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Research Article

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Numerical Investigation on Effect of Fire Fighting on Smoke Movement in Tunnels

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Abstract Smoke is the most deadly factor in vehicular tunnels fire since smoke spreads in heading harmonize with passenger's evacuation way. It reduces visibility and can cause fatalities by suffocation.

This paper presents a numerical study of the effect of extracting the smoke by different system of ventilation on smoke spread inside the vehicular tunnel, like (water mist system with transverse ventilation and longitudinal system with jet fans and solid curtain with transverse system and semi transverse system)

Also tenable conditions were checked at human level. FDS 6.5.1 ver. was used to predict the various parameters of temperature, and visibility and Co concentration. Eight cases were conducted; Cases 1, 2, 3 and 7 were done to compare between four different ventilation systems at 30 MW. Case 4, 5, 6 and 8 were done to compare between three different ventilation systems at 100 MW.

Keywords Smoke Management; Vehicular Tunnels; Ventilation; Visibility; FDS

Nomenclature:

c_p	constant pressure specific heat (kJ/(kg K))	$\dot{q}'''$	heat release rate per unit volume (kW/m^3)
D	diffusion coefficient (m^2/s)	T	temperature (K)
D^*	characteristic fire diameter (-)	T_0	temperature of ambient (K)
d	droplet diameter (μm)	t	time (s)
d_m	median droplet diameter (μm)	u	velocity vector (m/s)
f	external force vector (excluding gravity) (kg/s^2/m)	Y_l	mass fraction of *l*th species (-)
g	acceleration of gravity (m/s^2)	ρ	density (kg/m^3)
h	enthalpy (kJ)	ρ_0	dencity of ambient (kg/m^3)
k	thermal conductivity (W/m/K)	τ	viscous stress tensor (kg/s^2/m)
$\dot{m}'''$	production rate of *l*th species per unit volume (kg/s/m^3)	γ	empirical constants (-)
Q	heat release rate from fire (kW)	σ	empirical constants (-)
q_r	radiative heat flux vector (kW/m^2)		

1. Introduction

All countries resort to construction tunnels due to increasing population and for the expansion of transportation network, The most dangerous thing in the fire inside tunnels is smoke where it leads to low visibility and choking and death, as it threatens the lives of the people inside the tunnel, where about 70% of the deaths were caused by inhaling a large amount of smoke caused by the fires.

Knowing that is not the purpose of the SMOKE MANAGEMENT is the fire resistant, but it is a feature of life insurance and to provide an opportunity for an evacuation and to leave space for men of fire resistance for the performance of their jobs and to maximize the time between it possible to evacuate without extensive damage.

The ventilation system has to be designed to prevent the building up of Temperature beyond tolerable limit during traffic congestion where vehicles may pile up inside the tunnel. When there is a fire emergency, smoke control to enable safe Evacuation has to be addressed for main tunnel [1].

The most dangerous thing in the fire inside tunnels is smoke where it leads to low visibility and choking and death, as it threatens the lives of the people inside the tunnel, where about 70% of the deaths were caused by inhaling a large amount of smoke caused by the fires [2], Tenable conditions at human level 1.8 m are given by NFPA 502 Standard as illustrated in Table 1

Table 1: Tenability criteria given by NFPA 502 [2]

Hazard	Criterion for stated exposure	
	Few seconds	6 minutes
Temperature	60 °C	50 °C
Carbon monoxide	2000 ppm	1500 ppm
Air velocity	Up to 11 m/s	Up to 11 m/s
Visibility	It is recommended that the visibility should be maintained above 30 m for a sign internally illuminated 80 lx and 10 m for doors and walls.	

The tunnel fire safety has pulled in an ever increasing number of worries after various extreme fire accidents occurred everywhere throughout the world [3]. In tunnel fires, the smoke would spread longitudinally and dive to the ground at areas far from fire root, which may obstruct the escape route. Subsequently, safety evacuation of tenants might be influenced by high temperatures and toxic gasses. To lessen the hazard, previous researches have been done to examine the ventilation frameworks in controlling the smoke spread in burrows. To keep the warmth engendering of fire in a passageway like geometry. The DS-TJ system comprises of 2 twin plane planes providing separate hot air from the smoke territory and natural air from the secured range. Amano *et al*. [4] proposed water screen and water spray systems for tunnels.

The water screen arrangement of extraordinary spouts with a breadth of 200 lm organized in lines were utilized to shape the fire compartment to forestall smoke spread. A water-based compartmentation framework has been created by Able [5], which is named as water shield relief framework. This system has been tested in both scaled and full-scale burrows with longitudinal ventilation for fires up to 20 MW. The test outcomes demonstrated that the compartmentalization was effective on the upstream side however inefficient on the downstream side, and the constrained airflow significantly influenced the water shield relief framework. Sun *et al*. [6] talked about the viability of a water framework in counteracting smoke spread and decreasing temperature in a diminished scale burrow with and without constrained longitudinal ventilation. The outcomes showed that the water system can diminish the temperature of hot gas and keep the smoke from spreading when the longitudinal ventilation is missing.

From the literature review, it can be inferred that most past examinations concentrated on the smoke compartmentation in burrows while the smoke ventilation was not considered. Transverse ventilation and water fog screens ought to be utilized at the same time to control smoke spread. Van sanctum Horn [7] contended that the transverse ventilation may significantly supplement and enhance the execution of water shield moderation sys-tem. In any case, the viability of transverse ventilation added to the water framework was not contemplated inside and out,

Transverse ventilation is also effective in bi-directional tunnels (where vehicles are travelling in both directions in the same tunnel), for these traffic conditions [8].

The point of present study is to research the adequacy of the WMSTV system and comparison between solid curtain and semi-transverse system in different heat release rate. Numerical method with large eddy simulation model (LES) has been used in this research.

2. Numerical experiments

CFD has been widely used in tunnel fire researches [9]. Fire Dynamics Simulator (FDS, Version 6.5.1) developed by NIST is selected for numerical simulations of thermal driven flow in this study. Tiannian Zhou [9] in this paper, a set of full-scale experiments were con ducted to study the influence of transverse fire locations on maximum ceiling temperature distribution. Numerical simulations were also conducted to extend the fire scenarios with a wider range of fire locations than that involved in the experiments. Some of the simulation scenarios were the scaled-up version of a set of model-scale experiments reported in the literature, of which the normalized results were used in this study for comparison. The major results and observations are summarized as follows: 1- the wall constraint effect on the normalized impingement ceiling jet temperature rise seemed independent of the heat release rate of the fire.2- using FDS. A good agreement between the simulation and experimental results was achieved as shown in fig1. Previous studies have shown that FDS is an effective and reliable numerical tool for tunnel fire study.

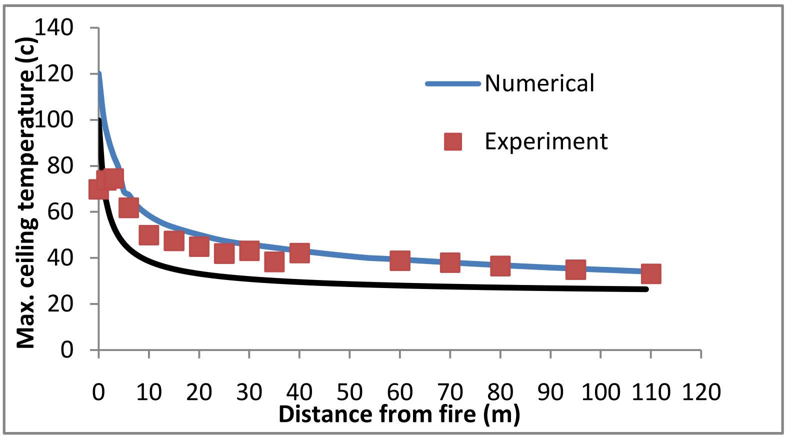

Figure 1: Comparison of temperature variation between simulation and experimental results (FDS v.6.5.1)

2.1. FDS

FDS has been regarded as a practical tool for simulating fire-induced environment as it solves numerically a set of the Navier-Stokes equations for thermally-driven flow. A description of the model, validations, and a bibliography of related papers and reports may be found on http://fire.nist.gov/fds/. It includes both DNS (Direct Numerical Simulation) model and LES (Large Eddy Simulation) model. The LES model, which is widely used in the study of fire-induced smoke flow behavior, is selected. The governing equations are [10]:

Conservation of mass:

$$\frac{\partial \rho}{\partial t} + \nabla . \rho U = 0$$

Conservation of species:

$$\frac{\partial}{\partial t}(\rho Y_\alpha) + \nabla . \rho Y_\alpha U = \nabla . \rho D_\alpha \nabla Y_\alpha + \dot{m}'''_\alpha + \dot{m}'''_{b,\alpha}$$

Conservation of momentum:

$$\frac{\partial}{\partial t}(\rho U) + \nabla . \rho UU + \nabla p = \rho g + f_b + \nabla . \tau_{ij}$$

Conservation of energy:

$$\frac{\partial}{\partial t}(\rho h_s) + \nabla . \rho h_s U = \frac{Dp}{Dt} + \dot{q}''' - \dot{q}'''_b - \nabla . \dot{q}'' + \varepsilon$$

3. Case Studies

3.1. Physical model

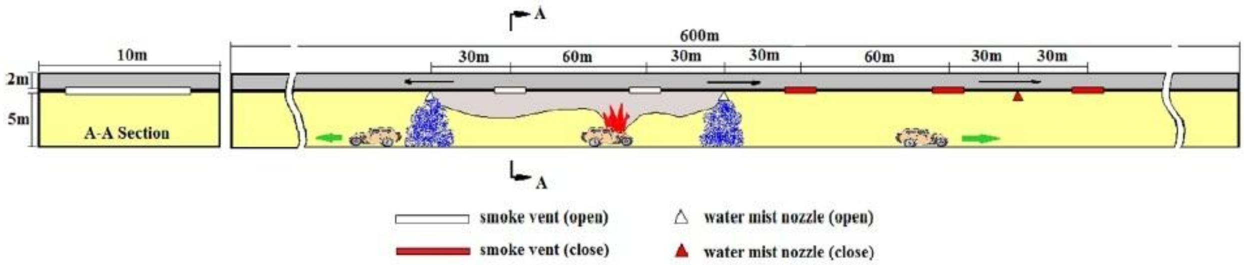

Figure 2: Schematic diagram of the tunnel and the layout of smoke vents and water mist screens

The model tunnel has a rectangular cross section of 10 m (W) X 5 m (H) and a length of 600 m, as shown in Fig. 1. The height of the smoke exhaust duct is 2 m, which has the same width with the tunnel. Grid size sensitivity studies have shown that the accuracy of the model depends on the characteristic fire diameter D⁄ [10]. According to NFAP 502, the fire load in this study is set as 30 MW. For a 30 MW fire, D⁄ is 3.74 m, 0.1D⁄ is 0.34 m and 0.5D⁄ is 1.87 m.

3.2. Fire scenarios

To investigate the performance of water-mist screen system, Solid curtain system both with transverse ventilation system and longitudinal ventilation system, eightfire scenarios are selected and listed in Table 2, transverse ventilation sys-tem is used and the exhaust vents are opened at 20 s after ignition and located at respective 15 m and 45 m at the downstream and upstream, water mist screens system is used for confining the smoke at x = 45 m and x = -75 m respectively.

The exhaust fans are located at both ends of the smoke duct with a flow rate of 120 m^3/s. The ends of the tunnel are set as open boundary in the simulations. Both the ambient temperature is 20.0 °C.

Table 2: Fire scenarios in numerical simulation

Name	Condition	HRR
Case 1	Water Mist With Transverse ventilation system without Firefighting system	30 MW
Case 2	Longitudinal ventilation system by Jet fans without Firefighting system	30 MW
Case 3	Solid curtain With Transverse ventilation system without Firefighting system	30MW
Case 4	Water Mist With Transverse ventilation system without Firefighting system	100 MW
Case 5	Longitudinal ventilation system by Jet fans without Firefighting system	100MW
Case 6	Solid curtain With Transverse ventilation system without Firefighting system	100MW
Case 7	Semi transverse ventilation system without Firefighting system	30MW
Case 8	Semi transverse ventilation system without Firefighting system	100MW

4. Results and Discussion

4.1. Smoke spread process

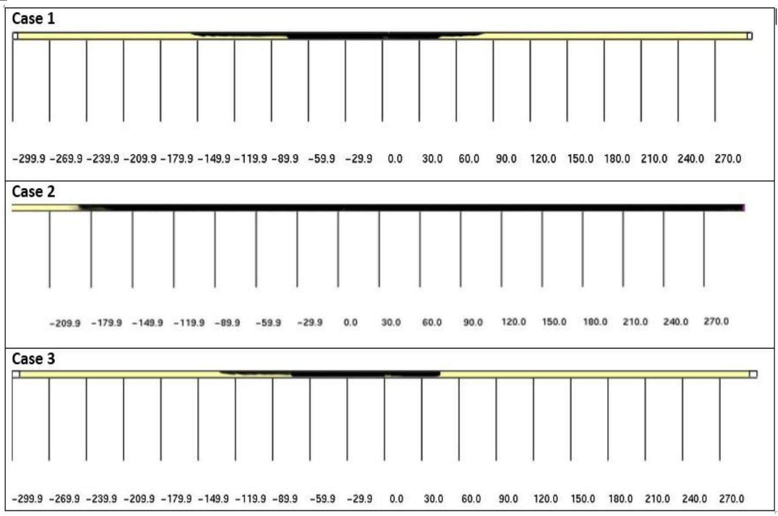

Figure 3: Comparison between Smoke spread distributions at (60 s, 120 s, 180 s, 240 s, and 300 s) in Case 1 & Case 2& Case 3 @30MW

The smoke spread in Case 3 along the tunnel at 300 s after ignition, the smoke can be confined within the space in between the two solid curtain. The smoke spread process in case 3 where the smoke is confined due to the combined effects of solid curtain system and transverse smoke exhaust system. The smoke spread is restrained

and the smoke layer in the confined zone is maintained, which would be benefit for the occupants' evacuation in the tunnel.
Shows in Fig. (4) show the Comparison between Smoke spread distributions (at 60 s, 120 s, 180 s, 240 s, and 300 s) in Case 1 & Case 2& Case 3 @30MW and From the comparison, that the solid curtain in case 3 is where the smoke spread is less than the other two cases 1&2 and therefore the higher efficiency is achieved in evacuating the people.

4.2. Temperature Distributions

Comparison between temperature distributions at human level at 2 m (at 60 s, 120 s, 180 s, 240 s, and 300 s) in Case 1 & Case 2& Case 3 @30 MW shown in Fig. (5), the high temperature zone is confined between the two solid curtains. The temperature under the ceiling is slightly low, the temperature outside the fire zone is close to the ambient temperature. The results clearly demonstrate that the high temperature zone cannot spread out of two solid curtain.

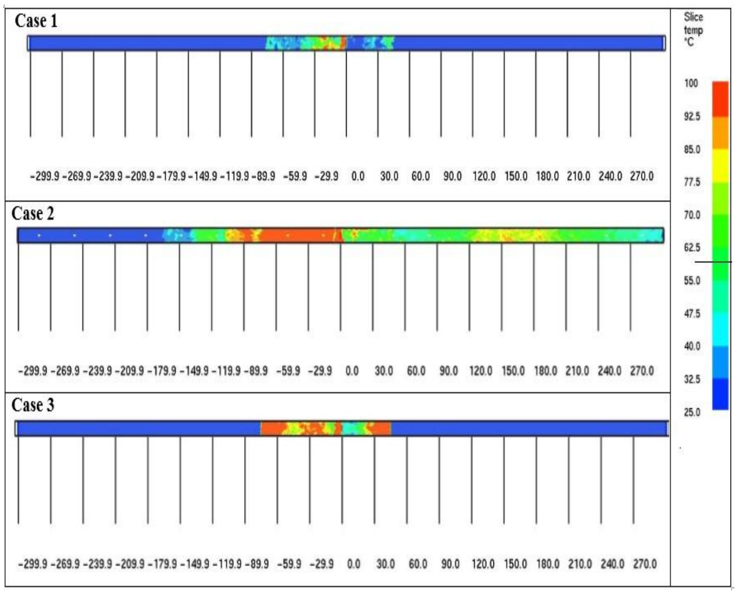

Figure 4: Comparison between temperature distributions at human level at 2 m (at 60 s, 120 s, 180 s, 240 s, and 300 s) in Case 1 & Case 2& Case 3 @30MW

4.3. Visibility distributions

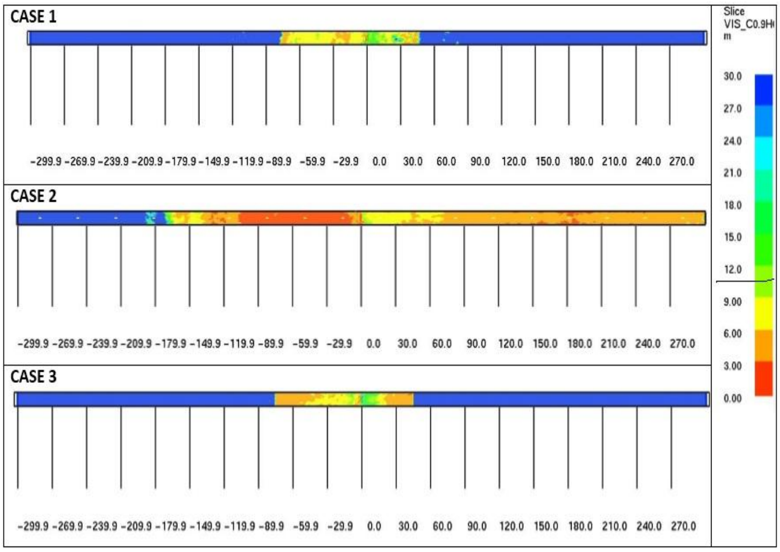

Figure 5: Comparison between visibility distributions at human level at 2 m (at 60 s, 120 s, 180 s, 240 s, and 300 s) in Case 1 & Case 2& Case 3 @30 MW

Figure. (6) Presents Comparison between visibility distributions at human level at 2 m (at 60 s, 120 s, 180 s, 240 s, and 300 s) in Case 1 & Case 2& Case 3 @30 MW this comparison show that the visibility in tunnel could be improved when the smoke exhaust system is used with water mist and solid curtain in case 1&3 but case 2 can't be improved when using longitudinal system with jet fans only at 30 MW. However, outside of the confined zone the visibility is high, which indicates that the smoke can be effectively confined using this system.

5. Conclusions

According to the results found in previous comparison obtained by using the numerical investigation, the following conclusions can be expressed:

- FDS is a powerful tool that can simulate smoke spread this was clear when comparing validation model with experimental data, which was presented by TiannianZhou [7].
- The present thesis reviewed and highlighted the importance of smoke management in general and emphasized the smoke management design standards for the safety of vehicular tunnels.
- While the Solid curtain as smoke barrier with transverse ventilation system gives better performance than (WMTVS and Jet fans) at 30 MW and has a great effect on the efficiency of smoke extraction and tenable conditions improvement at human level.

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