Research Article

Review of common fire ventilation methods and Computational Fluid Dynamics simulation of exhaust ventilation during a fire event in Velodrome as case study

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Abstract
The main purpose of fire engineering design is to ensure human safety in the situations of fire in buildings, car parks and tunnels. Toxic gases and carbon monoxide induced by fire get the life of many fire victims, hence, fire safety elements like velocity, heat and smoke dynamics have been focused by many researchers to facilitate safe exit in the case of fire. The goal of this paper is to review the fire ventilation methods in fire safety and measurement methods used as the performance of ventilation systems. Managing the smoke in case of fire can reduce the carbon monoxide that poses the deadliest risk to people. Thus, the control and removal of gases and smoke in the case of fire is crucial in human safety and saving a property. In addition, this paper conducts a case study on smoke propagation and removal of smoke from Velodrome environment in which fire occurred. To conduct this case study, Computational Fluid Dynamics (CFD) simulation of exhaust ventilation system for managing smoke in building's environmental called Velodrome has been developed. The results were investigated and analysed in 3-dimensional plane. The results of these CFD simulations show that the source of fire can be removed by activating exhaust system, and thus, the risk of fire victims's life and damaged property can be reduced.

Keywords Fire ventilation · Computational Fluid Dynamics · Exhaust ventilation · Velodrome · Human safety

1 Introduction

Effective smoke control system or ventilation systems during fire events is very important for saving lives since that bifurcation flow of smoke can reduce smoke propagation rates and give more time for passengers to escape. The important parameters of smoke extraction in case of fires including characteristics of velocity or smoke layer thickness are needed to be investigated by researchers in detail. Research done by [1] showed that most deadly factor in fire events is due to smoke where a huge quantity of toxic gases as a result of an incomplete combustion is released. Thus, the development of an effective ventilation system is a key element for personnel safety during evacuation in fire events. Hence, an increasing number of researches on smoke exhaust methods have been presented in recent years. Personnel safety in fire events is threatened due to various toxic gases, low oxygen content and high temperatures.

While the ability to firefighting and rescue as well as, high radiation heat, low visibility poses risk evacuation and high temperatures also result in an extension of the fire. Therefore, smoke management systems are necessary:

- To save lives by facilitating human evacuation and extinguishment;
- To reduce risk of explosions;
- To support firefighting operations and rescue;
- To decrease damage to structure, equipment and surrounding facilities in fire environments;

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There are literature reviews on ventilation systems that have been published. However, these review papers focus only on a specific domain of fire events and specific environments. None of these papers concentrate on the comprehensive analysis of fire ventilation systems in different environments with their influence on the air flow motion and the methods for fire schematization. For example, the study done by [1] provided an overview of road tunnel ventilation systems. It gives an overview on numerical aspects about fire in road tunnel. [2] presented an overview of ventilation strategies in buildings but their focus is not on fire events. It has been identified that there is no study so far that has been published or written that reviews fire ventilation systems in different environments such as car park, tunnels and buildings. It is hoped that this study provides the knowledge on fire ventilation systems for researchers in order to design a well ventilation system for the safety when a fire occurs. Hence, we have reviewed 51 papers on fire events and cluster them on fire Ventilation Methods with environments in which fire occurred and measurement methods used as the performance of proposed ventilation systems. The major contributions of this paper can be summarized as follows:

- Present an introduction of fire ventilation and smoke control systems in detail and survey of common fire ventilation methods.
- Give an overview on critical ventilation velocity about the cases of fire in car park, tunnels and buildings in order to raise safety when a fire occurs. This study provides valuable insights and acts as a guide for researchers and industrial practitioners.
- Computational Fluid Dynamics (CFD) simulation of exhaust ventilation system for managing smoke in building's environmental called Velodrome is developed.

2 Literature review

The purpose of this section is to reveal literature related to particular area of study and shows some of the fundamental aspects of the fire ventilation systems.

2.1 Introduction to fire ventilation and smoke control systems

The exhaust ventilation system is meant to eliminate contaminants. It provides the necessary control of the air which is full of contaminants and their sources. In this system, particulates, vapours and gases are managed by controlling the air. The components of a typical exhaust system usually include a hood, a duct, an air mover, an air cleaner and a vent or an outlet. Since the hood is where the air is drawn into the system and it is relatively close to the source of the contaminants, the design of the hood must be effective. The main categories of hood are the enclosed hood, the partially enclosing hood and the exterior hood [3, 4].

The most mortal factor during fire events is smoke. The development of an effective design of ventilation systems and smoke exhaust method is the most important protection measures for human health during evacuation in fire events. In the context of this research, fire ventilation systems including smoke production will be named fire ventilation. Smoke control during fire ventilation is achieved by dilution and evacuation of smoke. It is needed that smoke-filled air can be replaced by clean air, which is created mechanically in through the portals. Dilution can reduce the concentrations of toxic gases to improve tenability.

Fire ventilation system uses the extract ventilation to catch the contaminants from being breathed by personnel in workstations. The three main elements of Fire ventilation system are hood, duct, fan and discharge as showed at Fig. 1.

2.1.1 Hood

The entry point of contaminants into the exhaust ventilation system is the hood. The hood is designed to grant the necessary amount of air in order to control contaminants and draw them into the system. The hood can be of a simple round or rectangular opening or it can be specially designed for the mentioned purpose. There are three types of hood that can be fixed into an exhaust ventilation system. The first is the enclosed hood. In this type of hood, the amount and speed of air allowed into the enclosed cover prevents the contaminants and their sources to escape. As for the next type of hood, which is the exterior hood, it is usually installed outside and hence, far from the source of the contaminant. The right amount and speed of air is released to capture any contaminant at its furthermost distance from the hood and then, draws the contaminant into the system. This amount and speed of air is called the capture velocity of the hood. The next type of hood is the partial-enclosing hood or also known as the receiving hood. It can be defined as the hood that receives contaminants. In order for this type of hood to function properly, the flow of air must be accurate to remove contaminants so that they do not escape [3, 4].

Exhaust hood is widely utilized in many industries like metallurgy, mineral, mechanical, chemical, textiles medicine, health and tobacco. Since exhaust hood is widely used in the tobacco industry like the other industries. It is apparent that exhaust hoods are only efficient when the

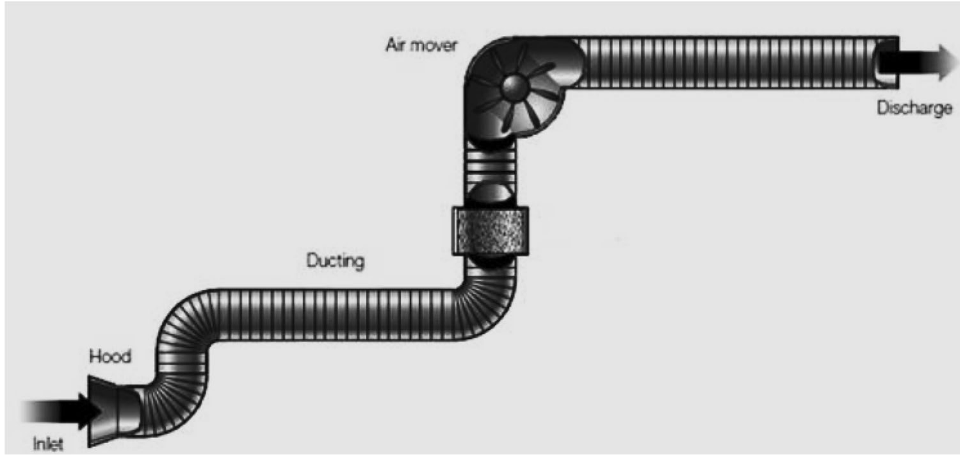

Fig. 1 Common parts of ventilation system

sources of contaminants are enfolded. Moreover, the efficiency of the hoods decreases rapidly with the distance of the sources of contaminants. This is due to the non-directional of the airflow entering the hood and clean air within the hood is also sucked in at the same time. The exhaust hoods are often becoming inefficient since they are placed at the app position due to access requirement [3].

2.1.2 Duct

The purpose of a duct system is to surround and direct the flow of air in a ventilation system from one point to another. In an exhaust system, the duct prevents the contaminated air from mixing with the workroom air as it is removed. In a supply system, the duct directs the supply air to the point where it is required. The duct can be considered as a pathway which the air in a ventilation system travel. The most common duct used in ventilation systems has a round cross section because round ducts result in a more uniformed speed profile within the system. However, in certain situations, the other cross-section configurations can be used.

2.1.3 Fan

A machine used to generate Flow, be called Fan. The fan includes of a rotating arrangement of blades which act on fluid or any mass. The rotating assembly of blades and hub is known as an impeller, a runner or a rotor. Usually, it is placed in housing. This may conduct the airflow and also increase safety by preventing any object from contacting the fan blades. The Majority of fans are powered by electric motor; however, other sources of power may also be utilized like hydraulic motors and internal combustion engines. General applications include personal thermal comfort and climate control e.g., floor fan or an electric table, vehicle engine cooling systems e.g. in front of a radiator, machinery cooling systems e.g., inside computers, ventilation, fume extraction, winnowing e.g., separating chaff of cereal grains, removing dust e.g. in a vacuum cleaner, provide draft for a fire. There are three main types of fans. They are axial, cross flow (also called tangential) and centrifugal (also called radial).

2.2 Common fire ventilation methods

The fire and smoke distribution in fire situations must be controlled by ventilation systems or smoke extraction system. Fire ventilation systems and fire situations have various philosophies in different environments such as car park, tunnels and buildings. Some researchers prefer to prevent movement of smoke upstream in fire to be called back-layering, others focus on keep low air velocities to decrease fire smoke movement. Among types of smoke extraction methods, jet fan is one of the most effective fire ventilation systems that suppression of the fire and enables early evacuation. Thus, a number of scalars encourage the fire brigades in equipment with a movable jet fan in order to improve the fire environment for rescue and extinguishment fires [5]. The studies on movable fans have showed that the functionality of them is better than the fixed fans located at the ceiling because its distance can be freely modified to adapt to the complicated fire situations. As you can see in Table 1 we summarise all ventilation system and methods of measurement in three environment Tunnel, carpark, Building.

Figure 2 illustrate 5 categories for ventilation system in carpark and tunnel and building. Base on this research in the tunnel famous ventilation system is Longitudinal ventilation system and, in the building, and carpark Mechanical ventilation have high usage base on reviewed papers.

Figure 2 shows the distribution of papers based on their analysis tools applied for investigating of measurement method in tunnel, building and carpark. As you can see,

Table 1 Distribution of research papers by environment, ventilation methods, measurement methods

Environment	Ventilation method	Measurement method	References
Tunnel	Longitudinal ventilation	CFD	Zhong et al. [6]
			Liu and Cassady [7]
			Wang and Wang [8]
			Li et al. [9]
			Heidarinejad et al. [10]
			Seike et al. [11]
			Musto and Rotondo [12]
			Guo and Zhang [13]
			Gannouni and Maad [14]
			Zhang et al. [15]
			Muhasilovic and Duhovnik [16]
			Fan et al. [17]
			Wang [18]
		Experimental	Yi et al. [19]
			Zhang et al. [15]
			Zhong et al. [20]
			Tanaka et al. [21]
			Tang et al. [22]
			Yao et al. [23]
			Du et al. [24]
			Chen et al. [25]
		Water mist	Beard [26]
	Natural ventilation	CFD	Fan et al. [17]
			Harish and Venkatasubbaiah [27]
			Ji et al. [28]
			Yuan et al. [29]
			Weng et al. [30]
		Experimental	Kashef et al. [5]
			Ura et al. [31]
			Ji et al. [32]
	Mechanical ventilation	CFD	Tilley et al. [33]
			Weng et al. [30]
			Muhasilovic and Duhovnik [16]
		Experimental	Zhou et al. [34]
			Mei et al. [35]
	Transversal ventilation	CFD	Vidmar et al. [36]
			Hahm and Igor Maevski [37]
		Experimental	Du et al. [24]
			Yi et al. [38]
Building	Mechanical ventilation	CFD	Wahlqvist and Van Hees [39]
			Hostikka et al. [40]
			Zhang et al. [41]
		Experimental	Su and Yao [42]
	Natural ventilation	CFD	Huang et al. [43]
			Węgrzyński and Krajewski [44]
			Xu et al. [45]
		Experimental	Su and Yao [42]
	Hybrid ventilation	Energy performance	Yang and Li [46]
			Lim et al. [47]
		CFD	Gao et al. [48]

Table 1 (continued)

Environment	Ventilation method	Measurement method	References
Car park	Mechanical ventilation	CFD	Deckers et al. [49]
			Enright [50]
			Tilley et al. [33]
			Viegas [51]
		Experimental	Merci and Shipp [52]
			Deckers et al. [49]

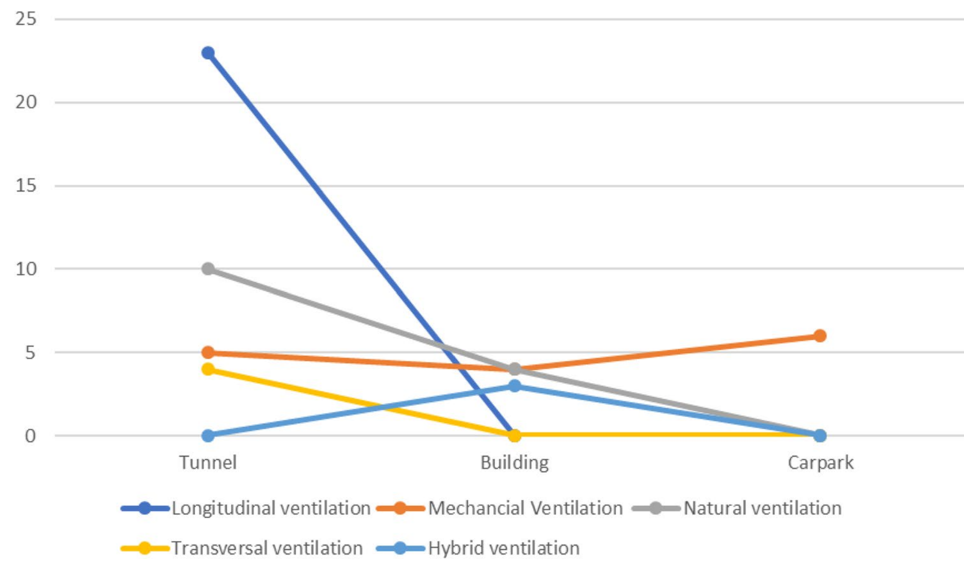

Fig. 2 Summary of ventilation system applied in Tunnel, Building, Car park

60% of papers used CFD for analysis and 35% of papers used experimental methods to do analysis.

There are the different techniques for smoke control depending on the type of fire ventilation system to be followed at sub-sections:

2.2.1 Common fire ventilation methods in tunnels

Tunnels may require ventilation for different reasons. The reasons can be for example, to ensure a sufficient air quality, to manage the propagation of smoke in case of fire or to decrease temperatures to passable limits. Vehicular tunnels e.g. rail, metro and road usually require high air quality during smoke control and normal operation in case of fire, while cable tunnels require smoke control, cooling and a certain amount of air exchange. Station tunnels and mine tunnels also require sufficient ventilation for physiological, smoke control and cooling requirements. Ventilation is essential in most road tunnels to limit the concentrations of contaminants to passable levels in tunnel. Ventilation systems are also used to manage heated gases and smoke that are produced during a tunnel fire emergency. Some short tunnels are ventilated naturally without applying fans; however, such tunnels could force a ventilation system to combat a fire emergency [53]. Common ventilation methods in tunnels are longitudinal, transverse, Mechanical as described as below:

2.2.1.1 Longitudinal ventilation system Longitudinal ventilation system can be installed in much longer tunnels, Depending on the maintenance and fire risk mitigation of sufficient air quality. For short tunnels that are three kilometres or less in length, longitudinal ventilation system is usually applied due to lowest construction cost. Smoke movement using longitudinal ventilation involves extracting smoke through a predetermined route downstream of fire and preventing smoke from spreading upstream. Hence, the minimum air speed is needed to prevent smoke from spreading against longitudinal ventilation flow. This is important in longitudinal ventilation mode. The critical speed should prevent smoke back-layering. Moreover, a suitable airflow velocity should prevent smoke from infiltrating the branches that are used for pedestrian evacuation [24]. The simplest form of ventilation in tunnel is Longitudinal ventilation that consists of fresh air and exhaust air. The level of pollution raises along the tunnel due to air flow direction and vehicles pass from one end to the other with generating emissions.

2.2.1.2 Transverse or semi transverse ventilation system Transverse ventilation systems employ remote-controlled dampers to extract the smoke close to the fire location. In these systems, the location of evacuating the concentrated smoke will be limited to the location of the smoke source. The effectiveness of these systems in control of air/smoke flow depends on confining smoke within a short region and on the capacity of smoke extraction. Monitoring of air or smoke movement in controlled operation of transverse ventilation related on correct air or smoke velocity readings, i.e. location of the sensors and their validity in fire situations [9, 15].

2.2.1.3 Natural ventilation systems In this method, the smoke produced by a fire was aerated through the openings in the ceiling, providing a natural buoyancy of hot smoke. The distance from the fire to the incline position of the spreading smoke and the thickness of smoke layers along the ceiling were investigated by changing the heat release rate and using two types of median structures experimental parameters. It was clarified that the smoke spreading distance was constant and independent of the heat release rate of the fire under the experimental conditions. Moreover, it was confirmed that the thickness of the smoke layers in the tunnel thinned out quickly due to the natural ventilation [23, 35].

2.2.2 Common fire ventilation methods in buildings

Ventilation systems move outdoor air into the buildings, and distribute the air within them. The building ventilation systems generate clean air for breathing by diluting the pollutants originating in the buildings and eliminating the contaminant from them. There are three basic elements in building ventilation systems:

1. Airflow path: the overall airflow path in a building which should be from clean zones to dirty zones;
2. Ventilation rate: the quantity of outdoor air provided into the space and the quality of outdoor air.
3. Air distribution or Airflow pattern: the external air should be delivered to each part of the space in an efficient method and the airborne contaminants provided in each part of the space should be eliminated in an efficient method.

Three ventilation systems are applied in buildings: natural, mechanical and hybrid (mixed-mode) ventilation as described here.

2.2.2.1 Mechanical ventilation system Mechanical ventilation systems are driven by Mechanical fans. Fans can be installed in windows or walls, or exhausting air from a room or installed in air ducts for supplying air. The kind of mechanical ventilation systems related to climate. For instance, a positive pressure mechanical ventilation system is used, in warm and humid climates. In these climates, infiltration needs to be prevented to decrease the interstitial condensation. Conversely, in cold climates, negative pressure ventilation is used as exfiltration is prevented to reduce interstitial condensation. For a room with locally generated pollutants, such as a kitchen, toilet or bathroom, the negative pressure system is often used [18, 23]. Ventilation systems are used in air-conditioned residential buildings in order to keep an acceptable indoor air quality. According to outcome of evaluating various ventilation strategies, it was finalized that the most appropriate ventilation strategy for air-conditioned residential buildings is short-term mechanical ventilation. However, there is still no a general design framework of short-term mechanical ventilation strategy for determining the appropriate design parameters, including ventilation frequency, start concentration of ventilation and ventilation period based on CO_2 generation rate, various combinations of indoor, infiltration rate, net room volume, and mechanical ventilation rate [53, 54].

2.2.2.2 Natural ventilation system Natural ventilation system due to reducing use of energy in building is efficient strategy. The effect of natural ventilation system is significant for buildings with high internal heat generation, for example commercial office buildings. This is because naturally ventilated buildings are becoming increasingly popular in Japan. According to review paper done by [55] the design of naturally ventilated buildings was analysed to compare the representative air change rates. The measurement results from studies shows that ventilation performance depends highly on the design and no strong correlation is found between the air change rates and floor areas. It is noted that, the performance of natural ventilation systems is considerably dependent on the building shape, that during the early stages of building design is generally discussed. It is important to provide a clear target air change rate in range of achievable values for natural ventilation in early design stage and consider this target throughout the building design process. One of the best strategies for lessening the energy usage in building is designing of the natural ventilation [53, 55].

2.2.2.3 Hybrid ventilation system The active ventilation systems in building which eliminate excess contaminants, heat and humidity from indoor environment, could be large energy consumers. In order to provide desired ventilation flow rates for all of the floors of a multi-story building and reduce the energy consumption is proposed a stack-based hybrid ventilation scheme. The most advantages of this hybrid scheme are when the required ventilation flow rate is beyond the one that pure buoyancy-driven ventilation schemes or the building has many floors. the optimal interface between the MVFs (mechanically ventilated floors), NVFs (naturally ventilated floors) and the vent sizes of different NVFs which guarantee a balance between the desired ventilation flow rate, room air temperature, and the heat inputs within the occupants' spaces, are derived. The design procedure is presented for stack-based hybrid ventilation scheme [46]. These hybrid ventilation systems adjusting the use of each system based on the time of day or season of the year have drawn worldwide attention. Hybrid ventilation technology provides sustainable development and energy saving and fulfils high requirements for indoor environmental performance by optimizing the balance between energy use, indoor air quality, environmental impact and thermal comfort [47, 48].

2.2.3 Common fire ventilation methods in car park

Underground car parks are common in urban or densely populated areas. These car parks can be associated with being exposed to risks such as fire and explosions. As such, fire safety is an important issue in managing underground car parks. Studies related to this issue such as those conducted on car park ventilation systems and available statistics on heat release rate from recent car fire experiments with modern cars and various setups show that fires in car parks should be a cause of concern even though car fires usually do not spread and therefore, there are less injuries and few deaths. However, a fire that consumes cars can bring detrimental effects to car owners and substantial structural damage can result in cases in which fire spreads between vehicles. The full-scale experiments on new cars have showed high fire HRR amounts which exceed 16 MW when three cars were on fire. The constant fire spread between cars and high heat release rates were due to the severe heat transferred to the neighbouring cars. However, there were several fires in various car parks in countries where these situations have been applied and the fire has extended to many cars. Ventilation systems effect in large car parks causes a decrease of the temperatures and thus, in order for a slower fire spread from the initial burning car to the neighbouring cars, the air flow must reach the fire source. Placing the position of fire in a recirculation zone shows that air flow will basically bypass it and effect of the ventilation will be very limited. In addition, fire sources near a wall provide a more challenging condition for heat control (SHC) system and smoke. This is because the fire-induced flows are stronger, and the fire development is faster. These affects the forced ventilation in which the air flow can reach the fire source and the air flow momentum can be strong enough to defeat the flow resistance provided by the fire-induced smoke flow [5, 44].

2.2.3.1 Mechanical ventilation system Jet fan ventilation systems are preferred over traditional ducted systems as ventilating pollutants from large spaces such as car parks. This ventilation system induces additional airflow within the environment by producing a high discharge thrust and velocity using the axial fans located at the ceiling of environment. Smoke and heat will be discharged from exiting portal within environment. It is very important to consider the selection and situation of jet fans inside environment for controlling the smoke/air velocity and avoiding smoke penetration through open cross-passage doors. Jet fan ventilation systems induce the turbulence in air and smoke movement. Thus, installed fans destroy the existing smoke layer within the smoke-filled zone. Jet fan ventilation systems activate upstream fans by activation of fans downstream of the fire location [5, 23]. These ventilation systems provide a low-pressure region downstream and an overpressure upstream of the fire.

3 Design methodology and parameters

Previous section reviewed the various types of ventilation systems and the existing common fire ventilation methods. It discussed the basic ideas behind ventilation systems with a centralize on the methodologies as well as on the requirements for systems of fire ventilation in various environmental for example car park, tunnel, and building. As result, one of the objectives of fire engineering design is life safety in the case of tunnel, buildings and car park. The fire events and its effects to the fire environments should be controlled, usually by ventilation systems. These systems play a key role in human safety and provide tenable environment. Ventilation system should provide passable air quality for the safe passage of users in order to simplify rescue situations during fire event. This Section describes the fire simulation and smoke spread using the CFD model in a Velodrome environment.

In order to optimize a smoke-control system, a CFD simulation for modelling requires multiple input parameters, a geometric setup and related physical models representing physical phenomena that will be used with focus on the safety issue. The simulation of the smoke spread using CFD in case of fire in Velodrome will be done due to human safety. Therefore, the obtaining trust in CFD and boundary conditions and grid size are important. CFD models usually need large capacity computer workstations or mainframe computers. In CFD models, the space is divided into many cells and uses the governing equations to solve the move of mass and heat between the cells. The governing equations include the equations of conservation of momentum, mass and energy. These partial various equations can be solved numerically by algorithms specifically developed for that purpose. For smoke management applications, the number of cells is generally in the range from tens of thousands to millions. Due of the very large number of cells, CFD models avoid the more generalized engineering equations used in zone models. Through the use of small cells, CFD models can test the situation in much greater detail and account for the impact of irregular unusual air movements and shapes that cannot be addressed by either algebraic equations or zone models [53].

4 Numerical simulation set-up

A schematic presentation of set-up for simulations set-up has been shown at Fig. 3. As seen at Fig. 3, we have 4 points that fresh air jet fan and also fresh air doors come from 4 side of Velodrome. We have installed exhaust systems as longitudinal in Velodrome in 4 zone. Fire cases were created in two positions for simulating behaviour of smoke propagation in various times.

5 Mesh generation

Total number of the elements in mesh generation is reached up to four million. The Fig. 4 show that 3-D View of mesh generation respectively in Velodrome Model. As you can see in these views, mesh cell near fire are very small to create accuracy of model for simulation.

6 Boundary condition

The most integral section of any Computational Fluid Dynamics (CFD) problem is the description of its boundary conditions. Therefore, it is required that the user understands and uses the boundary conditions correctly, wisely and effectively and also comprehend its role in the numerical algorithm. If the boundary conditions are not determined correctly, then the solution might result in blunders and if they are not applied wisely, then the problem-solving time may increase multiple. Different types of boundary conditions are used in CFD for Various conditions and purposes are as follows:

- Inlet boundary condition
- Outlet boundary condition
- Wall boundary conditions
- Constant pressure boundary condition.

The design fire is assumed to be 4 MW by rectangular duct with 3 m^3 with mass flow rate of 11.8 kg/s and with density 1.165 kg/m^3 and velocity of fire 3.376 m/s as shown at Table 2. In this model created the model of fire as a fluid zone with heat generation source with amount of 4 MW. The properties of fire fluid as illustrate in Table 2 in two different positions in Velodrome as we set it accordingly.

We defined 5 zone of boundary condition as you can see in Table 3 and named: Outlet, Fire-Inlet 1, Fire-Inlet 2, Fresh-air-doors, fresh-air-in. By considering to boundary condition, velocity inlet is adopted for fresh air inlets form doors. Outflow was chosen for exhaust ducting

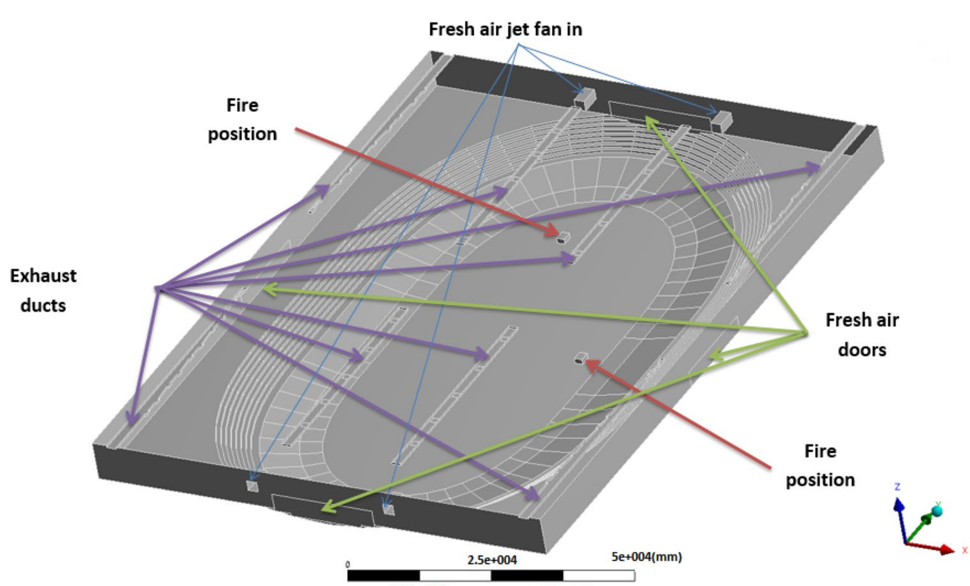

Fig. 3 Schematic presentation of Velodrome as modelled in the simulations

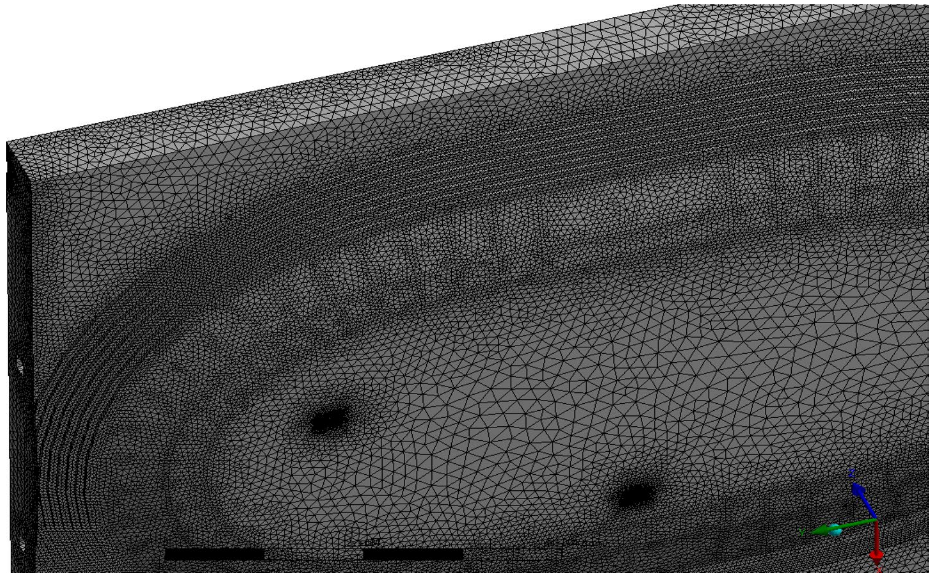

Fig. 4 3-D Mesh generations in Velodrome

Table 2 Fire parameters

Mass flow rate of smoke (kg/s)	Area of fire (m^2)	Density (kg/ m^3)	Velocity of Fire (m/s)	Smoke temperature (k)
11.8	3	1.165	3.376	629.9

Table 3 Parameters of Velodrome configuration and ventilation system

Parameter	Value
Velodrome cross section area	85.5 m (width)_124 m (length)_13.5 m (height) Volume properties: 1.2327e+014 mm^3
Velodrome ceiling height above ground	13 m
Design fire heat release rate (HRR)	4 MW
Smoke extraction rate	22175 CFM
Air flow generated with each jet fan	31405 CFM
Effective opening area per duct	4 m^2 for duct
Velocity fresh air from each door	0.2 m/s

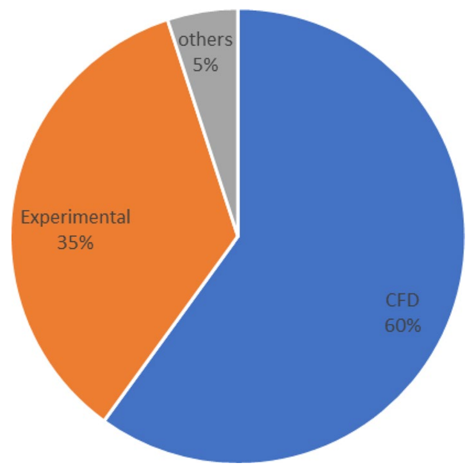

Fig. 5 Summary of measurement methods tools applied in Tunnel, building and car park

system. The wall boundary condition was taken to be adiabatic, and was applied on the solid walls of Velodrome. A velocity boundary condition was prescribed at the Velodrome Inlet. A free pressure outlet boundary condition was used for the Velodrome Outlet. The temperatures of the ambient air were assumed to be 300 °K.

Velodrome consist floors, ceilings, walls, was assumed as the concrete. Four unit of jet fan were defined as showed in Fig. 5 to blow air inside and air velocity was defined at each fan is 31405 CFM and velocity 3.66 m/s and temperature of 300 k as depicts that conduct throughout duct with Area of 4 m^2 into Velodrome. There are four doors can assist to intake fresh Air that assumed velocity of each door 0.2 m/s and Temperature of 300 K was specified as an air inlet in the natural ventilation situations as shown Table 3 we assumed eight-unit exhausted system to remove smoke from Velodrome with each fan capacity 22175 CFM and extracted smoke throughout Duct as outlet. Besides, the mechanical ventilation included smoke exhaust mode and air supply mode. A rectangular duct protrudes from the wall to create a velocity initiated close to the fire. This duct-mounted makeup air vent serves as the makeup air that will produce the maximum interaction between the flame zone and the fire. The magnitude of the velocity, as well as the location and size of the duct vary in each simulation configuration.

Ducting system in Velodrome throughout jetfans that velocity of fan inlet is 31405 CFM and each outlet has 2000 CFM. CFM stands for cubic feet per minute (airflow). The measurement is taken when the ceiling fan is on its highest speed and uses both the volume of air and the rate at which it moves.

The computational area includes a generic Velodrome segment with a dimension of 85.5 m (width)_124 m (length) and 13.5 m (height) with Total number of the elements in mesh generation is reached up to four million. Boundary conditions are assumed for the four side of the Velodrome segment that was modelled. Total effective extraction rate achieved at the fire location was calculated based on the velocity and the downstream air flow as well. Four unit of jet fan were defined to blow air inside and air velocity was defined at each fan to be 31405 CFM, with the velocity of 3.66 m/s and temperature of 300 °K that is conducted throughout duct into the Velodrome. There are four doors that assist to intake fresh Air with assumed velocity of each door to be 0.2 m/s and temperature of 300 °K was described as the air velocity inlet of the natural ventilation system. Eight-unit exhaust system is assumed to remove smoke from Velodrome with the fan capacity of 22175 CFM to extract the smoke throughout the duct as outlet. Besides, the mechanical ventilation included for smoke exhaust mode and air supply mode. This model is analysed in placing fire far from exhaust ducts that is being analysed below.

7 CFD modeling and analysis

In this section, the effects of ventilation airflow field as well as CO concentration inside Velodrome have been analysed and presented. Simulations were also executed for CO concentration, Velocity and Temperature, to simulate of growing environment in Velodrome is done to design and propose an improved air circulation system that provides a desired average air current speed. The design of air circulation system with perforated air tubes is able to improve the air movement at Velodrome. The four units of air jets on the perforated air tube have helped to expand the coverage of air flow at Velodrome.

CFD simulations are analysed to show the effects of duct mounted ventilation on the fire. This analysis concentrates on the effect of the increased air velocity on the mass flow rate of the fire as well as the smoke layer interface height within the Velodrome.

Table 4 Summary of simulation cases developed

Case ID	Case description
Case A	Mechanical ventilation system with smoke exhaust, fire is assumed located at the centre of Velodrome far side from exhausted system
Case B	Mechanical ventilation system with smoke exhaust, fire is assumed located at the corner of Velodrome between exhausted system

8 Smoke analysis of case study

The position of fire is located in far from exhaust system ducts in ceiling and Centre of Velodrome that smoke propagation, velocity and Temperature are analysed according to exhaust system.

To study the effect of variations of each individual parameter, only one parameter is changed between each case. This rolling baseline scheme, where a single parameter is modified in a simulation case, is used to identify unique impacts of each parameter. Variation sequences for the analysed cases are summarized in Table 4.

The engineering analysis employed Computational Fluid Dynamics (CFD) modelling techniques to simulate and visualize the smoke flow behaviour for the cases described above. Case A was different from Case B with the different position of fire. Figures 6 and 7 shows smoke pattern and propagation in different times 0–90 min when exhaust system turned "OFF" (a), and exhaust systems turned "ON" (b).

Compared to a fire located at the Velodrome, for a fire on the lane near the Velodrome wall that is far from the exhaust duct, as shown in Fig. 6, the required critical velocity to maintain the Velodrome visibility and tenability was required to be increased by 20%. Supplemented by smoke extraction, a modified critical velocity of 3.0 m/s can control the smoke back layering, which is an increase compared to the case with the fire cantered in the Velodrome.

9 Conclusions

This paper presents a review of the literature that analyses the use of fire ventilation methods in fire safety and measurement methods used as the performance of ventilation systems. We conclude that ventilation system can play a main role in the ensuring human safety in Tunnel, Building, Carpark. Hence, ventilation systems have attracted huge attention of academics and practitioners. In this research, we have identified longitudinal, mechanical, transitive,

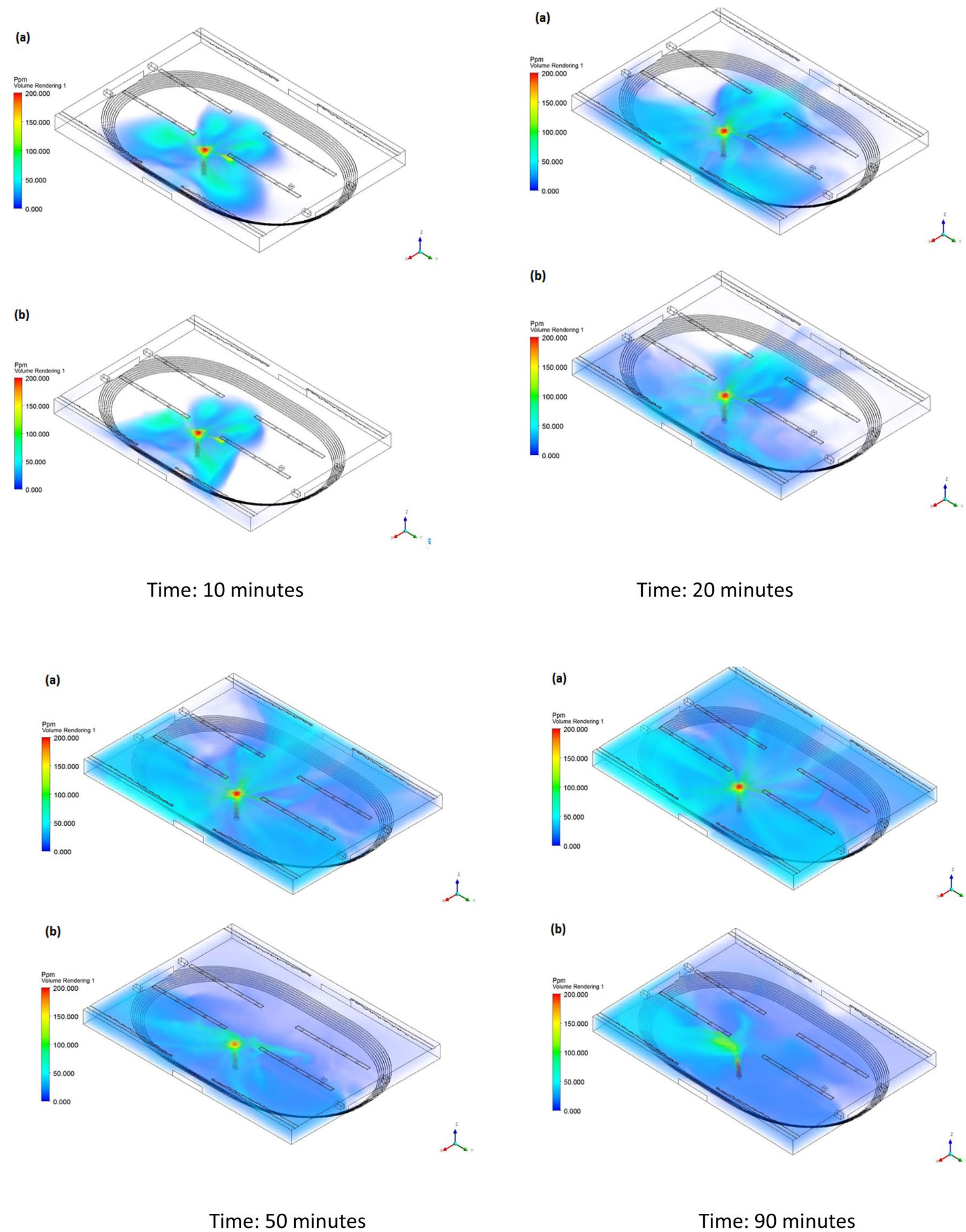

Fig. 6 View of the smoke propagation in PPM, Exhaust system "OFF" (**a**) and Exhaust system "ON" (**b**) in case A after 10, 20, 50, 90 min

natural, hybrid ventilation as ventilation methods in Tunnel, Building, Carpark and around 60% of papers used CFD method to analysis their works.

In additional, the behaviour of fire in building's environmental named Velodrome and the effect of ventilation system were studied. We proposed a Computational Fluid Dynamics (CFD) simulation of exhaust ventilation system for controlling smoke and air flow pattern during fire condition in Velodrome. The CFD model would give a clear picture on smoke movement and control in the case of fire. Performance of our ventilation system in two different location of fire sources (case A and B)

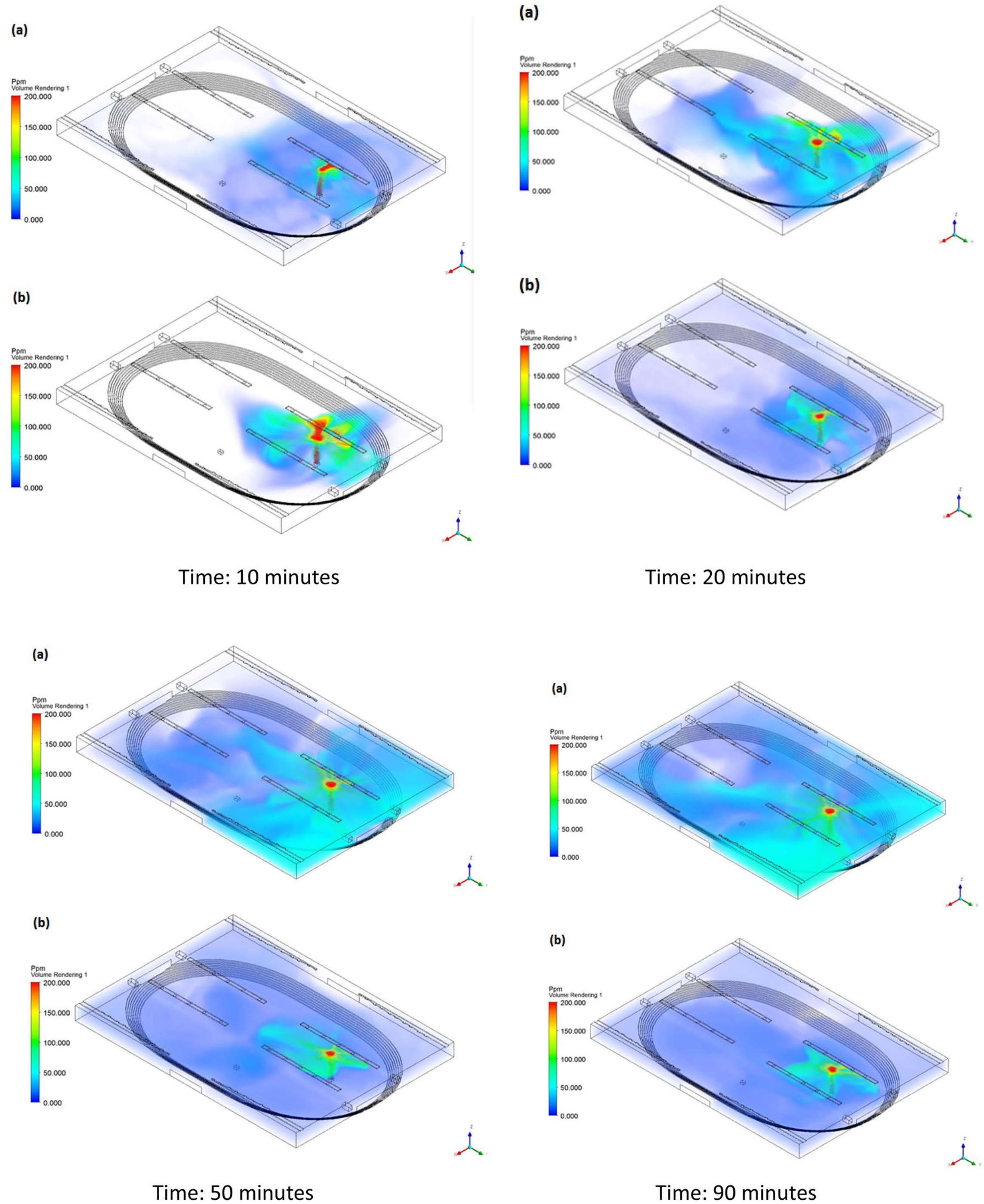

Fig. 7 View of the smoke propagation in PPM, Exhaust system "OFF" (**a**) and Exhaust system "ON" (**b**) in case B After 10, 20, 50, 90 min

were evaluated and the result showed that the effect of fire plumes on case B is better due to near opening of exhaust system and critical ventilation velocity is related to fire location in the Velodrome. As result, based on analysis of case A and B, higher performance of the exhaust system has been achieved with Case B.

It is important to consider the fire location in design of smoke ventilation system. The smoke ventilation system can be designed to slow down the smoke layer descent rate or keep an acceptable smoke layer height to extend the smoke filling time. By considering the overall performance of our ventilation system, a critical velocity of

2–3 m/s, and operation of 20 duct with a total face area of 80 m^2 was discovered that it is able to manage the smoke within a fire zone.

Compliance with ethical standards

Conflict of interest The author(s) declare that they have no competing interests.

References

1. Barbato L, Cascetta F, Musto M, Rotondo G (2014) Fire safety investigation for road tunnel ventilation systems: an overview. Tunn Undergr Space Technol 43:253–265
2. Solgi E, Hamedani Z, Fernando R, Skates H, Orji NE (2018) A literature review of night ventilation strategies in buildings. Energy Build 173:337–352
3. Cao C, Gao J, Wu L, Ding X, Zhang X (2017) Ventilation improvement for reducing individual exposure to cooking-generated particles in Chinese residential kitchen. Indoor Built Environ 26(2):226–237
4. Cao Z, Wang Y, Duan M, Zhu H (2017) Study of the vortex principle for improving the efficiency of an exhaust ventilation system. Energy Build 142:39–48
5. Kashef A, Yuan Z, Lei B (2013) Ceiling temperature distribution and smoke diffusion in tunnel fires with natural ventilation. Fire Saf J 62:249–255
6. Zhong W, Lv J, Li Z, Liang T (2013) A study of bifurcation flow of fire smoke in tunnel with longitudinal ventilation. Int J Heat Mass Transf 67:829–835
7. Liu Y, Cassady S (2014) A modified critical velocity for road tunnel fire smoke management with dedicated smoke extraction configuration. Case Stud Fire Saf 2:16–27
8. Wang F, Wang M (2016) A computational study on effects of fire location on smoke movement in a road tunnel. Tunn Undergr Space Technol 51:405–413
9. Li L, Li S, Wang X, Zhang H (2012) Fire-induced flow temperature along tunnels with longitudinal ventilation. Tunn Undergr Space Technol 32:44–51
10. Heidarinejad G, Mapar M, Pasdarshahri H (2016) A comprehensive study of two fire sources in a road tunnel: considering different arrangement of obstacles. Tunn Undergr Space Technol 59:91–99
11. Seike M, Kawabata N, Hasegawa M (2017) Quantitative assessment method for road tunnel fire safety: development of an evacuation simulation method using CFD-derived smoke behavior. Saf Sci 94:116–127
12. Musto M, Rotondo G (2015) CFD analysis of a realistic reduced-scale modeling equipped with axial jet fan. Fire Saf J 74:11–24
13. Guo X, Zhang Q (2014) Analytical solution, experimental data and CFD simulation for longitudinal tunnel fire ventilation. Tunn Undergr Space Technol 42:307–313
14. Gannouni S, Maad RB (2015) Numerical study of the effect of blockage on critical velocity and backlayering length in longitudinally ventilated tunnel fires. Tunn Undergr Space Technol 48:147–155
15. Zhang S, Yao Y, Zhu K, Li K, Zhang R, Lu S, Cheng X (2016) Prediction of smoke back-layering length under different longitudinal ventilations in the subway tunnel with metro train. Tunn Undergr Space Technol 53:13–21
16. Muhasilovic M, Duhovnik J (2012) CFD-based investigation of the response of mechanical ventilation in the case of tunnel-fire. Strojniski Vestnik/J Mech Eng 58(3):183–190
17. Fan CG, Ji J, Wang W, Sun JH (2014) Effects of vertical shaft arrangement on natural ventilation performance during tunnel fires. Int J Heat Mass Transf 73:158–169
18. Wang HY (2009) Prediction of soot and carbon monoxide production in a ventilated tunnel fire by using a computer simulation. Fire Saf J 44(3):394–406
19. Yi L, Xu Q, Xu Z, Wu D (2014) An experimental study on critical velocity in sloping tunnel with longitudinal ventilation under fire. Tunn Undergr Space Technol 43:198–203
20. Zhong W, Li Z, Wang T, Liang T, Liu Z (2015) Experimental study on the influence of different transverse fire locations on the critical longitudinal ventilation velocity in tunnel fires. Fire Technol 51(5):1217–1230
21. Tanaka F, Majima S, Kato M, Kawabata N (2015) Performance validation of a hybrid ventilation strategy comprising longitudinal and point ventilation by a fire experiment using a model-scale tunnel. Fire Saf J 71:287–298
22. Tang F, Cao ZL, Chen Q, Meng N, Wang Q, Fan CG (2017) Effect of blockage-heat source distance on maximum temperature of buoyancy-induced smoke flow beneath ceiling in a longitudinal ventilated tunnel. Int J Heat Mass Transf 109:683–688
23. Yao Y, Cheng X, Zhang S, Zhu K, Shi L, Zhang H (2016) Smoke back-layering flow length in longitudinal ventilated tunnel fires with vertical shaft in the upstream. Appl Therm Eng 107:738–746
24. Du T, Yang D, Peng S, Liu Y, Xiao Y (2016) Performance evaluation of longitudinal and transverse ventilation for thermal and smoke control in a looped urban traffic link tunnel. Appl Therm Eng 96:490–500
25. Chen Y, Zhou X, Fu Z, Zhang T, Cao B, Yang L (2016) Vertical temperature distributions in ventilation shafts during a fire. Exp Thermal Fluid Sci 79:118–125
26. Beard AN (2016) Major fire spread in a tunnel with water mist: a theoretical model. Tunn Undergr Space Technol 53:22–32
27. Harish R, Venkatasubbaiah K (2014) Effects of buoyancy induced roof ventilation systems for smoke removal in tunnel fires. Tunn Undergr Space Technol 42:195–205
28. Ji J, Gao ZH, Fan CG, Sun JH (2013) Large Eddy Simulation of stack effect on natural smoke exhausting effect in urban road tunnel fires. Int J Heat Mass Transf 66:531–542
29. Yuan Z, Lei B, Kashef A (2015) Experimental and theoretical study for tunnel fires with natural ventilation. Fire Technol 51(3):691–706
30. Weng MC, Yu LX, Liu F, Nielsen PV (2014) Full-scale experiment and CFD simulation on smoke movement and smoke control in a metro tunnel with one opening portal. Tunn Undergr Space Technol 42:96–104
31. Ura F, Kawabata N, Tanaka F (2014) Characteristics of smoke extraction by natural ventilation during a fire in a shallow urban road tunnel with roof openings. Fire Saf J 67:96–106
32. Ji J, Wan H, Gao Z, Fu Y, Sun J, Zhang Y, Li K, Hostikka S (2016) Experimental study on flame merging behaviors from two pool fires along the longitudinal centerline of model tunnel with natural ventilation. Combust Flame 173:307–318
33. Tilley N, Rauwoens P, Merci B (2011) Verification of the accuracy of CFD simulations in small-scale tunnel and atrium fire configurations. Fire Saf J 46(4):186–193
34. Zhou W, Qin H, Qiu J, Fan H, Lai J, Wang K, Wang L (2017) Building information modelling review with potential applications in tunnel engineering of China. R Soc Open Sci 4(8):170174
35. Mei F, Tang F, Ling X, Yu J (2017) Evolution characteristics of fire smoke layer thickness in a mechanical ventilation tunnel with multiple point extraction. Appl Therm Eng 111:248–256

36. Vidmar P, Petelin S, Luin B (2012) Upgrade of a transverse ventilation system in a bi-directional tunnel. Therm Sci. https://doi.org/10.2298/TSCI120212053V
37. Hahm D, Igor Maevski PE (2014) The effects of ventilation systems on fixed fire suppression systems in tunnels. ASHRAE Trans 120:T1
38. Yi L, Wei R, Peng J, Ni T, Xu Z, Wu D (2015) Experimental study on heat exhaust coefficient of transversal smoke extraction system in tunnel under fire. Tunn Undergr Space Technol 49:268–278
39. Wahlqvist J, Van Hees P (2013) Validation of FDS for large-scale well-confined mechanically ventilated fire scenarios with emphasis on predicting ventilation system behavior. Fire Saf J 62:102–114
40. Hostikka S, Janardhan RK, Riaz U, Sikanen T (2017) Fire-induced pressure and smoke spreading in mechanically ventilated buildings with air-tight envelopes. Fire Saf J 91:380–388
41. Zhang Y, Kacira M, An L (2016) A CFD study on improving air flow uniformity in indoor plant factory system. Biosyst Eng 147:193–205
42. Su C, Yao C (2016) Performance measurement of a smoke extraction system for buildings in full-scale hot smoke test. Measurement 93:340–350
43. Huang H, Ooka R, Chen H, Kato S (2009) Optimum design for smoke-control system in buildings considering robustness using CFD and Genetic algorithms. Build Environ 44(11):2218–2227
44. Węgrzyński W, Krajewski G (2017) Influence of wind on natural smoke and heat exhaust system performance in fire conditions. J Wind Eng Ind Aerodyn 164:44–53
45. Xu Z, Lu XZ, Guan H, Chen C, Ren AZ (2014) A virtual reality based fire training simulator with smoke hazard assessment capacity. Adv Eng Softw 68:1–8
46. Yang D, Li P (2015) Dimensionless design approach, applicability and energy performance of stack-based hybrid ventilation for multi-story buildings. Energy 93:128–140
47. Lim YH, Yun HW, Song D (2015) Indoor environment control and energy saving performance of a hybrid ventilation system for a multi-residential building. Energy Procedia 78:2863–2868
48. Gao R, Li A, Hao X, Lei W, Zhao Y, Deng B (2012) Fire-induced smoke control via hybrid ventilation in a huge transit terminal subway station. Energy Build 45:280–289
49. Deckers X, Haga S, Sette B, Merci B (2013) Smoke control in case of fire in a large car park: full-scale experiments. Fire Saf J 57:11–21
50. Enright PT (2014) Impact of jet fan ventilation systems on sprinkler activation. Case Stud Fire Saf 1:1–7
51. Viegas JC (2010) The use of impulse ventilation for smoke control in underground car parks. Tunn Undergr Space Technol 25(1):42–53
52. Merci B, Shipp M (2013) Smoke and heat control for fires in large car parks: lessons learnt from research? Fire Saf J 57:3–10
53. NFPA, NFPA 92 Standard for Smoke Control Systems 2015 Edition, 2015
54. Ai ZT, Mak CM (2016) Short-term mechanical ventilation of air-conditioned residential buildings: a general design framework and guidelines. Build Environ 108:12–22
55. Nomura M, Hiyama K (2017) A review: natural ventilation performance of office buildings in Japan. Renew Sustain Energy Rev 74:746–754