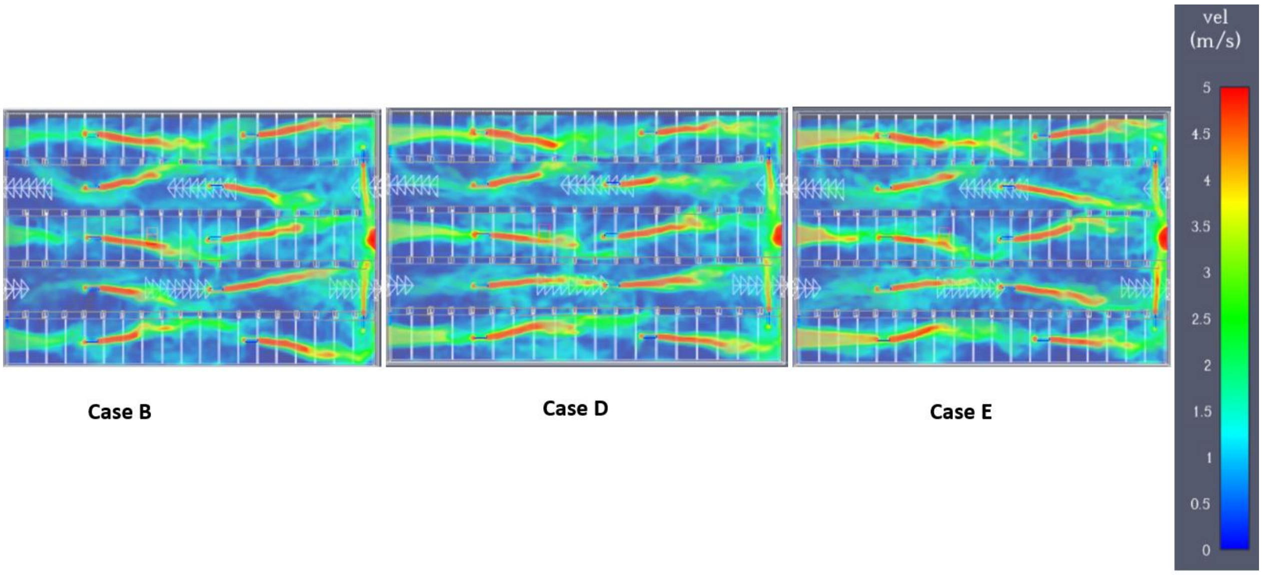

Figure.11: Velocity contours stagnation points for cases B and D-E

3.2. Impact of Air Changes per Hour (ACH)

To evaluate the efficiency of the Impulse Ventilation System (IVS) in smoke control, a comprehensive investigation into its performance based on air changes per hour (ACH) is conducted. This assessment includes a comparative analysis of three scenarios: Case-B, Case-D, and Case-E as described in Table 1. The visibility contours in Figure 8 clearly indicate that as the air changes per hour increase, visibility rates also increase. Additionally, in Figure 9, it is evident that temperature decreases with an increase in the air change rate. Notably, stagnation points decrease as the air change rate rises.

While analyzing the scenarios, Case-E exhibits some overlapping areas, mixed flows, and increased turbulence due to its specific configuration. In contrast, Case-D stands out as the best configuration, demonstrating more stable airflow and reduced turbulence. This observation underscores the positive correlation between higher air change rates and improved visibility, decreased temperature, and fewer stagnation points, with Case-D being the most favorable configuration in achieving these outcomes.

Conclusions

In this study, the evaluation of the Impulse Ventilation System (IVS) for smoke control in the examined parking area has yielded significant insights. A comprehensive analysis encompassed various critical factors, including fan numbers and locations, air changes per hour (ACH), visibility, temperature, and stagnation points. The results shed light on the performance of different configurations, emphasizing key findings and trends that contribute to a nuanced understanding of the IVS effectiveness in the specified context.

The outcomes underscore the importance of meticulous design considerations, particularly in optimizing fan placement and determining the suitable air change rates. Case-B consistently emerged as the optimal configuration, excelling in both visibility and temperature control, while effectively addressing stagnation points. Furthermore, the positive correlation between increased air changes per hour and improved conditions, exemplified by Case-D, underscores the relevance of considering airflow dynamics in smoke control strategies.

These findings not only enhance our current understanding of the IVS functionality in parking areas but also provide valuable guidance for future research endeavors. Given the challenges associated with conducting extensive experimental studies, the insights derived from this simulation-based analysis offer practical and informative directions for advancing smoke control strategies in confined spaces.

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