CFD MODEL OF FIRE INSIDE A TUNNEL

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Abstract

Simulation of evacuation qualities of a tunnel due to accidental fire inside the tunnel has been carried out using three-dimensional Computational Fluid Dynamics (CFD) model *fluidyn*-PANACHE Ver PANTUNNEL. This model also includes component models for turbulence, fire and gravity etc. In this article, we present two case studies for different tunnel cross sections. The first case investigates the propagation of thermal flux and concentration of other products of fire as a result of accidental fire inside a tunnel of rectangular cross section. This case also evaluates the importance of the trap door provided as ventilation system for 30MW and 100MW fires. The second case investigates the propagation of thermal flux and concentration of other products of fire inside a tunnel of rectangular with an arc top cross section. This case also predicts the adequacy of the provided ventilation system for 30MW fire.

1. INTRODUCTION

Numerical models based on Computational Fluid Dynamics (CFD) are becoming popular as predictive tools in fire safety area for describing the fire spread and the dispersion of fire products. They are mainly used to assess the effectiveness of alternative ventilation strategies and to evaluate the impact of fire on air quality due to accidental fire inside the tunnel.

Tunnel vents or trap doors are commonly associated with road tunnels serving uni-directional traffic flow. In the event of a fire, it is usually assumed that the traffic ahead of the fire will proceed to the exit portal and the traffic behind the fire will come to a stop. The ventilation system would be operated to force the smoke and hot gases in the direction of empty tunnel to provide a clear and safe environment behind the fire to evacuating people and fire fighters.

If the ventilation capacity is sufficient, all of the heated air and smoke will flow in the downstream direction. If ventilation is weak, the upper layers of heated air and smoke may flow in the opposite direction causing “backlayering.” The occurrence of backlayering depends on many factors including the intensity of fire, the slope and geometry of the tunnel, and the velocity of the ventilating air approaching the fire. The ability of the ventilation system to prevent backlayering is the current industry standard to measure the adequacy of the system for smoke control.

A CFD model that is intended for use in tunnel fire simulations should be capable of handling different types of tunnel cross sections, ventilation systems, turbulence, traffic induced airflow in the tunnel, propagation of thermal flux (both convective and radiative) and products of fire etc.

The CFD model used here is designed specially for simulating evacuation qualities of a tunnel due to accidental toxic gas release inside a tunnel such as fire products, ammonia, nuclear-bio-chemical agents etc. It has an inbuilt powerful Navier Stokes[1] solver which uses multi-step SIMPLEC/PISO algorithm[2,3] for solving transient compressible turbulent[6,7,8,9,10,11,12] flows on 3D unstructured meshes with combustion[13] and heat transfer including radiation[14,15]. Higher order schemes[4,5] both in time and space are provided for accurate results. Extensive validation has shown that this model meets all the requirements of a tunnel fire simulation and can be used to provide reliable assessment of the efficiency of ventilation system.

The following are the main objectives of the simulations described in this article:

- To assess alternative ventilation strategies to be adopted for tunnels in the event of fire.
- To highlight the propagation of thermal energy and the products of fire such as Carbon Dioxide (CO_2) and depletion of Oxygen (O_2) so as to delineate regions of unacceptably high pollutant build-up.

2. CASE STUDIES

2.1 Case Study I: Tunnel with One way traffic

2.1.1 Description:

The length of the first tunnel is over 500m with rectangular cross section and it has a slope of 5% with the horizontal ground level. The cross section of the tunnel is as given in the Fig 1. Geometry of the tunnel is as shown in Fig 2. In this case study, a trap door in the roof the tunnel is proposed for ventilation at the middle of the tunnel length i.e. at approximately half the distance from the entrance of the tunnel as shown in Fig 3. During normal operations the trap door is closed. But during instances of fire the trap door is open and acts as exhaust to extract air from the tunnel. The fire source is located at a distance of about 75m from the exit of the tunnel.

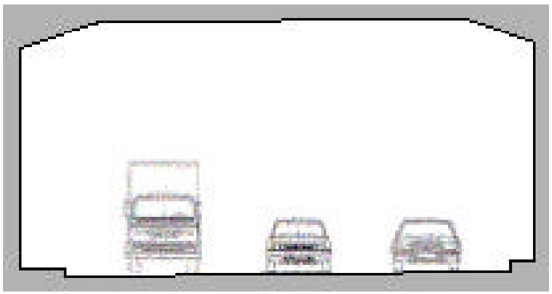

Fig 1: Cross section of the Tunnel

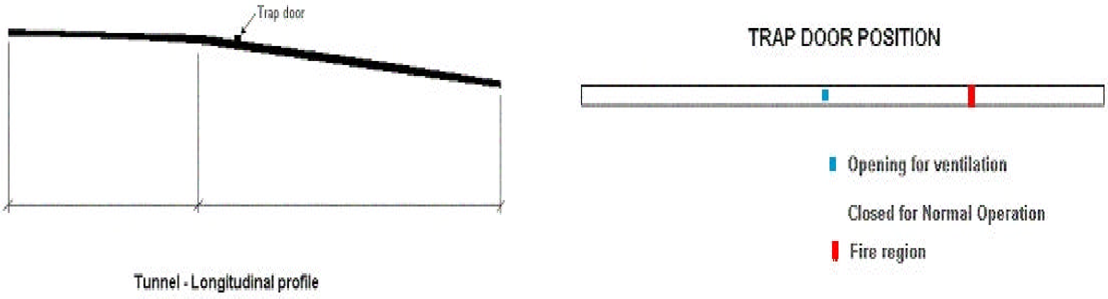

Fig 2-3: Geometrical Details and Trap door and fire location

The objectives of this study are:

1) to investigate whether it is really important to open the trap door very soon after the fire begins,
2) to confirm whether identical operational responses are acceptable for fires of 30MW and 100MW,
3) to find the maximum concentration of CO_2 in the tunnel, and also
4) to assess whether the O_2 present in the tunnel is sufficient for the survival of people inside the tunnel.

Table 1. Data for Case Study –I

S.No	Particulars	Data
1	**Tunnel data**	
	Length of the Tunnel	+500m
	Cross section of the Tunnel	Rectangular (13.6m x 4.65m)
2	**Road & Traffic data**	
	No of road lanes inside the Tunnel	3
	Total number of vehicles	25.0
	a) Heavy Vehicles	10%
	b) Light vehicles	90%
	Vehicle speed	90.0 kmph
	Frontal area of vehicles	
	a) Heavy Vehicles	10.0 m^2
	b) Light Vehicles	2.50 m^2
3	**Fire data**	
	Duration of Fire	45 minutes
	Light Vehicle: Energy released (convective)	20 MW
	Oxygen consumed	2.25 kg/s
	Carbon dioxide released	3.0 kg/s
	Surface area of the fire	30m^2
	Volume of fire	30m^3
	Heavy Vehicle: Energy released (convective)	90 MW
	Oxygen consumed	7.5 kg/s
	Carbon dioxide released	10.0 kg/s
	Surface area of the fire	30m^2
	Volume of fire	30m^3
4	**Others**	
	Laminar Viscosity	1.895e-005 N-s/m^2
	Prandtl Number	0.72
	Turbulence Model	k-ε model
	Gravity Model for steady state case	No gravity
	Gravity Model for fire case	Buoyancy model

2.1.2 Results:

In the present study a steady state for normal operation of the tunnel is simulated. The flow field is forced by the vehicles motion and shows a vertical shear with larger velocities along the traffic lanes. These resulting fields are used as initial conditions for the fire simulations. Two cases of fire viz. light vehicle and heavy vehicle are simulated. For both the cases the fire occurs at a distance of 450 m from the entrance of the tunnel. The Fire is simulated by feeding in constant convective heat energy for two different cases, viz., 20MW convective heat energy for 30 MW fire and 90 MW for 100 MW fire, into the cells corresponding to the fire region. Duration of fire for the two cases is 45 minutes. The fire region acts as a sink for Oxygen and as a source for Carbon dioxide. These two species are absorbed/released at a constant rate during fire. The trap door of the tunnel is opened 2 minutes after the fire takes place. The results of the simulation for this case study are presented in figures 4 to 9 for 30MW and 100 MW fires.

From the results of 30MW fire, figures 4 to 7, it is observed that before opening the trap door, the temperature and CO_2 fields are spreading uniformly under the tunnel ceiling towards both the ends of the tunnel from the location of fire region. Stratification of the smoke and temperature occurs immediately. However, from 2 minutes onward, a quick reversal of the flow occurs due to the hot convection related to the slope. The fire area is blown upward toward the tunnel entrance with an extended area of destrastified layer. Stratification is recovered farther up toward the trap location. Classical formulations (for flat tunnel fires) are providing semi-empirical criteria for velocity predicting such a destratification. The average velocity towards the fire region dominates the buoyancy effect. The maximum temperature observed before opening the trap door is 796°C, but once the airflow is established, it drops to 231°C (fig. 4 & 5).

It can also be concluded that the trap door is to be opened soon after the fire to restrict the pollutant spread to only one direction. Opening the trap door after 2 minutes of fire is sufficient enough to keep the pollutants inside the Tunnel.

The mass fraction of CO_2 is found to be 0.11 for 30MW fire at the fire location before the opening of the trap door (fig. 6) . However, after its opening, CO_2 concentration decreases drastically with a mass fraction of 0.031. (fig.7), due to established air inflow from the near end of the tunnel and due to extraction of CO_2 from the trap door.

From the results of 100MW fire, figures 8 to 9, it is observed that before the opening of the trap door, the temperature and CO_2 are higher at the roof of the tunnel. The buoyancy effect is quite significant . The maximum temperature observed before opening the trap door is 1512°C, where as after established airflow comes out it is 224°C from the figures 6,7,12 and 13. As for the CO_2 concentration, we see the same trend as for 30MW, its mass fraction is 0.155 before and 0.021 after the opening of the trap door.

Depletion of O_2 at the fire source can also be seen in proportion to the temperature for both the fires. However, the availability of Oxygen in the tunnel is sufficient enough for survival of the tunnel users except in the vicinity of the fire location.

In both the above fire cases (30MW and 100MW) it is observed that the proposed trap door played a major role in forcing the smoke and hot gases in the direction of far end of the tunnel to provide a clear and safe environment behind the fire. And it also shows that the trap door is very efficient in tunnel ventilation as well as in extracting the pollutants during instance of fire.

A. Light Vehicle Fire – 30MW Results

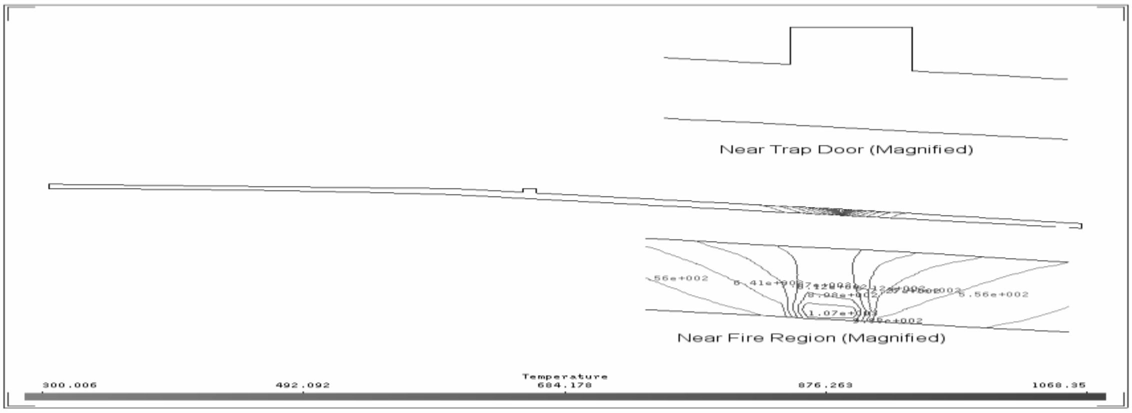

Fig 4: Temperature contours on a longitudinal section passing through the middle of the Tunnel 1 minute after Fire

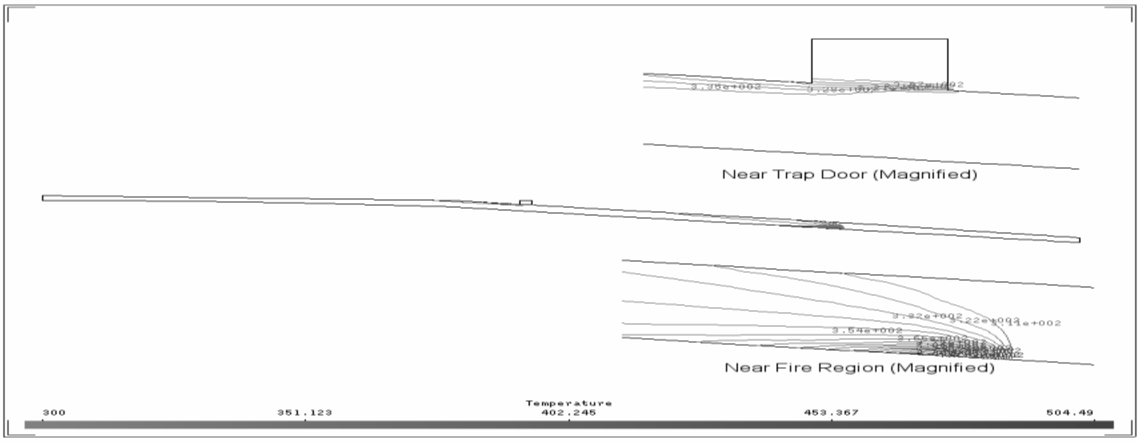

Fig 5: Temperature contours on a longitudinal section passing through the middle of the Tunnel 25 minutes after Fire

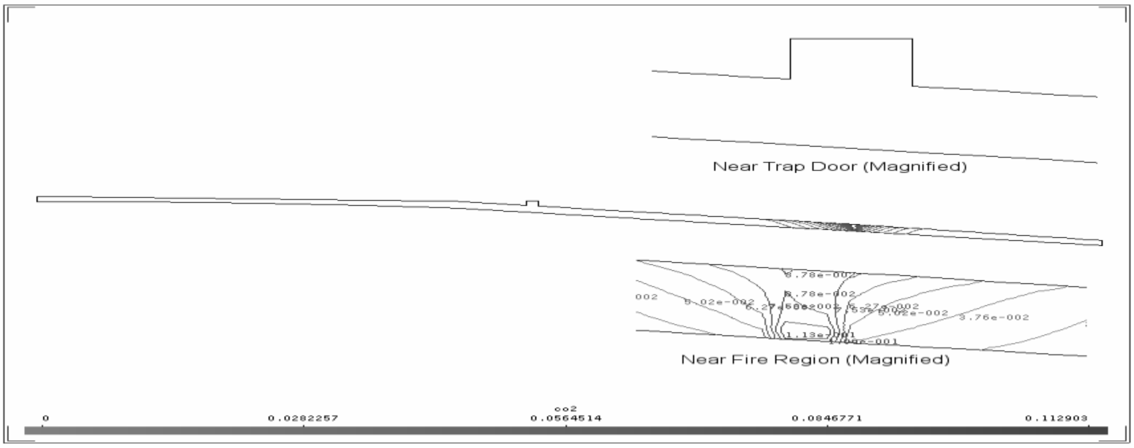

Fig 6: Mass Fraction contours of CO_2 on a longitudinal section passing through the middle of the Tunnel 1 minute after Fire

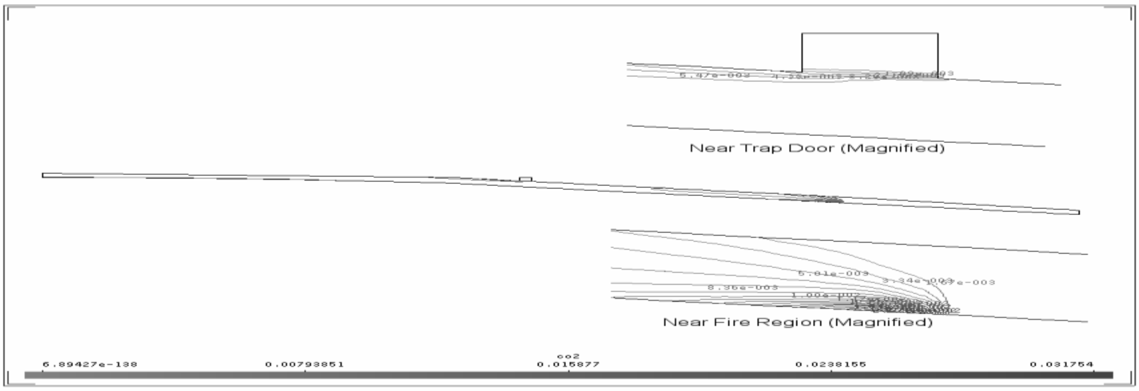

Fig 7: Mass Fraction contours of CO_2 on a longitudinal section passing through the middle of the Tunnel 25 minutes after Fire

B. Heavy Vehicle Fire – 100MW Results

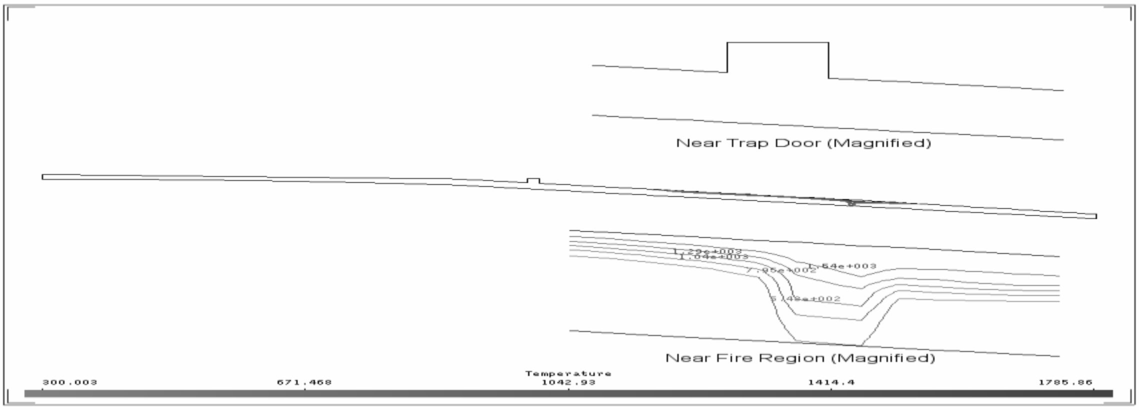

Fig 8: Temperature contours on a longitudinal section passing through the middle of the Tunnel 20 seconds after Fire.

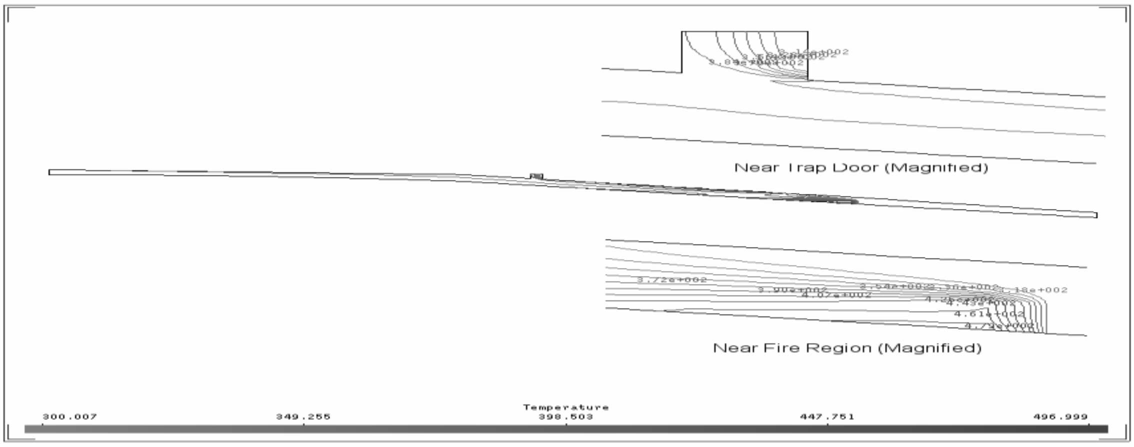

Fig 9: Temperature contours on a longitudinal section passing through the middle of the Tunnel 7 minutes after Fire.

2.2 Case Study II: Transversal ventilation/extraction

2.2.1 Description:

The second tunnel is a semi-cylindrical tube with a length of 1590m (see fig.10). It contains one platform at each side. The cross section of the tunnel is divided into two regions. Region-1 is the proposed ventilation part at the top of the tunnel and this region is separated along the length at the center by a wall. At each end of the tunnel in this region, two reversible ventilators are used. Through these ventilators either air inflow or air outflow can take place. Region 2- is for the users and the vehicles. This part is the bottom of the tunnel and it has two road lanes.

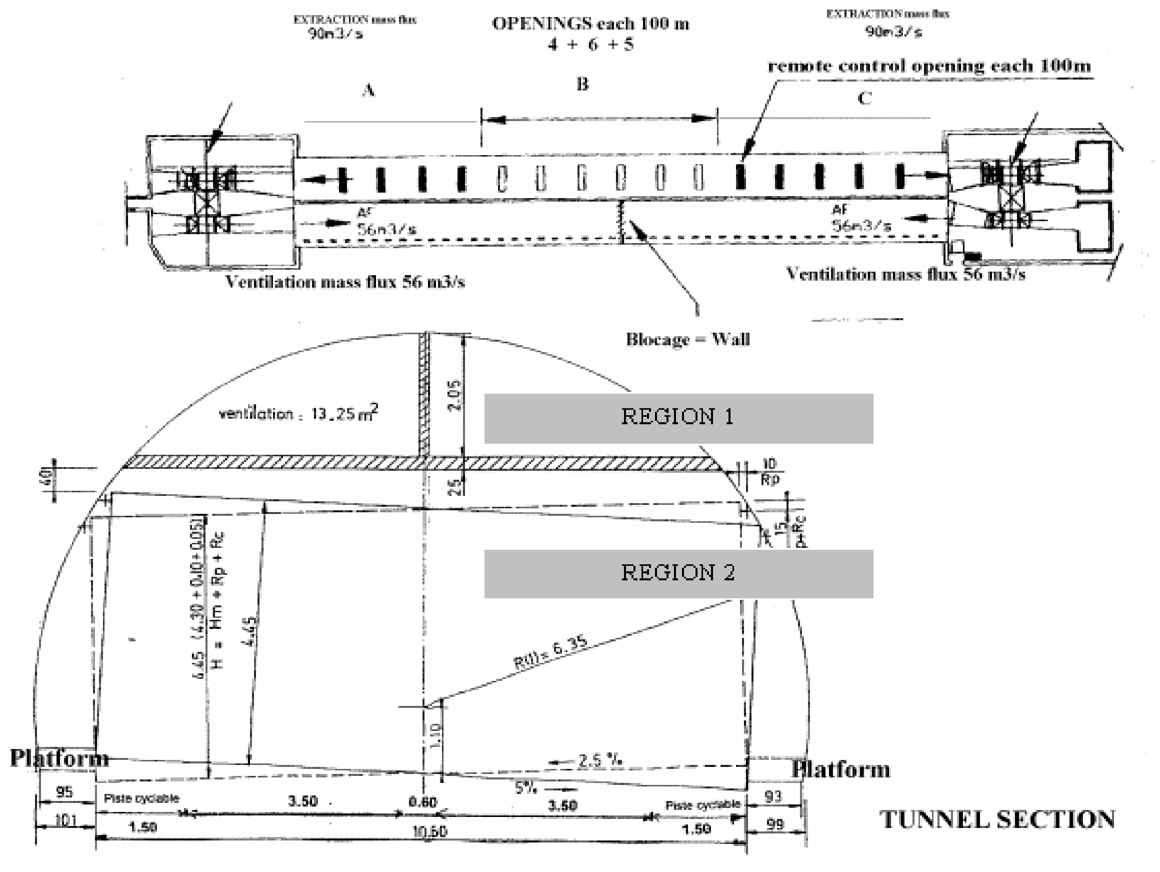

Fig 10: Cross section of the Tunnel

Fig 11 shows the geometry of the tunnel and Fig 12 shows the location of the proposed trap doors in the ceiling. The trap doors are used to ventilate the tunnel by feeding in air during normal operation. During instances of fire the ventilators are used as exhausts to extract the air from the tunnel. The trap doors are divided into three regions and are open during normal operations. During instances of fire, only the doors corresponding to the region of fire are open.

The objectives of this study are:

1) to investigate whether it is really important to open the trap door very soon after the fire begins and also to find which ventilators are to be opened and which are to be closed to minimize the pollutant spread inside the tunnel,
2) to assess the O_2 present in the tunnel is sufficient enough for survival of the people inside the tunnel.

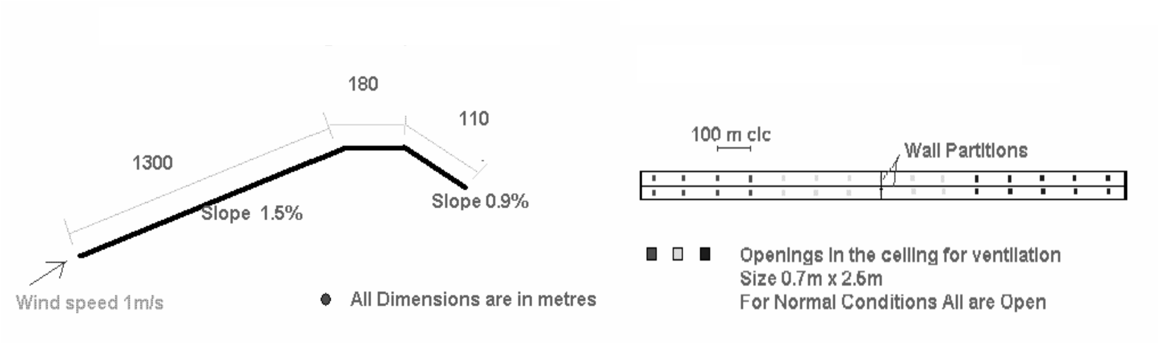

Fig 11-12: Longitudinal Profil-Trap door positions

Table 2. Data for Case Study –II

S.No	Particulars	Data
1	**Tunnel data** Length of the Tunnel Cross section of the Tunnel	 1590m Rectangular with curved (arc) top
3	**Fire data** Surface area of the fire Heat Energy of the Fire for Light Vehicle Triangle shape for time evolution of source (peak at 2mn)	 $80m^2$ 30MW
4	**Others** Laminar Viscosity Prandtl Number Turbulence Model Gravity Model for steady state case Gravity Model for fire case	 1.895e-005 $N\text{-}s/m^2$ 0.72 k-ε model No gravity Buoyancy model

3.2.2 Results:

In the present study, the flow, fire conditions and the geometry are symmetric along the length of the tunnel and so only half of the cross section is considered for simulation. Only trap doors at the center region of the tunnel (Grey color in fig. 12) are open during fire. Other trap doors are closed. A steady state for normal operation of the tunnel is simulated and these results are used as initial conditions for the fire simulation. In this study, one case of fire for light vehicle is simulated and it is assumed that the fire occurs at the center of the tunnel. The surface area of the fire considered as $80m^2$.

The Fire is simulated by feeding in the convective heat energy as per the energy v/s time curves (Fig 13) for 30 MW fire into the cells at the base corresponding to a surface area of $80m^2$. Since only half of the tunnel is modeled the fire surface area is considered as $40m^2$ (16 X 2.5m). This Fire region acts as a sink for O_2 and source for CO_2. These two species are released/absorbed according to time dependent curves (triangular shape). The results of the simulation are presented in figures 14 to 17.

Fig 15 shows that the maximum temperature of 1420^oC at the center of the fire region. Fig 17 shows the mass fraction of CO_2 is 0.24 at the center of the fire region. The temperature and concentrations of CO_2 are at negligible quantities outside the fire region as the opened trap doors in the middle of the tunnel extract the pollutants from inside of the tunnel. From the results, it is also observed that the temperatures and CO_2 concentrations follow the energy curve and mass flow rate curves as the input is taken with respect to time from these curves

Analysis of the concentration variation with time shows that it is very important to open the trap door very soon after the fire begins in order to restrict the pollutant spread to a very small area in the vicinity of the fire source. And also it shows that the opening the trap doors near to the location of fire source is helpful in extracting the pollutants quickly so as to bring the pollutant concentration levels to a considerably lower level inside the tunnel.

The fire study (30MW) shows that the proposed trap doors near to fire source play a major role in extracting the pollutants and thermal flux to provide a clear and safe environment within the tunnel. It also shows that the provided ventilation system is sufficient enough as the available O_2 is sufficient enough inside the tunnel and the temperature and concentration of CO_2 are not up to a significant level except at the fire location.

The mass fraction of CO_2 is found to be 0.24 for 30MW fire at the center of the fire location as shown in the Fig 17. However, its value is considerably low at the edges of the fire source as it is being extracted by the opened trap doors.

Depletion of O_2 at the fire source can also be seen in proportion to the temperature. However, the availability of Oxygen in the tunnel is sufficient for the survival of tunnel users except in the vicinity of the fire location.

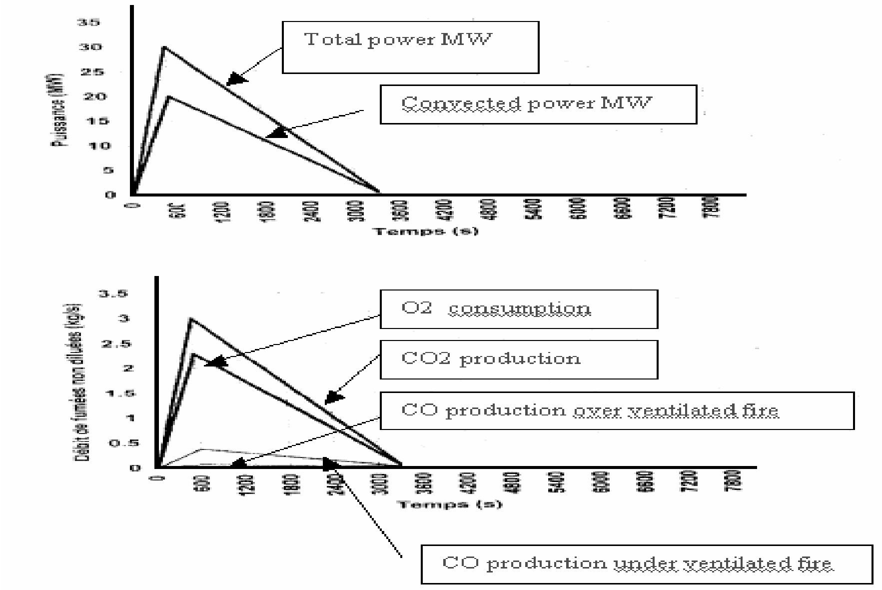

Fig 13**: Energy & concentrations vs Time Curve**

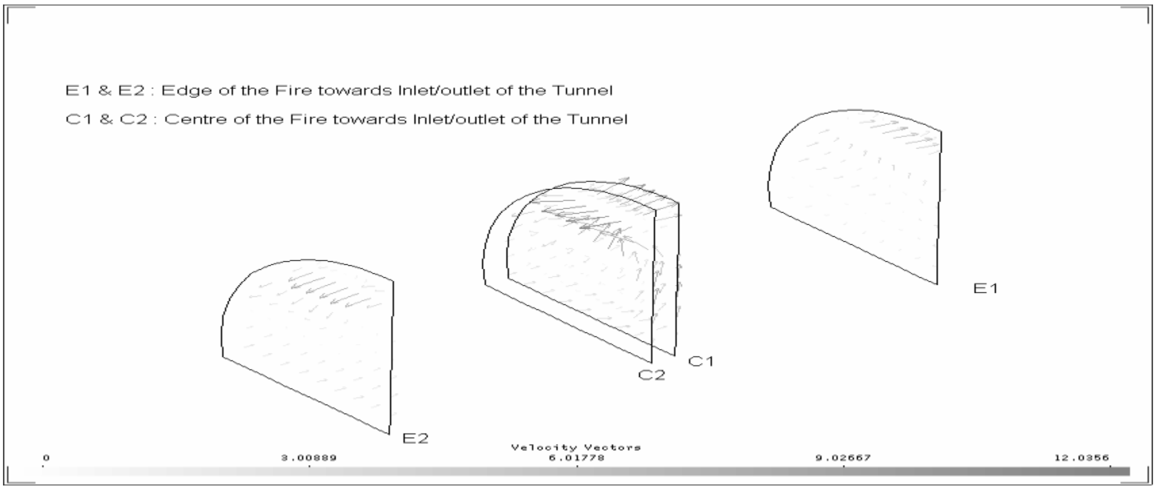

Fig 14: Velocity Vectors at sections in the fire region corresponding to simulation time of 600seconds

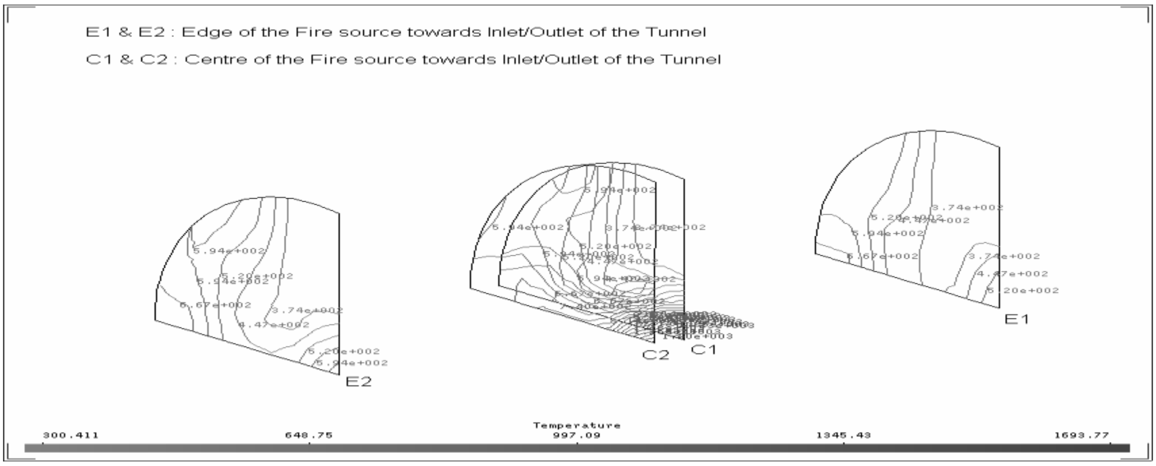

Fig 15: Temperature Contours at sections in the fire region corresponding to simulation time of 600seconds

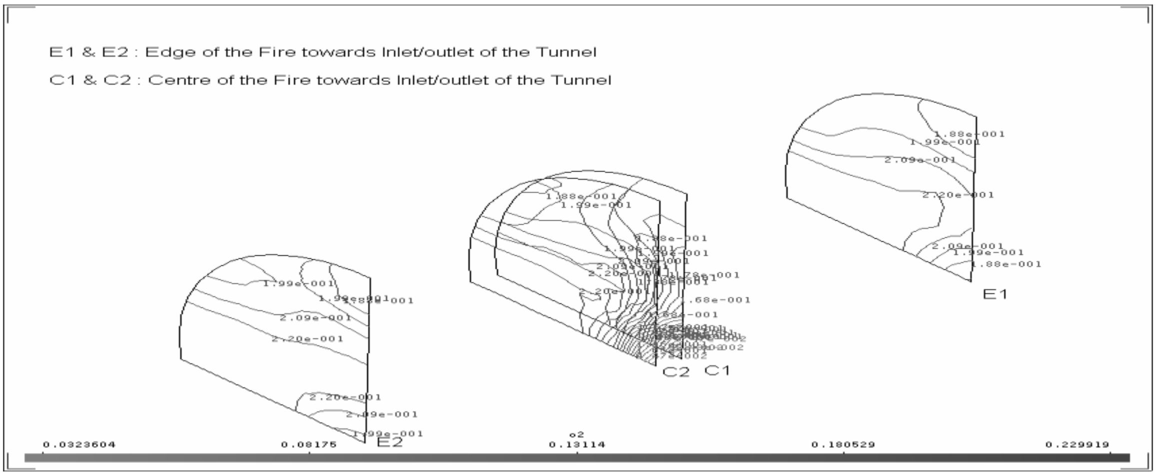

Fig 16: O_2 Mass Fraction Contours at sections in the fire region corresponding to simulation time of 600seconds

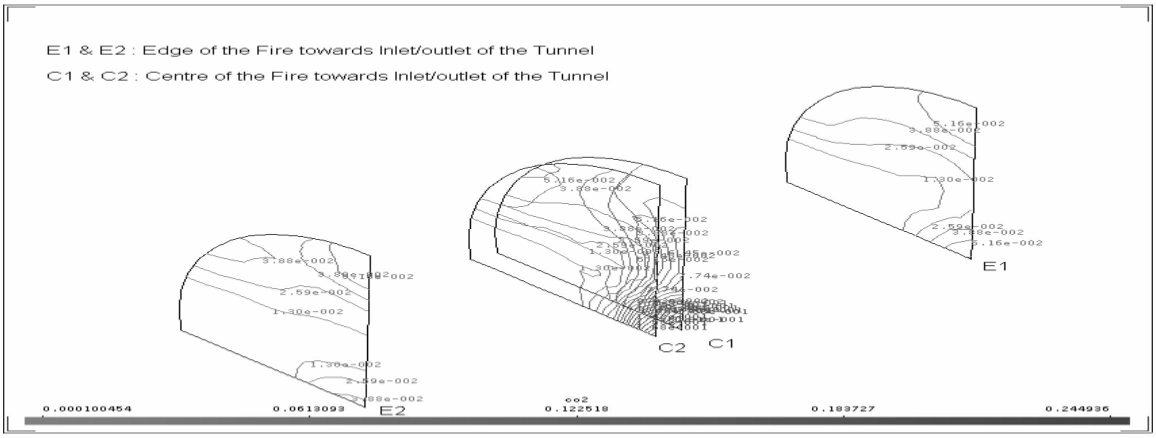

Fig 17: CO_2 Mass Fraction Contours at sections in the fire region corresponding to simulation time of 600seconds

4. Conclusions

Instead of one dimensional calculations, a 3D calculation can furnish substantially more information in fire safety area for describing the fire spread and the dispersion of fire products inside a tunnel. It can also be used to assess the effectiveness of alternative ventilation strategies and to evaluate the impact of fire on air quality due to accidental fire inside the tunnel.

As examples, two case studies were investigated using the CFD model. The first case study simulated the dispersion of fire and its products inside a tunnel with rectangular cross section for 30MW (light vehicle) and 100MW (heavy vehicle) fire with a trap door located approximately at the middle of the tunnel. Based on the results of this study, the necessity of opening the trap soon after the fire begins was evaluated and also the maximum concentration of CO_2 and depletion of O_2 were predicted.

The second case study simulated the dispersion of fire and its products inside a tunnel with rectangular and curved (arc) top cross section for 30MW (light vehicle) fire. Based on the results of this study, the location of trap doors to be opened is identified and the adequacy of number of trap doors to be opened are discussed and also the maximum concentration of CO_2 and depletion of O_2 were predicted.

These two studies helped in locating the regions of high temperature and CO_2 concentration and the region of maximum O_2 depletion. And these studies also helped in identifying the alternative ventilation strategies to be followed in such type of accidental fire inside a tunnel.

5. References

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