ENGINEERING RESEARCH JOURNAL (ERJ)

Vol. 1, No. 43 Jan. 2020, pp. 44-50

Journal Homepage: http://erj.bu.edu.eg

Numerical Investigation of Smoke Extraction of a Burning Vehicle in a Roadway Tunnel with Roof Openings

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Abstract. : Smoke spread and extraction in a tunnel, which is caused by a burning vehicle, are studied and investigated using Fire Dynamics Simulator (FDS). Roof ventilation openings are used in this model to maintain a safe evacuation and to reduce the number of injuries and fatalities. Hence a 3D tunnel model with heat release of 5MW is implemented using 40 roof openings with heat, visibility, and toxic gases detector. The properties and the flow rate of smoke are recorded at different locations, including the nearest emergency exit from the burning vehicle. The results recorded at the nearest emergency exit, which is located at 45m from the burning vehicle after 40s, indicate safe records and conditions for evacuation as the air temperature is 20℃, the visibility limit is 10 m, the Carbon Monoxide is 6.3ppm, and Carbon Dioxide is 504 ppm . Thus, the roof openings effectively reduce the tunnel fire hazards.

Keywords: Tunnel Fire, Roof Opening, Ventilation

NOMENCLATURE

$\dot{q}_c^n$	convective heat flux (W/m^2)	S	visibility (m)
$\dot{q}_r^n$	Radiative heat flux (W/m^2)	K_c	Conductivity (W/m.°C)
$\dot{q}_{con}^n$	conductive heat flux (W/m^2)	K	light extinction coefficient (m^2/kg)
h	convective heat transfer coefficient (W/m^2.K)	K_m	mass specific extinction coefficient (m^2/kg)
T_g	gas temperature (°C)	I	intensity of monochromatic (W/m2)
T_w	surface wall temperature (°C).	I_o	intensity (W/m2)
T_a	ambient temperature (°C)	ρ_s	smoke density (kg/m^3)
A	area (m^2)	L_m	material thickness (m)
$\mathcal{E}$	emissivity (W/m^2)	C	Weber contrast
Σ	Stefan-Boltzmann constant ($5.670\times10-8$ W/m^2·K^4)		

1. INTRODUCTION

In the past years, many tunnel fire accidents occurred in different countries and they resulted in a huge number of injuries and fatalities. In 1999 one of the most catastrophic accidents took place in Mont Blanc tunnel, between France and Italy, which lead to the death of 39people and the destruction of34 vehicles[1].Damages in tunnels include tunnel collapse, explosion, burned vehicles, and the release of hazardous materials . Moreover, the spread of the flame radiation results in the occurrence of multiple vehicles ignition scenario which is one of the most common causes of such catastrophic incidents. The hazards of a burning vehicle include heat, smoke and toxic gases; which may fill the tunnel and prevent the emergency rescue attempts and firefighting operations[2]. Ventilation systems are used to reduce tunnel fire hazards and to prevent low visibility in cases of tunnel accidents. Also, ventilation systems are used for air circulation inside the tunnels. There are various types of ventilation systems; namely, longitudinal, natural and roof openings ventilation, single or multipoint smoke extraction, transverse and semi transverse ventilation.

Many researchers studied the designs of different types of ventilation systems in order to find the best design, namely, the one which reduces the effects of fire hazards in a tunnel. LI et al.[3]presented asimulation of a multi scale coupling model to study the effect of the jet fans set number on the performance of the longitudinal ventilation system. The results show that when three sets of jet fans are operated the smoke back-layering is eliminated .Then to simulate the fire scenarios, Karaaslan et al.[4]placed a pool of fire in a short tunnel to analyze the effect of the longitudinal ventilation on the smoke movement in the tunnel. They noticed that there was an uncontrolled movement of the smoke. Moreover, the smoke velocity, and the locations and the operations of the jet fans affect the smoke vents .Li et al.[5]investigated the critical velocity and the smoke back layering length in a longitudinally ventilated tunnel by using two models of tunnels and a theoretical analysis. They observed that the critical velocity is a necessary factor for avoiding the smoke back layering .Furthermore , an experimental study was conducted by Hu et al.[6]to investigate the relation between the effect of the velocity of different air layers and the fire induced buoyant flow. It was noticed that thermal stratification was influenced by the forced ventilation; consequently, a semi-empirical model was carried out by Hu et al.[7]to study the relation between the back-layering length and the critical longitudinal ventilation velocity. It was proved that the length of the back layering increased with the increasing the fire size and decreased with the tunnel height and the longitudinal ventilation velocity.

Xu et al.[8]analyzed the multi scale coupling of the partial transverse ventilation system. They concluded that the air supplement volume was lower than the engineering standard recommended value of smoke exhaust. A Numerical study of the performance of the ventilation systems in the tunnels was done by Li and Chow[9]using CFD. This study showed that the disadvantages of the transverse ventilation system are the high cost and the ineffective smoke management. Whereas , the disadvantages of the semi transverse system are the lack of control in the smoke direction, the sensitivity to fire location and the high cost. Linand Chuah [10]used a CFD to study the simulation of smoke extraction by applying different numbers of extraction points. They show that the simple single point of smoke extraction is suitable only for small regions.

Ciambelli et al.[11]simulated the natural ventilation of fire in tunnels. Their results show that sometimes the natural ventilation was not appropriate for evacuation and safety precautions. Carlstedt[12]pinpointed that the natural ventilation system is not recommended to be in use due to the number of shafts and the low velocity of the longitudinal air which cause the natural ventilation to be considered unsafe as a ventilation system. Recently, new types of tunnels with the roof openings were constructed such as the tunnels ChengduHoxing and Nanjing Xianmen in China, and it has been noticed that the quality of air in these types of tunnels is safe. Also, the ventilation system could be determined through certain parameters, namely, the traffic flow and the number of vehicles .Jin et al.[13]conducted 12 experiments to show that the airflow at the roof openings is not affected by the number of openings or the vehicle speed. The feasibility of using the roof openings was studied by Tong et al.[14]to determine that the temperature and smoke concentration are at the safe limit. They showed that the traffic wind was decreased through the roof openings.

A CFD model was conducted by Ura et al.[15].They shows that the roof openings ventilation is suitable for safe evacuation and to show that the thickness of the smoke layer can be extracted quickly. This study showed that at 15% opening ratio, the smoke flow rate can reach to zero. A full-scale experiment was carried out by Wang et al.[16]to show that the maximum smoke temperature at the safe height decreases quickly to the ambient temperature. Hence, the smoke layers are stable but the evacuation time should not exceed 10 minutes because the smoke will spread out causing difficulty in invisibility and breathing. Another research was done by Wang et al.[17].They show that the temperature decreases with the increase in the longitudinal distance, which does not threat the tunnel structure, hence smoke spreads around 200 m from the source of fire after 400 s which results in a safe evacuation. Thus, the roof openings system is recommended because most of the smoke flows out of the tunnel through these openings.

The previous researchers did not consider the visibility limit and toxic gases at different sites from the fire location with roof openings. The objective of this research is to investigate the numerical simulation of the smoke ventilation through roof openings. Also, to find the roof openings effect on the visibility limit, heat, ventilation and the suitable environment for evacuation.

2. TUNNEL SYSTEM DESCRIPTION:

This research investigates an underground tunnel with 1800m length, 5m height and 13.5m width. The cross-sectional area of the tunnel is shown in Fig. 1. The tunnel roof has 40 roof openings with a 4m^2 area for each. The roof openings are located in the center of the roof and directly connected to the fresh air as shown in Fig.2. The distance between each roof opening is 43m.It is assumed that the tunnel has an emergency exit every 100m for evacuation. A burning vehicle is located in the middle of the tunnel and it was used in the simulation as a source of fire.

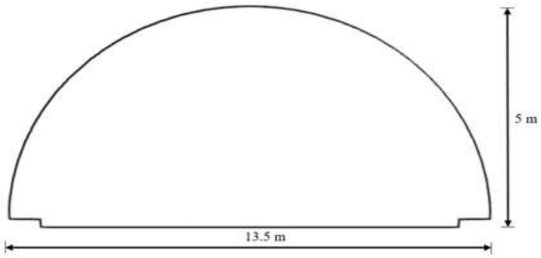


FIG 1. Tunnel cross sectional area

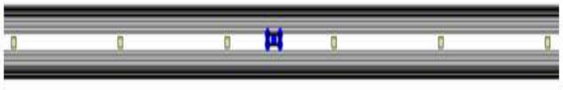


FIG2. Roof openings and burning vehicle in the middle of the tunnel

3. NUMERICAL MODELING:

Visibility, temperature and toxic gases detectors were fixed at 5, 15, 20 m from the burning vehicle and at every 100 m in the emergency exits. These detectors were used to record the generated heat, visibility limit and the percentages of toxic gases.

The main objective of the present work is to find the effect of the roof openings on the smoke ventilation, visibility limit and evacuation conditions. The convective heat flux is given by:

$$\dot{q}_c^n = hA(T_g - T_w) \qquad (1)$$

where h is the convective heat transfer cofficient, T_g is the gas temperature, T_w is the tunnel wall temperature.

The radiative heat flux can be calculated by the equation:

$$\dot{q}_r^n = \mathcal{E}\sigma A({T_w}^4 - {T_a}^4) \qquad (2)$$

Where $\mathcal{E}$ is the emissivity, σ is Stefan-Boltezman constant (5.670×10−8 W/m2·K4),A is the surface area for heat transfer, T_w is the tunnel wall temperature and T_a is the ambient temperature surrounding the surface.

The conductive heat flux can be calculated by :

$$\dot{q}_{con}^n = -K_c^2 A \frac{(T_g - T_w)}{Lm} \qquad (3)$$

Where K_c is the conductivivty, A is the surface area for heat transfer, T_g is the gas temperature, T_w is the tunnel wall temperature and Lmis the material thickness.

We will use equations (1), (2), and (3) to calculate the temperature.

The light extinction coefficient K is the key parameter used to calculate both visibility and light obscuration. The intensity I of monochromatic (single wavelength) light passing a distance L through smoke is attenuated as follows:

$$I = I_o\, e^{-KL} \qquad (4)$$

Where I_o is the intensity. The light extinction coefficient K can be calculated using the mass specific extinction coefficient K_m and smoke density ρ:

$$K = K_m \rho_s \qquad (5)$$

Once the light extinction coefficient is known, the visibility is calculating:

$$S = C / K \qquad (6)$$

The extraction of the smoke from the tunnel was simulated using Fire Dynamics Simulator (FDS) and Pyrosim software. Using mesh independent test by simulating different mesh sizes were investigated in this model at the same operating time (600s). The main target from mesh independent test to make sure that the selected operating mesh size, the number of cells is the most accurate model to ensure the accuracy of the results and to save the computational time. The mesh size was increased gradually and uniformly from 489,600 cells to 662,400 cells. The mesh size with 662,400 cells was selected time as shown in Fig. 3.The heat release rate of the burning vehicle is 5 MW[18].

Many records slices were used to record the heat, visibility and toxic gases. The first slice was installed at 5m from the fire location, the second slice was installed at 15 m, the third one was installed at 20 m while the rest of the slices were installed every 100 m and they are located at the emergency exits (x plan).

One slide was installed to cover the entire tunnel roof (z plan) and another one was installed in (y plan) as shown in Fig.4.

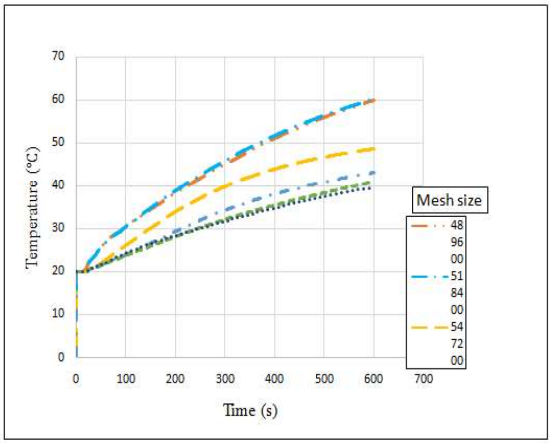


FIG3. Mesh size independent test at 600s

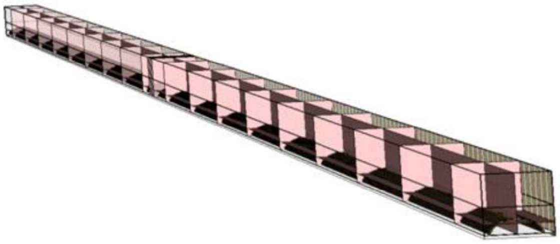


FIG4. Measurement slices in different planes (x, y, z)

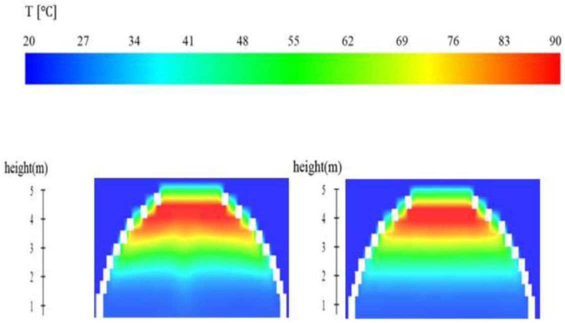
4. RESULTS:

The main target of this model is to ensure a safe evacuation during the fire caused by the burning vehicle in the tunnel. As mentioned before, the most important parameters are the visibility limit, temperature and toxic gases. A time with 600s was conducted in FDS model as shown in Fig.5

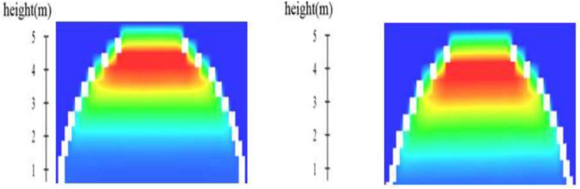
FIG5. Model simulation after 600s

4.1. Temperature:

The air temperature which was recorded at 2m height from the tunnel ground after600s at different locations as shown in Fig. 6&Fig. 7 &Fig.8. The air temperature record reached to an unsafe level as shown in Fig.6a after 600s. The air temperature decreased at 15m,20m and at the nearest emergency exit to the safe limit for evacuation.



(a) Temperature at 5 m from fire location
(b)Temperature at 15m from fire location



(c) Temperature at 20 m from fire location
(d) Temperature at the nearest emergency exit

FIG 6. Temperature simulations at different locations from fire locations at 600s (x plane)

The air temperature increased at the whole tunnel after 600s. as shown in Fig.7&Fig.8

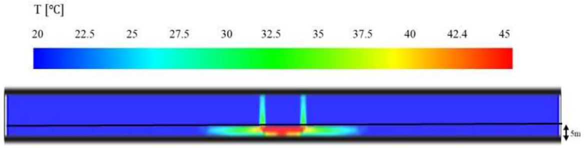


FIG7. Temperature simulation in the whole tunnel at 600s (y plane)

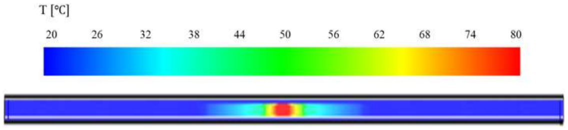


FIG8. Temperature simulation in the whole tunnel at 600s(z plane)

The temperature results are recorded at 2m height at different locations from the burning vehicle. The first location is 5m from the fire location; the air temperature is 22.6°Cat 30s which is a safe time to move towards the nearest emergency exit. The second graph records the location at 15 m from the fire location, the air temperature is 20.7°C at 30 s which is a safe time for evacuation. The third records the location at 20 m from the fire location, the air temperature is 20.3°C at 30s which is an enough time for evacuees. The last graph records the location at 45m which is the nearest emergency exit from the fire location. The air temperature is 21°C at 60s as shown in Fig.9

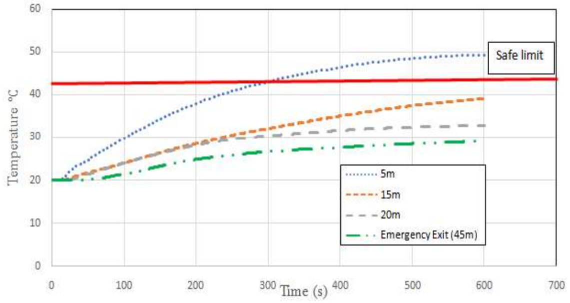
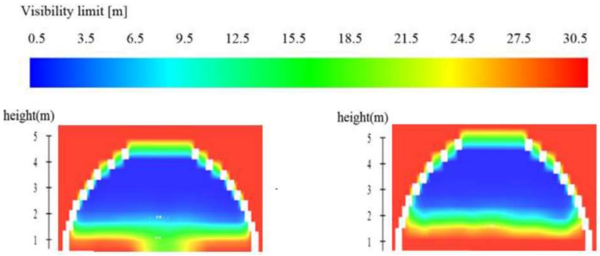


FIG9. The air temperature records at different locations from fire location at 600s

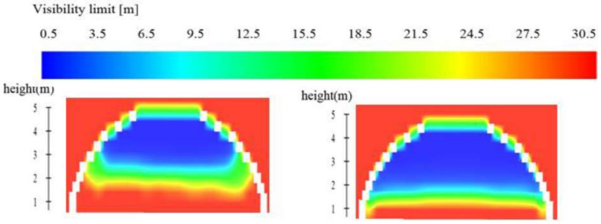
4.2Visibility:

Visibility limit is one of the most effective parameters to ensure safe evacuation. The visibility limit which was recorded at 2m from the tunnel ground at different locations as shown in Fig.10& Fig.11&Fig.12. The records were recorded at 30s for the 5, 15, 20 m from the burning vehicle and at 60s at the nearest emergency exit to maintain a safe evacuation. The visibility limit recorded at the whole tunnel after 600s as shown in Fig.11&Fig.12



(a)Visibility limit at 5m from fire location at 30s

(b)Visibility limit at10m at 30s



(c) Visibility limit at 20m at 30s

(d)Visibility limit at the nearest emergency exit at 60s

FIG10. Visibility simulation at different locations from fire locations (x plane)

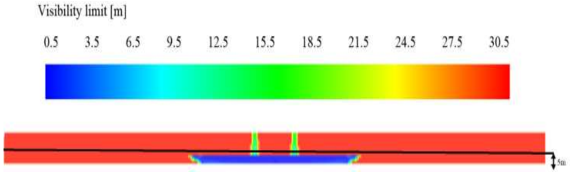


FIG11. Simulation of visibility in the whole tunnel at 600s (Y plan)

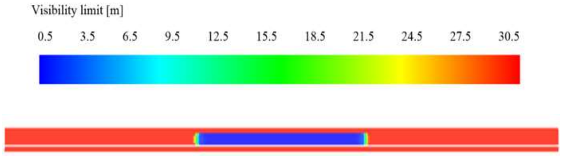


FIG12. Simulation of visibility in the whole tunnel at 600s (z plan)

The first one records location at 5m from fire location, the visibility limit is 0.9 m at 30 s. The second records location at 15m from fire location, the visibility limit is 1.34 m at 30 s. The third records location at 20 m from fire location , the visibility limit about 1.87 m after 30 s which is an enough time to escape. The last visibility examination records location at 45m which is the nearest emergency exit from fire location. The visibility limit is 30 m at 30 s as shown in Fig. 13

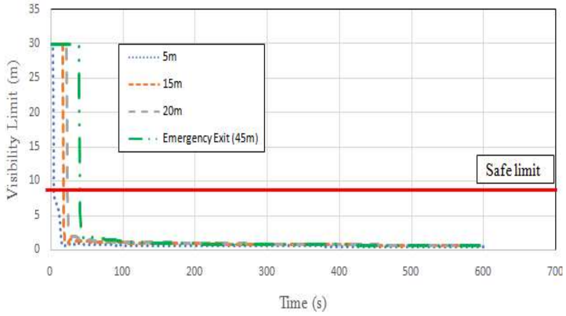


FIG13. The visibility limit records at different locations from fire location after 600s

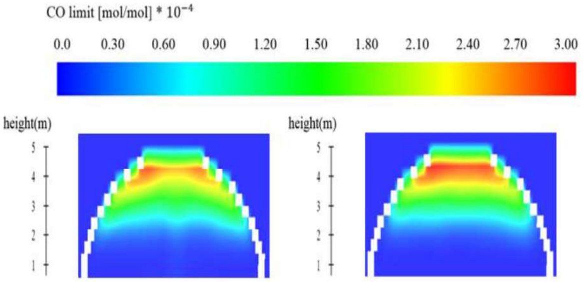
4.3Toxic Gases

(Carbon Monoxide & Carbon Dioxide):

Carbon dioxide affects the lungs, increasing the respiration rate and at high levels inhibit, depress the rate of respiration leading to fainting and even death. Carbon monoxide is more toxic that carbon dioxide and also affecting the lungs and blood causing headache, drowsiness, flushed appearance and ultimately asphyxiation. The measurements of carbon monoxide and carbon dioxide are shown below.

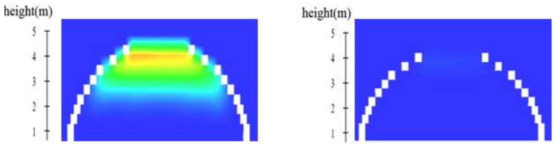
4.3.1Carbon Monoxide (CO):

Carbon monoxide records were recorded at 5,15,20 m and at the nearest emergency exit from the burning vehicle after 30s as shown in Fig 14. The carbon monoxide recorded at the whole tunnel after 600s as shown in Fig. 15



(a) CO at 5 m from fire location

(b) CO at 15 m from fire location



(c) CO at 20m from fire location

(d) CO at the nearest emergency exit

FIG14. Carbon monoxide simulation at different locations at 30s (x plane)

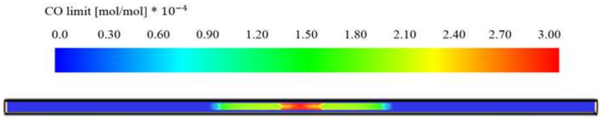


FIG15. CO simulation at different in the whole tunnel at 600s (z plane)

The first record of CO concentration location at 5m from fire location, the concentration limit is 75.9 ppm at 30 s .The second record of CO concentration location at 15 m from fire location, the concentration limit is 49.2 ppm at 30 s The third record of CO concentration location at 20 m from fire location, the concentration limit is 34.5 ppm after 30 s. The last record of CO concentration limit location at 45m which is the nearest emergency exit from fire location. CO concentration limit is 32.27ppm at 50 s as shown in Fig. 16.

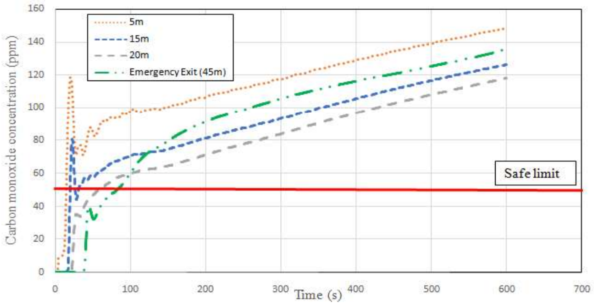
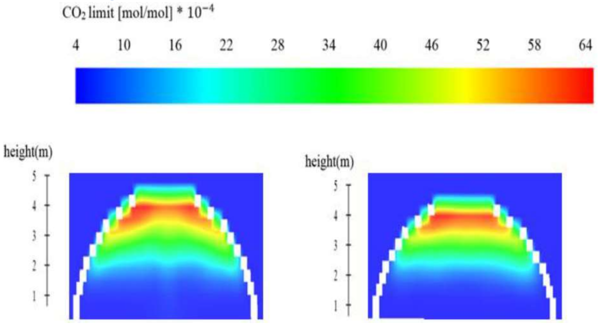


FIG16. CO records at different locations from fire location at 600s

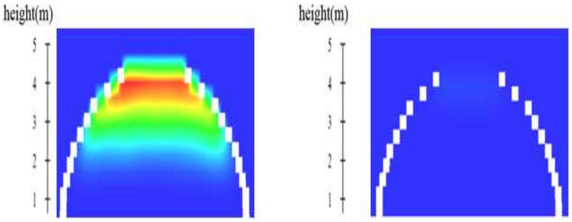
4.3.2 Carbon Dioxide (Co_2 Concentration (ppm)):

Carbon dioxide records were recorded at 5,15,20 m and at the nearest emergency exit from the burning vehicle after 30s as shown in Fig.17and at the whole tunnel after 600s as shown in Fig. 18



(a)CO_2 at 5 m from fire

(b) CO_2 at 15 m from fire location



(c)CO_2 at 20 m from fire location

(d) CO_2 at the nearest emergency exit

FIG 17. CO_2 simulation at different locations from fire locations at 30s (x plane)

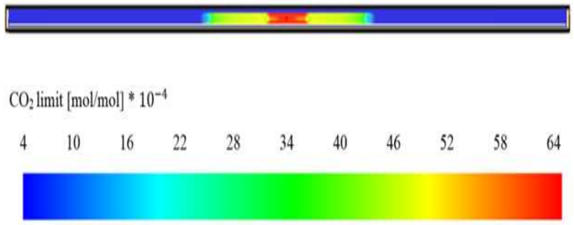


FIG18. CO_2 simulation in the whole tunnel at 600s (z plane)

The first record of CO_2 concentration location at 5 m from fire location, the concentration limit is 1.68 ppm at 30s.The second record of CO_2 concentration location at 15 m from fire location, the concentration limit is 1.4 ppm at 30s. The third record of CO_2 concentration location at 20m from fire location, the concentration limit is 1.16 ppm at 30s as shown in Fig.19. The last record of CO_2 concentration limit location at 45m which is the nearest emergency exit from fire location, the concentration limit is 386.9 ppm at 30 s as shown in Fig.20

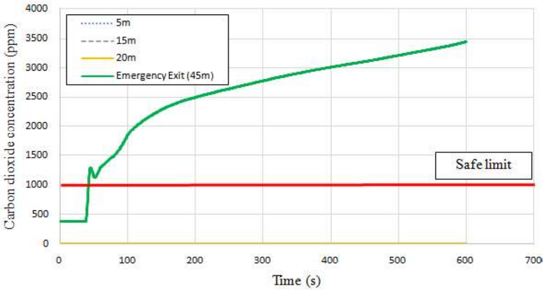


FIG19.CO_2 concentration at 45 m from the burning vehicle (emergency exit) at 600s

5. CONCLUSION:

In this study a numerical investigation is implemented using a 3D model of roadway tunnel to simulate the smoke extraction from the tunnel through roof openings. The following conclusion can be drawn:

a. Roof openings help to slowly increase the radiated temperature; thus the air temperature reach to 36 ℃ after 600s which is considered to be a good condition for safe evacuation.
b. The visibility limit also decreases gradually in a safe limit; hence ,the visibility limit is recorded 10 m at the nearest emergency exit after 40s
c. The results of carbon monoxide and carbon dioxide are safe limits which ensure a safe evacuation for the evacuees.

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