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A new tunnel fire detection and suppression system based on camera image processing and water mist jet fans

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ABSTRACT

Several tunnel fire detection and fighting systems are currently available in the market, each with its own pros and cons. Although no single system is perfect, the water mist system is one of the top-performing conventional tunnel fire suppression systems available. The problem is that such system is expensive. More affordable equipment with similar performance would be a breakthrough in the field of tunnel safety. Accordingly, this study develop a new water mist system, in which ventilation jet fans are utilized in such a way to achieve economical feasibility. The system features monitoring cameras use to determine fire coordinates and mist-generating jet fans employed to suppress fire. The front of the ventilation jet fans is equipped with nozzles, which spray water frontward through the fans, thereby creating mist and propelling it toward the location of a fire. The mist that shoots out of the fans reduces ambient temperature, flushes oxygen, cools the surface of inflammable materials, and weakens radiative and convective effects. The simulation of the proposed system shows a low heat release rate, smoke and toxic fumes reduction, tunnel ventilation speed increases, and improved visibility. These improvements enhance tunnel safety and make tunnel conditions during a fire less threatening to human health. The cost of the system put forward in this work can be further reduced by optimizing the materials that constitute the pipes and fittings and removing the firefighting pumps.

1. Introduction

A water mist system is a fire protection system that controls and suppresses fire by projecting ultrafine droplets onto a target, thereby reducing ambient temperature, replacing oxygen with vapor, and eliminating fire radiation effects. The droplets are produced by the high-pressure pumping of water through a small nozzle. Water mist systems are widely used during fires in road tunnels. In the past, the use of water systems in such underground passages were prohibited by European and North American standards. For example, Annex D of the Standard for Road Tunnels, Bridges, and Other Limited Access Highways of the National Fire Protection Association (i.e., NFPA 502) rejected the use of water systems in tunnels for reasons such as reduced vision, the possibility of gas explosion due to water spray, and potential steam damage to people. This standard also advised against the installation of sprinkler systems in tunnels, except in those traversed by hazardous heavy vehicles.

These stipulations were reconsidered by road tunnel authorities after the tunnel fires that occurred between 1995 and 2005 and the consequent financial losses. Attempts to rectify the flaws of existing water mist systems followed. Over time, these systems gradually became a cornerstone of tunnel safety. Despite the limitations associated with water mist systems, the installation of such firefighting equipment in tunnels presents merits, including desirable control over fire size and spread rate and reliable maintenance of tunnel conditions [1, 2, 3]. In its latest edition, NFPA 502 recommends the use of water mist technology with deluge configurations in Category C and D tunnels [4].

The effective and reliable preservation of breathing conditions in tunnels necessitates the rapid detection of fire and the implementation of firefighting measures [5]. With these requirements in mind, we developed a new tunnel fire detection and suppression system, through which fire is detected with the help of image processing and controlled in a manner similar to how water mist systems operate but with the added advantage of ventilation jet fans. In the proposed system, an image processing subsystem is fed data by monitoring cameras that identify the occurrence and coordinates of a fire in a tunnel. Upon fire detection, the mist required to control the fire is generated via the pumping of water provided by low-pressure urban water pipelines through a series of nozzles located in front of the ventilation jet fans. The fans operate at higher-than-normal revolutions per minute and thereby produce water

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droplets with a diameter less than 300 μm.

The rest of the paper is structured as follows. Section 2 presents a review of standards and studies on fire detection and firefighting in tunnels. Section 3 explains the proposed system, its structure, how it detects and locates fire, how firefighting procedures are implemented, and how the water mist jet fans suppress fire. Section 4 is dedicated to the analysis of the system via the Fire Dynamics Simulator (FDS) used with Pyrosim. It also provides comparison tables and the results of the FDS and computational fluid dynamics analyses, which are necessary to evaluate improvement in firefighting performance and tunnel safety. Section 5 concludes the paper with a summary of the findings.

2. Related work

Upon the occurrence of a fire, the most important step in limiting its consequences is the timely response of a fire detection system in alerting people and triggering firefighting procedures. A study conducted by the Canadian national research council revealed that among the fire detectors widely used in tunnels, CCTV cameras have one of the best response times under adverse tunnel conditions. They have exhibited a response time of less than 1 minute for large fires with a rapid spread rate [6]. Because CCTV cameras can reliably monitor a fire, they can also identify its size, location, and spread rate. These devices are equipped with image processing technology that enables the identification of the coordinates of a fire in a tunnel by simply zoning the tunnel and synchronizing the zones with camera images [7, 8, 9].

In recent years, water-based firefighting systems have undergone major developments; various fire protection systems for tunnels are currently available, ranging from sprinkler systems that release large water droplets to water mist systems that are based on different technologies [1]. Until 2004, fire protection authorities were opposed to the use of water-based firefighting systems in tunnels, arguing that water may facilitate gasoline explosion and that water vapor may hurt people and reduce vision; these factors collectively increase the possibility of additional incidents in a tunnel [10]. With the lessons learned from the tunnel accidents that occurred between 1995 and 2005, further efforts were made to control fires and their effects. Such efforts involved the use of ventilation jet fans and the retrofitting of tunnels. These measures, however, were proven insufficient during tests conducted in a Norwegian tunnel; the researchers found that fire fueled by a bus accident produces about 20 MW of heat a problem that cannot be adequately addressed by the existing fire protection systems [11]. This deficiency prompted the revision of fire protection standards, which now recommend the use of water spray or water mist firefighting systems to control and suppress fires. The effectiveness of this recommendation was confirmed in a tunnel in Spain. A water mist system has promising potential for not only controlling fire but also improving air quality and reducing toxic fumes. As a result, the system became known as an effective suppression system for fires in tunnels [12, 13, 14].

Analysis of vehicle fires and testing data shows that heat release rates can reach 20 MW in a few minutes. Based on this data following frame of plausible fire scenarios could be drawn:

1. A small slow growing passenger car fire (HRRmax = 0.5 MW)
2. A fast growing passenger car (HRRmax = 4 MW)
3. A collision involving two passenger cars (HRRmax = 8 MW)
4. A fast bus fire (HRRmax = 30 MW)
5. A HGV fire (HRRmax = 100 MW)

The main objectives of water mist systems in tunnel are to reduce:

1. The rate of growth of the fire;
2. The heat release rate of the fire;
3. The limit size of the fire;
4. The risk of fire spread from one vehicle to another.

Building upon existing smoke and fire suppression systems, we introduce a new water mist system that utilizes ventilation jet fans to achieve an efficiency higher than that of its predecessors. The advantage of the system lies in the changes applied to the functioning of ventilation jet fans that are already installed in a tunnel. This refinement renders the system more economic than its counterparts.

3. Theory

The proposed system consists of three subsystems, namely, the detection, processing, and firefighting subsystems. Each subsystem and the principles that underlie its operation are explained in the succeeding sections.

3.1. Fire detection

The fire detection subsystem detects fires through the processing of images captured by monitoring cameras and liner heat detector that work simultaneously. Once a fire is detected, its coordinates are determined and sent to the processing subsystem [made of field-programmable gate arrays (FPGAs)], which then directs the firefighting subsystem to activate local water mist jet fans and accordingly focus a control measure on the exact location zone of the fire. The segmentation of tunnel space during the fire detection stage is performed with the help of fire detection by Video Image Processing cameras (Fig. 1) [2, 3].

As shown in Fig. 1, smoke coordinates are rapidly detected when a fire is at a considerably small magnitude (i.e., releasing less than 1 MW of heat). At this stage, fire and smoke can be effectively controlled with a small amount of water and energy, as required by fire protection standards. The water required for this purpose is provided by a water mist jet fan, which shoots the water toward the desired coordinates.

Fig. 2 presents the algorithm for detecting smoke or flame and activating the countermeasure system accordingly. Fire coordinate codes can be attached to fire alarm signals so that information on fire location can also be sent to the processing subsystem.

Early fire detection by Video Image Processing combined with LHD in tunnel can detect fire less than 1 minutes then the proposed fire extinguish system actives while the fire is under 3MW.

3.2. Fire data processing

Today, remote control centers that are equipped with intelligent systems and run by expert operators are extensively used in nearly all major cities in the world to improve traffic management and transportation performance. In a fire detection system, detection can be made either by the human operators who monitor tunnels or by a dedicated subsystem that operates on the basis of a predetermined algorithm [6]. The proposed fire detection and control system comes with a control center that is responsible for the automatic control and management of the system. However, this control center can also be operated and programmed from a distance by human operators in response to unforeseeable events.

Once smoke or flame is detected, its characteristics, such as flame dimensions, generated smoke, and location coordinates (XYZ), are fed to an FPGA chip, which processes the information to produce commands that must be sent to the components of the water supply system and water mist jet fans. The commands sent to the water supply components include the activation of fire pumps and the opening of solenoid valves that allow water to flow into the nozzles located in front of the jet fans. The proposed system also allows for the advance estimation of the quantity of water required for each jet fan on the basis of type of fire and fire dimensions. In the event of a fire, flame and smoke detection cameras identify the site where the fire has occurred and convert the ascertained location into a coordinate code, which is then sent to the motors that control the direction of the jet fans. The code directs the motors to turn the jet fans toward the fire. The rotational speed of the jet fans are then

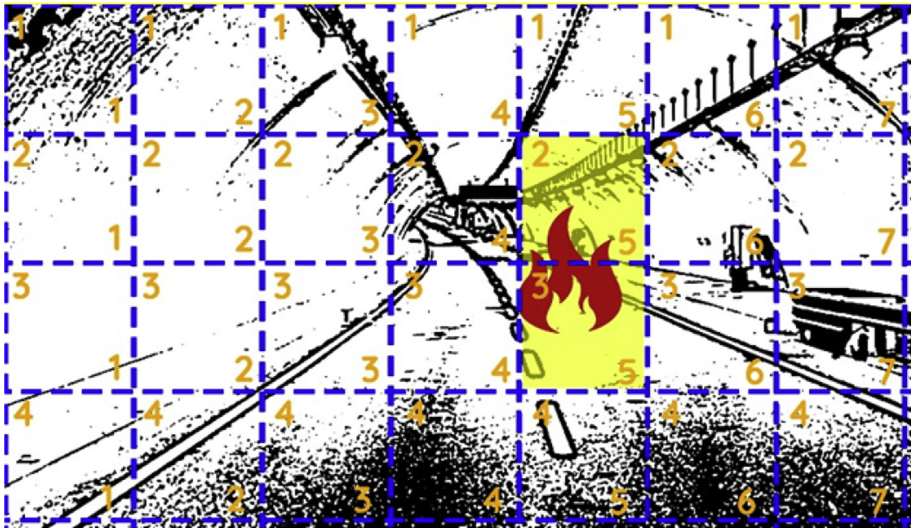

Fig. 1. Fire detection and location by image processing.

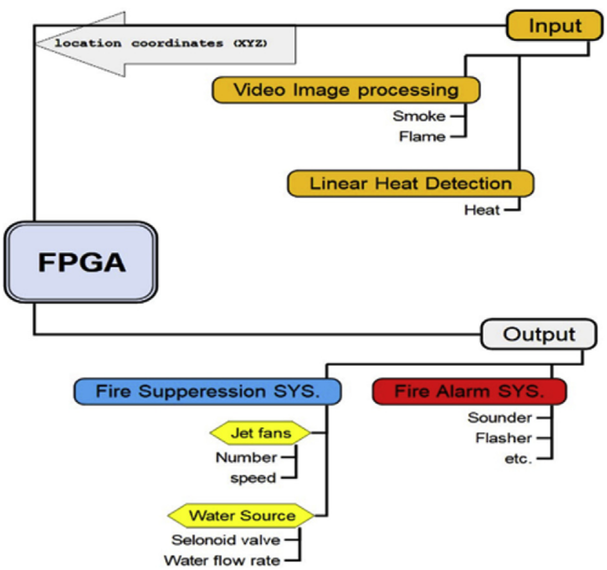

Fig. 2. Fire and smoke detection and signaling algorithm.

adjusted in such a way as to spray water mist toward the exact location of the fire. The amount of water for suppressing the fire is controlled by means of solenoid valves. The mechanism that underlies control over water pipes and valves is explained in Section 4. Fig. 3 illustrates the procedure with which fire data are processed in the proposed water mist system.

3.3. *Firefighting*

The NFPA standard classifies tunnels into five categories according to size [4].

1. Category X: Tunnels with a length shorter than 90 m.
2. Category A: Tunnels with a length equal to or longer than 90 m.
3. Category B: Tunnels with a length equal to or longer than 240 m or tunnels where one segment is located at least 120 m from the nearest safe point.
4. Category C: Tunnels with a length equal to or longer than 300 m.
5. Category D: Tunnels with a length equal to or longer than 1000 m.

According to Clause 7.10.1 of NFPA 502 (2017), Category C and D tunnels must be fitted with a fixed firefighting system. It also states that firefighting systems for tunnels can be classified into two categories: fire control systems and fire suppression systems. The system put forward in this work corresponds to both these categories. It consists of two sections, namely, the water supply and mist generation sections. The water supply section comprises urban water resources, water pipelines, remote-controlled solenoid valves, and water spray nozzles installed in front of the jet fans. As stipulated in Clause 10.2 of NFPA 502, the water to be used for suppressing a fire in a tunnel should be connected to a resource large enough to provide the required volume of water for at least 1 hour. In the mist generation section of the system, ventilation jet fans are used to generate water mist. For this purpose, water is pumped from a resource via pipelines toward the nozzles located in front of the jet fans. Simultaneously, the rotational speed of the jet fans are increased to sharply enhance their exhaust power. In the nozzles, water is combined with air and then propelled toward the fans to generate water mist and concentrate it onto the exact location of a fire. This action dramatically reduces the temperature and oxygen content of the fire and thereby suppresses the blaze. Note that this feature also leads to considerable water conservation and cost savings in terms of firefighting pumps and pipes. Furthermore, the use of a low volume of water causes minimal damage to a tunnel's structure.

Tunnel fires can be categorized into two classes: Class A fires, which are caused by inflammable solids, and Class B fires, which are caused by inflammable liquids. These fires can be suppressed through sprinkler systems, deluge water spray systems, water mist systems, and foam systems, each with their own flaws and merits (Table 1). As indicated in Table 1, a water mist system exhibits the best performance in tunnels and is highly recommended by the majority of today's standards [15, 16].

However, it is far more expensive than conventional water-based systems because it requires extremely high-pressure equipment, such as fire pumps and steel pipes, and relatively expensive solenoid valves. According to the NFPA 750 standard, there are three classes of water mist systems: high-, medium-, and low-pressure systems. High-pressure water mist systems have an operating pressure of about 100–160 bars and transform water completely into mist, resulting in approximately 1700 times higher heat absorption than that achieved with conventional sprinklers. Low- and medium-pressure water mist systems have an operating pressure of less than 35 bars and generally work at pressures of 4–12 bars, which is close to the pressure range of conventional sprinklers. In these systems, water is converted completely into powder form and subsequently into ultrafine droplets. Compared with ordinary sprinklers,

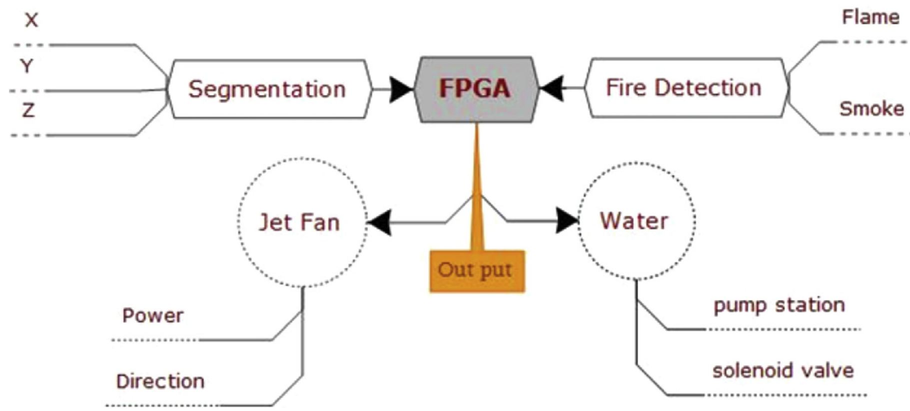

Fig. 3. Procedure for processing fire data and issuing commands in the proposed system.

Table 1
Comparison of water-based firefighting systems System type.

Measure of comparison	System type			
	Sprinkler	Deluge	water mist	Foam
Operating pressure	5 bars	5-12 bars	12-160 bars	17 bars
Particle diameter	millimeters 1<	millimeters 1>	300< microns	-
Performance	Poor	Medium	Good	Excellent
Cost	Low	Medium	High	-

water mist systems have 1.4 times lower water consumption and can suppress fire 50 times faster because of the greater surface area spanned by released water droplets.

As indicated in Table 1, the best systems for firefighting in tunnels are water mist and foam systems, but the latter is impractical because of associated high costs. Our approach, therefore, was to improve the water mist system by applying slight modifications to existing ventilation jet fans and transforming them into mist-generation machines capable of producing water particles smaller than 300 μm. The majority of tunnels are equipped with a system of ventilation jet fans that control and flush out smoke, heat, and toxic fumes. In Category D tunnels, the use of emergency ventilation systems is mandatory. The number and capacity of jet fans can be calculated using various methods, but conformity to Clause 11.4 of NFPA 502 requires that the design of tunnel ventilation systems satisfy the release rate requirements for smoke, carbon dioxide, and heat [4]. Correspondingly, we modified a conventional tunnel fire detection and suppression system to establish the firefighting subsystem for controlling fire parameters and tunnel ventilation. In the subsystem (Fig. 4), jet fans more strongly home in on suppressing smoke and toxic fumes rather than on flushing them out of an area. Nevertheless, because of the high operating speed of the jet fans in this subsystem during fires, the fumes created by fire suppression and light toxic fumes are still rapidly expelled from a tunnel (Fig. 5).

Fig. 5 is a general diagram of fire suppression via the proposed water mist system. As indicated in the figure, the combined use of water mist with the ventilation system enables improved control over fire, smoke, and toxic fumes.

4. Calculation

This section presents the results of tests performed using the advanced fire simulation software PyroSim to estimate the performance of the proposed system and improvements in terms of addressing heat, smoke, and vision problems. In essence, PyroSim is a user interface that facilitates working with two applications: the FDS and Smokeview. These applications can simulate the behavior of fires with extreme precision.

Computational Fluid Dynamics (CFD) and Fire Dynamics Simulator (FDS) developed by National Institute of Standards and Technology (NIST), one of the world's largest physics laboratories. Most of studies about tunnel fire safety system are shown that FDS is a reliable and effective numerical tool for tunnel fire simulation. For this reason, we use this software as a simulator of the proposed system.

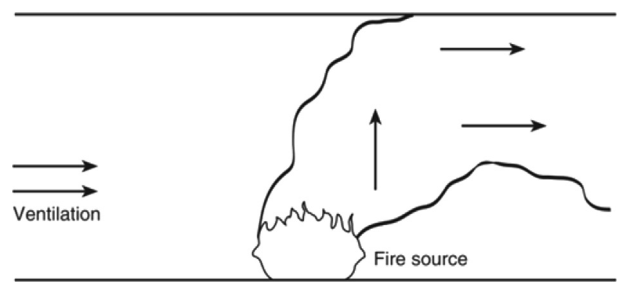

Fig. 4. Path of fire spread in the presence of ventilation [4] [1].

4.1. FDS

FDS simulation software has important applications in the field of simulated combustion and flue gas movement and flame propagation during fire. We considered FDS as a feasible tool to simulate fire happen in environment as it works out numerically a collection of the Navier-Stoker equations for thermally-driven flow. Both DNS (Direct Numerical Simulation) and LES (Large Eddy Simulation) models are included. In this investigation, we chose LES model since it is broadly used in the study of fire induced smoke flow behavior. The governing equations for conservation of mass (1), species (2), momentum (3) and of energy (4) are as follows:

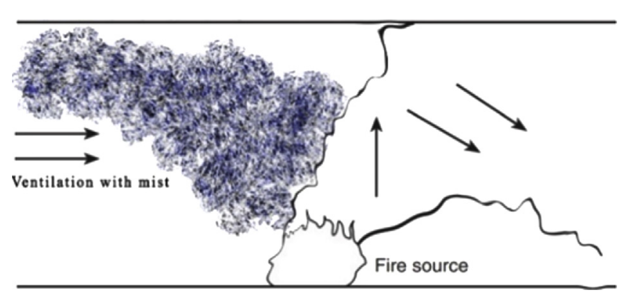

Fig. 5. Fire suppression by the jet fans in the proposed water mist system.

[1] Reproduced with permission of NFPA from NFPA 502, Standard for Road Tunnels, Bridges, and Other Limited Access Highways, 2017 edition. Copyright: copyright© 2016, National Fire Protection Association.

$$\frac{\partial \rho}{\partial t} + \nabla.(\rho u) = 0 \tag{1}$$

$$\frac{\partial}{\partial t}(\rho Y_l) + \nabla.\rho Y_l u = \nabla.(\rho D)_l \nabla Y_l + \dot{m}''' \tag{2}$$

$$\rho\left(\frac{\partial u}{\partial t} + (u.\nabla)u\right) + \nabla p = \rho g + \boldsymbol{f} + \nabla.\tau \tag{3}$$

$$\frac{\partial}{\partial t}(\rho h) + \nabla.\rho h u - \frac{Dp}{Dt} = \dot{q}''' - \nabla.q_r + \nabla.k\nabla T + \nabla.\sum_l h_l(\rho D)_l \nabla Y_l \tag{4}$$

There is a collection of parameters consisting the fluid thermal properties, droplet size distribution and injection features. By using them, the spray specifications are determined at the injection point. FDS spray modeling represents water droplets by using lagrangian particles. Rosin-Rommler and log-normal distributions (5) indicate the droplet size distributions [17].

$$F(d) = \begin{cases} \frac{1}{\sqrt{2\pi}} \int_0^d \frac{1}{\sigma d'} e^{-\frac{\left[\ln\left(d'/d_m\right)^2\right]}{2\sigma^2}} dd', & d \le d_m \\ 1 - e^{-0.693\left(\frac{d}{d_m}\right)^\gamma}, & d_m < d \end{cases} \tag{5}$$

5. Results

PyroSim was used to simulate a 2 × 2 m2 fire in a 500 m long tunnel with a square 6 × 6 m cross-section over a period of 200 seconds. Simulations were performed in four scenarios. The first scenario involves fire in the basic tunnel without any ventilation or fire suppression system. The second features the use of a jet fan system to control smoke. The third scenario was intended to estimate the results of a basic water mist system, and the fourth was designed to evaluated the performance of the proposed water mist jet fan system.

Fire set in Pyrosim simulation is polyurethane. Polyurethane (PUR and PU) is a polymer composed of organic units joined by carbamate (urethane) links, while most polyurethanes are thermosetting polymers that future like class A and class B fire.

The Standard NF EN2 distinguishes among four classes of fires depending on the nature of the fuel:

Class A: fires are solid material fires, generally producing embers when burning.

Class B: fires are liquid or liquefied.

Class C: fire are gas fires.

Class D: fires are metal fires.

In the case of tunnels, the most commonly encountered fire are of class A or B. Given the specificities of tunnel fires, the most appropriate extinguishing agent seems to be pure water. It is applicable to the fires likely to occur in tunnels; it is also the most widely used and best known agent.

5.1. Scenario 1: basic tunnel

Figs. 6, 7, 8, and 9 show the heat release rate (HRR) and the smoke emission, temperature, and vision contours in transverse and longitudinal cross-sections at a height of 2 m above the tunnel floor. The simulation was run at t = 200 seconds.

5.2. Scenario 2: tunnel with a jet fan system

In this simulation, a jet fan with an operating speed of 35 m3/s at a 60 m distance from a fire is used to flush smoke and toxic fumes in one direction. Smoke and toxic fumes generated by vehicles during rush hours need to be expelled from the tunnel, and tunnel ventilation systems have no control over the spread of a fire. Figs. 10, 11, 12, 13, and 14 illustrate the HRR and the smoke emission, temperature, and vision contours in transverse and longitudinal cross-sections at a height of 2 m above the tunnel floor. This simulation was run at t = 200 seconds.

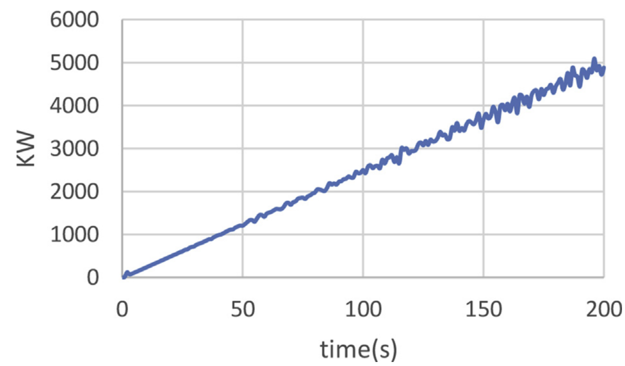

Fig. 6. HRR

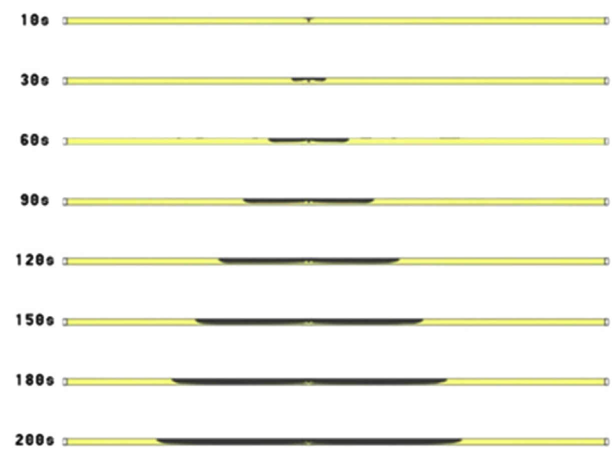

Fig. 7. Smoke emission contour.

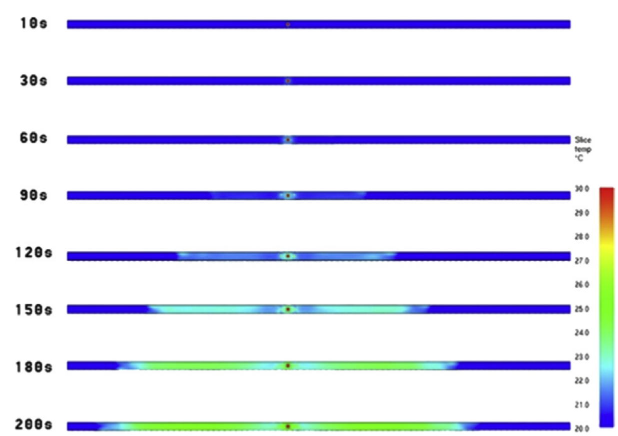

Fig. 8. Temperature contour at 2 m above the tunnel floor.

As shown in Figs. 12, 13, and 14, the jet fans can manage only the smoke and toxic fumes produced by vehicles. Once a fire starts, so much smoke is produced that, in practice, the jet fan system will fail to significantly contribute to smoke management. Even worse, fans can facilitate the spread of fire because they infuse fresh air into a location. These problems highlight the need to design tunnel ventilation systems in such a way as to enable jet fans near a fire to be turned off and an airflow velocity of 8 m3/s to be maintained. These features allow the flushing out

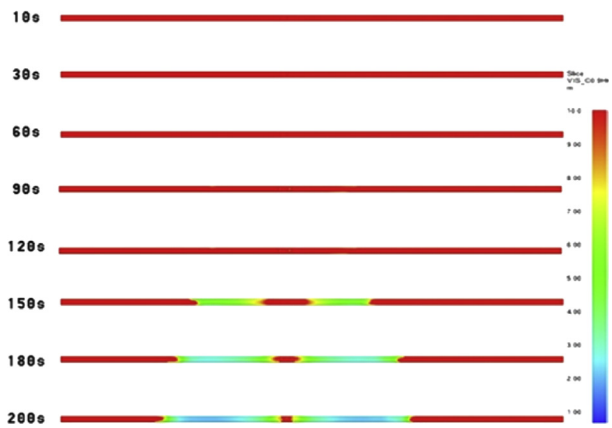

Fig. 9. Vision contour at 2 m above the tunnel floor.

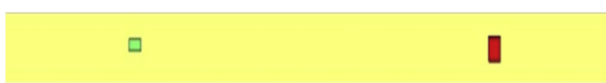

Fig. 10. Location of the jet fan with an operating speed of 35 m3/s at 60 m from a fire.

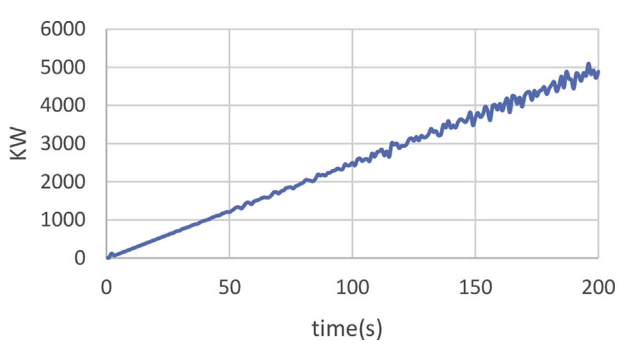

Fig. 11. HRR in the presence of the jet fan.

Fig. 12. Smoke emission contour in the presence of the jet fan.

of toxic fumes without spreading fire. According to the NFPA 502 standard, this scenario is applicable to Category X, A, and B tunnels.

5.3. *Scenario 3: tunnel with a basic water mist system*

The water mist system considered in this simulation has an operating pressure of 80 bars and a nozzle with a K-factor of 4.3

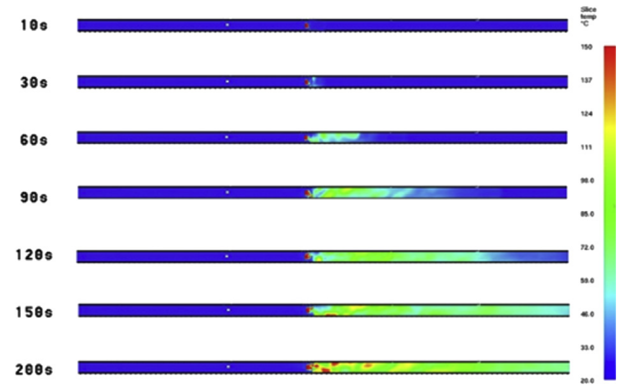

Fig. 13. Temperature contour at 2 m above the tunnel floor in the presence of the jet fan.

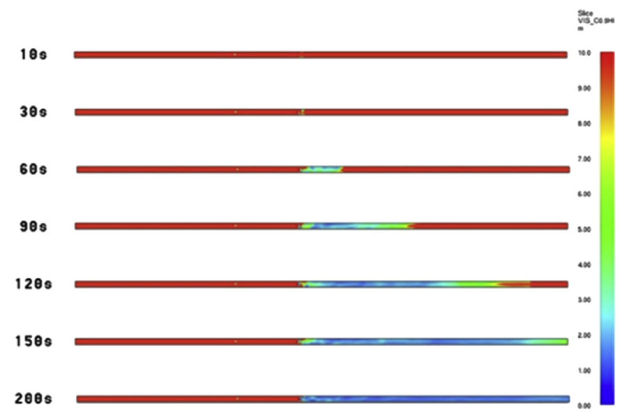

Fig. 14. Vision contour at 2 m above the tunnel floor in the presence of the jet fan.

L/(min. 〚atm〛^(1/2)). It produces water particles with a size of 100 μm. Nozzle activation time was assumed to be 7 seconds after the initiation of a fire. Fig. 15 shows the location of nozzles in the vicinity of the fire.

Figs. 16, 17, 18, and 19 illustrate the HRR and the smoke emission, temperature, and vision contours in transverse and longitudinal cross-sections at a height of 2 m above the tunnel floor. The simulation was run at t = 200 seconds.

The HRR is about 1000 kW, and it takes about 100 seconds for the fire to be completely extinguished. As depicted in Figs. 17, 18, and 19, although the water mist system exerts a minimal effect on smoke, toxic fumes, and field of vision, it excellently controls and suppresses the fire and is therefore a desirable choice for firefighting in the simulated tunnel space.

5.4. *Scenario 4: tunnel with the proposed system*

This scenario involves the proposed system, in which the ventilation jet fans in the tunnel can generate water mist. The water provided by low-pressure urban water pipelines are fed into two nozzles installed in front of the jet fans, which inject the water at the required rate. At the same time, the operating speed of the jet fans is adjusted to propel the water across the desired distance. Fig. 20 presents the location of the nozzles in the PyroSim simulation.

The jet fan has an operating speed of 40 m3/s and is located 29 m away from a fire. System activation time was assumed to be 20 seconds after the initiation of the fire. Fig. 21 shows the location of the jet fans in the tunnel.

The HRR obtained from this simulation is plotted in Fig. 22, which indicates that the fire is completely suppressed after approximately 90 seconds and that the maximum HRR is about 600 kW. As it can be seen,

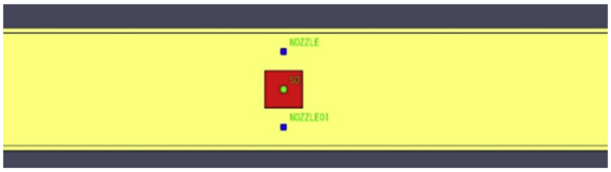

Fig. 15. Location of the water mist nozzles above a fire.

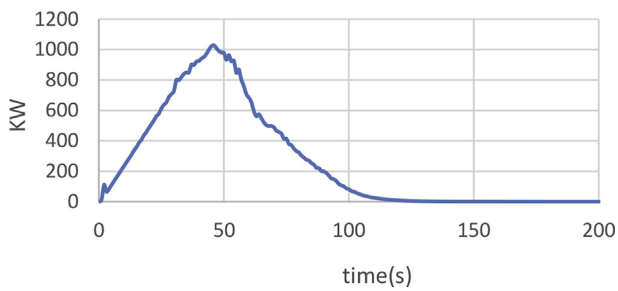

Fig. 16. HRR in the presence of the basic water mist system.

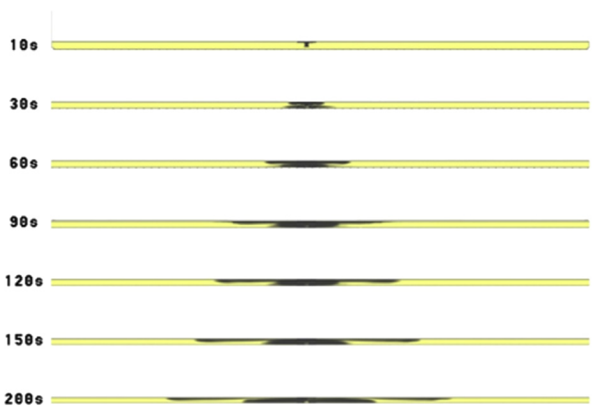

Fig. 17. Smoke emission contour in the presence of the basic water mist system.

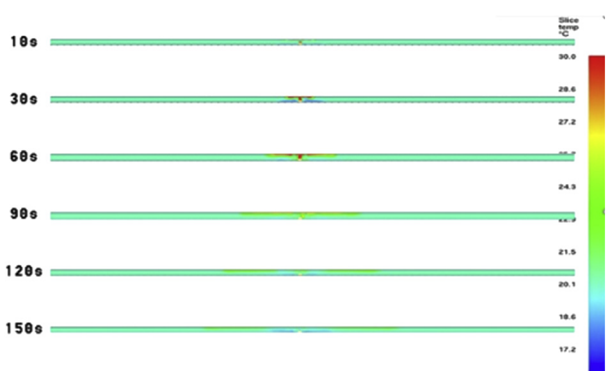

Fig. 18. Temperature contour at 2 m above the tunnel floor in the presence of the basic water mist system.

fire suppression time in this scenario is 10 seconds shorter and the HRR is 400 kW lower than in the third scenario. This reduction in suppression time and HRR can be attributed to the high speed at which water mist is generated by the jet fans. Such generation accelerates the cooling of the surface of inflammable materials and the tunnel space.

Fig. 23 indicates a faster reduction of smoke within the tunnel space in the fourth scenario compared with the third scenario. In the proposed

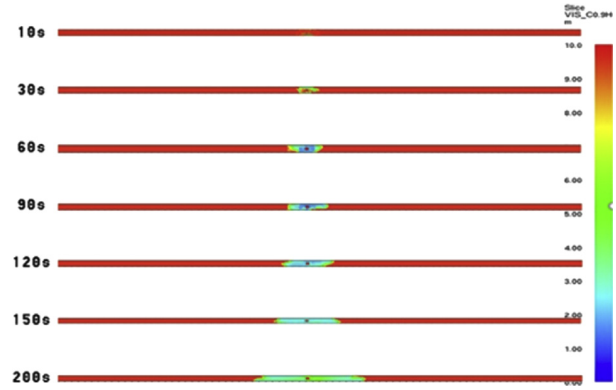

Fig. 19. Vision contour at 2 m above the tunnel floor in the presence of the basic water mist system.

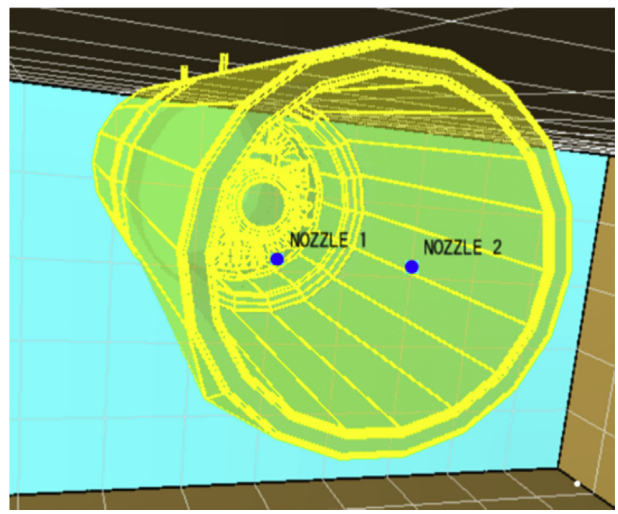

Fig. 20. Location of the nozzles in front of the jet fans.

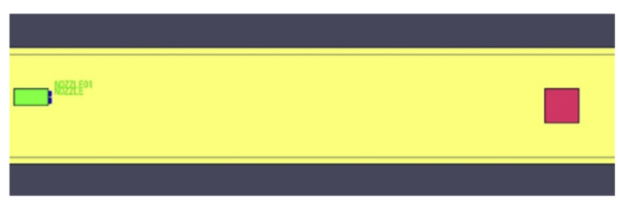

Fig. 21. Location of the jet fans in the tunnel.

system, smoke reduction is achieved in two ways: (i) smoke suppression through the weighing down of particulates following their combination with high-speed water mist and (ii) flushing of light gases through the air circulation above the jet fan water mist system. Given the features of the proposed system, it can also be used to improve air quality in tunnels during rush hours as the system circulates fresh air at a high rate and injects small amounts of water onto a target to facilitate the deposition of fumes and particulates.

The contours of temperature and field of vision at a height of 2 m above the tunnel floor are presented in Figs. 24 and 25. The proposed system restores tunnel temperature to the normal level within 100 seconds and provides a better field of vision than do the systems in the previous scenarios.

For a better understanding of the performance of the proposed system, a three-dimensional diagram of system performance is presented in Fig. 26.

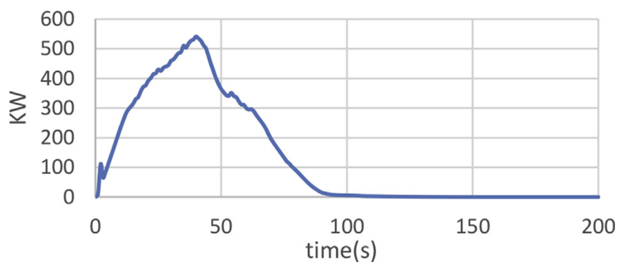

Fig. 22. HRR in the presence of the proposed system.

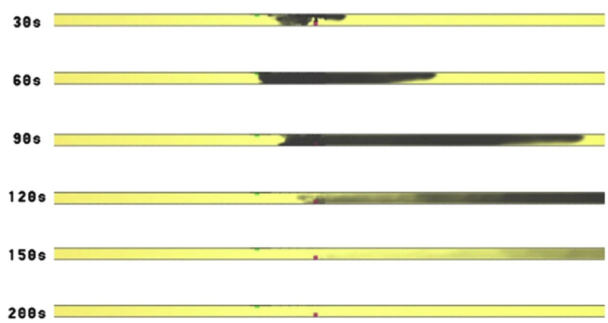

Fig. 23. Smoke emission contour in the presence of the proposed system.

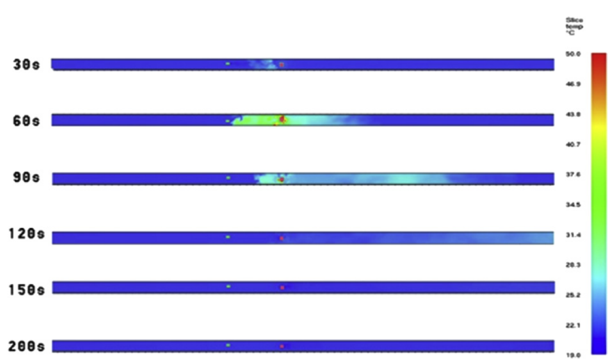

Fig. 24. Temperature contour at 2 m above the tunnel floor in the presence of the proposed system.

6. Conclusion

This study developed a new tunnel fire detection and suppression system based on camera image processing and the use of water mist jet fans. Building upon a conventional water mist system, we proposed the use of ventilation jet fans for mist generation. This method of water mist generation increases the flow of fresh air into a tunnel space and improves fire control and suppression performance. The simulation results showed a 10% shorter fire suppression time and a 40% lower HRR than those achieved with a conventional water mist system. The results also indicated dramatic improvement in the field of vision.

The result of the simulation was, that the proposed water mist system successfully passed all criteria as required by the notified testing institutes.

These criteria were:

1. successful prevention of spread of the fire
2. Providing access to the scene for the fire brigade to finally extinguish the fire, which was the main problem of the tunnel fires in the past.
3. Protecting the tunnel structure and prevent the concrete from spalling.

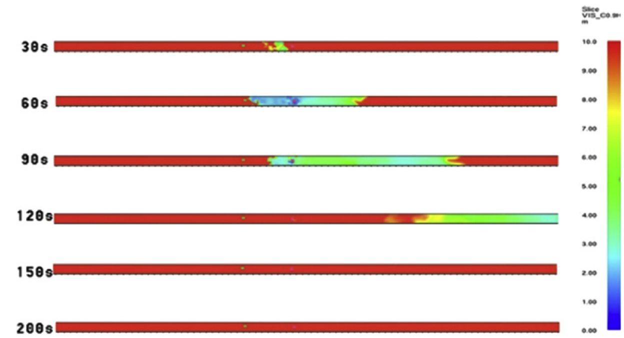

Fig. 25. Vision contour at 2 m above the tunnel floor in the presence of the proposed system.

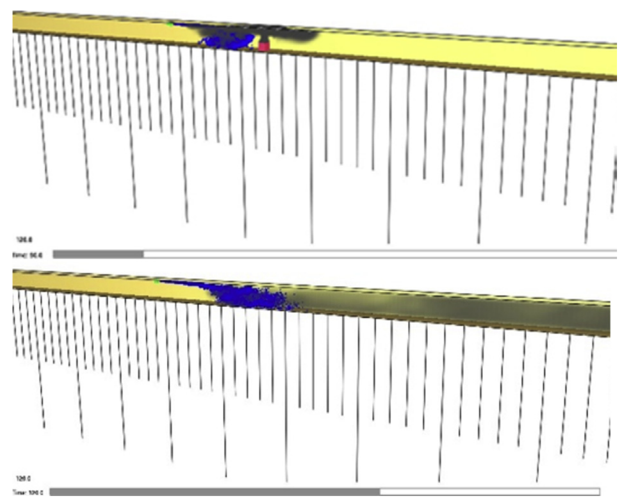

Fig. 26. Three-dimensional diagram of the proposed system's performance.

The use of the proposed system can result in significant cost savings with the elimination of a fire pump setup and the replacement of high-pressure pipes and expensive nozzles with low-pressure and inexpensive pipes and fittings. The system can also improve normal ventilation during rush hours by infusing mist into a tunnel space for the reduction of toxic fumes and particulates. The proposed system is feasible not only technically but also economically because in Category D tunnels, where the use of ventilation jet fans is mandatory, the system can be implemented through slight modifications in jet fans capacity and structure. This eliminates the need to procurement of separate fans and expensive equipment. Ultimately, the proposed system can easily replace old ventilation and fire suppression systems and thus constitutes a positive step toward the integration of tunnel safety systems.

Declarations

Author contribution statement

Alireza Sarvari & Sayyed Majid Mazinani: Conceived and designed the experiments; Performed the experiments; Analyzed and interpreted the data; Contributed reagents, materials, analysis tools or data; Wrote the paper.

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Competing interest statement

The authors declare no conflict of interest.

Additional information

No additional information is available for this paper.

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