Computational Fluid Dynamics Study of Fire Management And Ventilation inside Rail Tunnel

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ABSTRACT

The disastrous effects of fire accidents in underground (both rail and road) tunnels have often been acknowledged. This paper presents the numerical analysis of a fire accident inside a generic two-lane rail tunnel using the techniques of Computational Fluid Dynamics (CFD). Airflow induced due to the train motion and the ventilation system inside the rail tunnel is obtained using CFD. The fire is modeled as a volumetric source. Based on the results, the performance of mechanical ventilation systems is evaluated in a potentially fatal fire scenario inside the tunnel. The performance is evaluated in terms of the temperature evolution and subsequent distribution of the combustion products like CO and CO_2 and NOx. The ventilation systems considered in this study include a combination of longitudinal ventilation and semi-transverse ventilation equipments.

1. INTRODUCTION

The very image of a fire in a tunnel is horrifying; people and vehicles helplessly trapped below ground while flames feed on their limited oxygen. Two incidents amongst several others in last decade have highlighted the horrendous scale of possible consequences of fire in a mass transit system

- In 1998, a fire in the Mont Blanc tunnel running from France to Italy lead to more than 40 casualties.
- In 2003, 200 persons died following an arson fire in an underground railway station in South Korea.

In both cases, an improper ventilation design was partly responsible for the number of casualties. In case of Mont-Blanc for example, a total of 29 vehicles were running through the tunnel when the fire ignited. Because of inappropriate ventilation strategy, virtually all the smoke traveled towards France, leaving no fresh air in the tunnel. The majority of the people who died may have survived if the designers had adopted a different ventilation strategy at the start.

The study of previous accidents revealed that the major catastrophe in tunnel-fire accident is due to smoke and heat transfer. In particular, the railway system with an average capacity of several hundred passengers has a high potential for casualties in the event of a fire. It is found that a fire normally spreads faster towards the tunnel openings or the stations due to the higher oxygen availability in these regions, which increases the danger to passengers. Hence, the smoke and oxygen distribution should be controlled by proper ventilation. Indeed implementing a proper ventilation system is often the best alternative for tunnel designers to ensure safety of travelers and goods.

1.1 VENTILATION SYSTEMS FOUND IN RAIL TUNNELS

Ventilation system can affect the tunnel fire in many ways. An increase in ventilation velocity may reduce the fire severity by preventing the fire spread but on the other hand it may cause the fire to produce heat more rapidly by increasing its heat release rate. Carvel and his co-worker [1] have presented useful conclusions about heat production and its dependence on tunnel configuration and ventilation strategy.

The major classifications in the ventilation systems are:

- Natural ventilation
- Mechanical ventilation: longitudinal and transverse ventilation

Natural ventilation
Natural ventilated tunnels rely on traffic flow density and meteorological condition like weather conditions, wind speed, tunnel slope. The airflow inside tunnel is governed by the piston effect of traffic, differential pressure difference across tunnel length and wind speed. However, the natural ventilation is not the most reliable strategy in emergency evacuation during fire configuration. Usually natural ventilated system resulted in unaccepted pollutant and temperature level at the exit portal.

Mechanical ventilation
The different mechanical ventilation designs are longitudinal ventilation, transverse ventilation and combination of these strategies.

In longitudinal ventilation, airflow is injected into the tunnel through the high velocity jet of a Saccardo nozzle at one end of the tunnel, where it mixes with the air brought in by the piston effect of the incoming traffic. The advantage of longitudinal ventilation is that it precludes the necessity of separate ventilation duct. The level of pollutants and temperature increases as the tunnel length increases. Further, an adverse atmospheric condition may reduce the effectiveness of the system.

Transverse flow is created by the uniform distribution of fresh air or collection of vitiated air along the length of the tunnel. The uniform airflow throughout the length of a tunnel will provide a consistent level of temperature and pollutants through out the tunnel. The transverse ventilation can be configured as transverse and semi transverse. A supply and an extraction duct running through out the tunnel length characterize the fully transverse system. While semi transverse system includes either uniform collection or distribution through the length of the tunnel. During fire, air extracted by the semi-transverse system prevent entrainment of smoke and reduce the temperature level to the tenable limit.

The wide effects of ventilation on hazardous effects of fire necessitate the evaluation of performance of different ventilation strategies for the rail tunnel separately, especially in emergency situation. In case of a fire accident, a ventilation system is implemented to accomplish following aims:

1. To maintain a tenable environment inside the tunnel during evacuation
2. To control distribution of smoke inside the tunnel length.
3. To facilitate emergency response personnel in the rescue operations

The development of appropriate strategies to achieve the objectives of installation of a ventilation system requires information about the fundamental nature of the problems such as fire source, temperature distribution, production and stratification of toxic gases, visibility and opacity of system. The current study is a step forward in emergency evacuation strategy and proper ventilation design in case of fire accident inside a rail-tunnel due to spillage of an inflammable substance.

2 NUMERICAL DISCUSSIONS

Computational Fluid Dynamics (CFD) models are becoming increasingly popular as a predictive tool in the area of rail/road tunnel fire safety [2]. In conventional tunnel ventilation software like SES and MFIRE, the tunnel network is considered as a closed circuit of airways intersecting at the junctions. These network-based approaches provide no detail of local fire generated flow and their interaction with the ventilation.

The CFD model used here is Fluidyn-Ventunnel [3], which 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 solver [4], which uses multi-step SIMPLEC/PISO algorithm [5], [6] for solving transient compressible flows 9], [110], [11], 12], 13] , 14],15] on 3D unstructured meshes with combustion16] and heat transfer, including radiation17]. Higher order schemes [7], [8] both in time and space are provided for accurate results. Extensive validation has shown that this model meets the requirements of a tunnel fire simulation and can be used to provide reliable assessment of the efficiency of ventilation system.

2.1 FIRE DYNAMICS

Due to limited availability of oxygen inside the tunnel confines, a tunnel fire is characterized as "oxygen limited" [18]. Generally, fire development is a gradual process. However, in this study, the development of fire is assumed to be rapid to test the upper bound of performance of the ventilation equipments. To design an emergency strategy in case of a fire accident, tunnel designer requires data about the heat release rate, duration of the fire and interaction of buoyant plume with the tunnel environment.

In CFD calculation, a fire can be modeled using a combustion model for the oxidation reaction of a particular fuel. However, the complex interaction between the turbulence and combustion may introduce additional instabilities. Moreover, the source of the combustion is much more complicated since the information of total fire area and total heat release rate is not adequate. In current study, the fire source "hearth" is represented as a volumetric source with a fixed heat release rate of 50 MW for fire inside a tunnel [19]. The radiation fraction of heat transfer is taken as 30% and only the convective portion (70%) has been modeled. The consumption of oxygen [20], 13,000 KJ/kg, is based on previous study for hydrocarbon fire. The production of $CO2$ and CO [20] is of the order of 0.1kg/s and 0.02kg/s respectively per MW of the heat released.

2.2 MATHEMATICAL MODELING

The CFD approach solves the following governing equations describing conservation of mass, momentum, and energy

$$\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho \mathbf{U}) = 0 \tag{2.1}$$

$$\frac{\partial (\rho \mathbf{U})}{\partial t} + \nabla \cdot (\rho \mathbf{U}\mathbf{U}) = \nabla \cdot \tau - \nabla p + S_{\mathbf{U}} \tag{2.2}$$

$$Cp\left[\frac{\partial (\rho T)}{\partial t} + \nabla \cdot (\rho \mathbf{U} T)\right] = \nabla \cdot \mathbf{q} - \left[\frac{\partial (\ln \rho)}{\partial (\ln T)}\right]_p \left[\frac{\partial p}{\partial t} + \mathbf{U} \cdot \nabla p\right] + S_T \tag{2.3}$$

NSNT solves for pressure directly, density is computed from an equation of state, which is of a generic form:

$$\rho = f(p,T) \tag{2.4}$$

The term $\left[\frac{\partial (\ln \rho)}{\partial (\ln T)}\right]_p$ in above equation is evaluated from this equation of state.

3. CASE STUDY

This analysis presents performance evaluation of a proposed ventilation strategy in case of a fire accident inside a rail tunnel. The proposed ventilation system includes a combination of a longitudinal and a semi transverse system. The longitudinal ventilation is the primary ventilation strategy, which is switched on just after the fire ignites. The transverse ventilation is the emergency strategy, which is switched on when the combustion products start entraining into the station environment. The delay time of ventilation equipments is neglected under the assumption of fully developed fire at the start.

3.1. GEOMETRY

The domain of interest includes a bi-directional two-lane underground rail tunnel with a station. The geometrical configuration for this case is shown in the Figure 1a. The sideways exits (ExitA-D) protruding from the station end are simplified representation of passage from subway to the ground level. In order to preserve the simulation time, the domain of interest is limited to 150m from the left end and 50m from the right end of the station respectively. The choice resulted from the need to represent correctly the effect of fire downstream inside the tunnel and the station. The smoke propagation (due to CO_2 and CO) is not allowed to move more than 30m [2] before entering into an exit portal. Taking norms into consideration, seven transverse vents, ventA being closest to tunnel ENDA, are located through out tunnel length at an interval of 20m. The location and dimension of train are shown in Figure 1b and 1c. A uniform cartesian grid has been chosen having 300, 40 and 24 cells in X, Y and Z direction respectively with a total of approx 2,50,000 cells.

3.2. BOUNDARY CONDITION

The rapid evolution of fire generates a buoyant plume. The air near the source gets lighter and moves upward. The hot air is replaced by heavier cold air from the surrounding and develops a re-circulation region near the fire source. An improper boundary condition may extend this re-circulation region beyond the tunnel confine. To ensure uniform longitudinal ventilation at the initial stage of fire, an inflow and an outflow condition is imposed at the left and right tunnel end respectively. The pressure opening condition at the exits allow the flow to develop inside the tunnel and the station. The transverse vents are provided with an extraction rate of 25 m3/s [2].

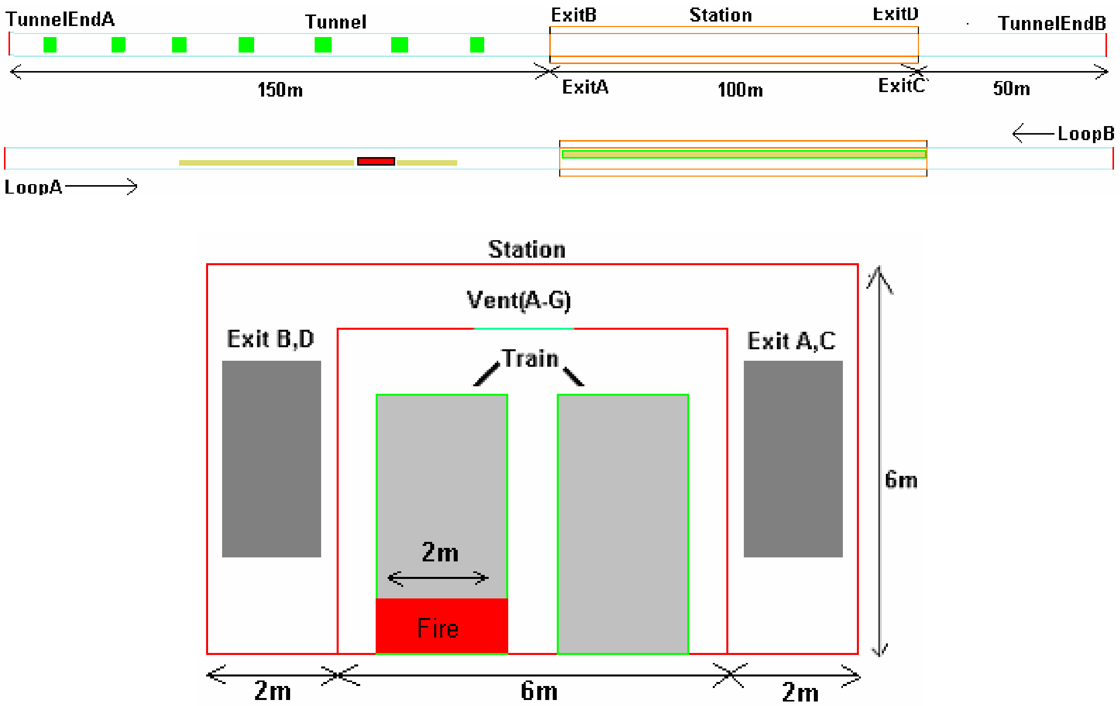

Figure 1: a) Longitudinal sectional view of the domain showing the tunnel, the station and the subway passage b) Longitudinal sectional view of the domain for including the hearth and the trains d) Cross Sectional View of the Domain

3.3 INITIAL CONDITION

A fire is ignited when both the trains were approaching the station. The train in loop-A got engulfed in the fire and stopped 50m away from station. The train in loop-B arrived and stopped at station. In absence of train motion, the initial flow condition depends upon the wind field established by the meteorological conditions and the available longitudinal ventilation started by then. The transverse ventilation is switched on when the smoke entrain into the station environment.

3.4 RESULTS

The primary aim of installation of the fire safety equipments is to prevent passengers, inside the tunnel and those waiting at the station, getting affected from the hazardous effects of fire. The next concern is to facilitate the fire rescuers by evacuating the hot toxic gases accumulated inside the tunnel using transverse ventilation. In case of fire, the longitudinal draught pushed the hot combustion products towards the tunnel end away from the station. The numerical simulation of the fire inside the tunnel with a longitudinal draught of 0.5m/s put forward the following points:

1. Figure 2 presents the temperature distribution at various instants on a tunnel section passing through the heat source, after the fire had started. The hot exhaust air from the fire caused a buoyant plume in the upward direction. In first two seconds the plume reached the tunnel ceiling. The confinement at the tunnel upper bound hindered the radial movement and spread the buoyant plume longitudinally in both directions.

2. The draught (0.5m/s) towards tunnel-end A has negligible effect on longitudinal movement of plume, which is close to 4m/s near the ceiling. The spread of fire is governed by oxygen presence inside the tunnel confine and is pushed towards the nearest subway opening. With in 12 s, the smoke entered into the station.

3. Figure 3 presents the velocity vectors and temperature distribution at different instants on a transverse section passing through the source. According to Haertes[22], the temperature rise of 180 K is above the tenable limit. The high temperature layer should remain 2m high above ground for human evacuation. However, in the present case it is seen from the vector plots at 12 s that the re-circulation region is shifted upwards, which increased the entrainment rate. This causes the high temperature layer to further descend down.

4. To prevent further spreading of smoke upstream, the outflow transverse vents were switched on at t=12 s. The outflow from the transverse vents removes the exhaust gases accumulated in the station. The reduced re-circulation prevents entrainment of air and maintains a stable smoke layer at the top of tunnel.

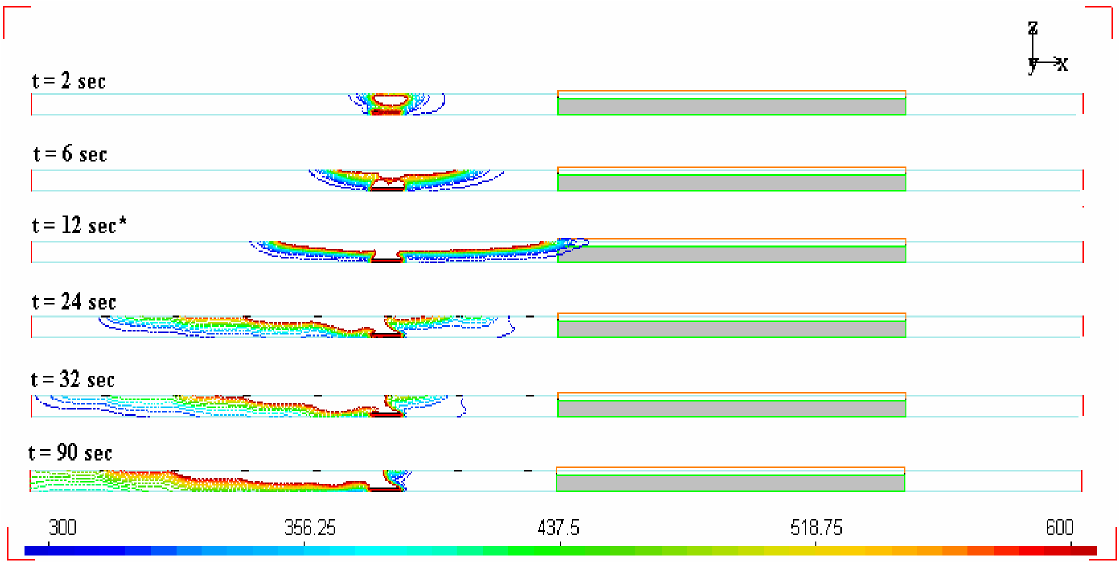

Figure 2: Contour plot of Temperature [K] on section passing through fire source at various instants in presence of longitudinal draught, 0.5 m/s.

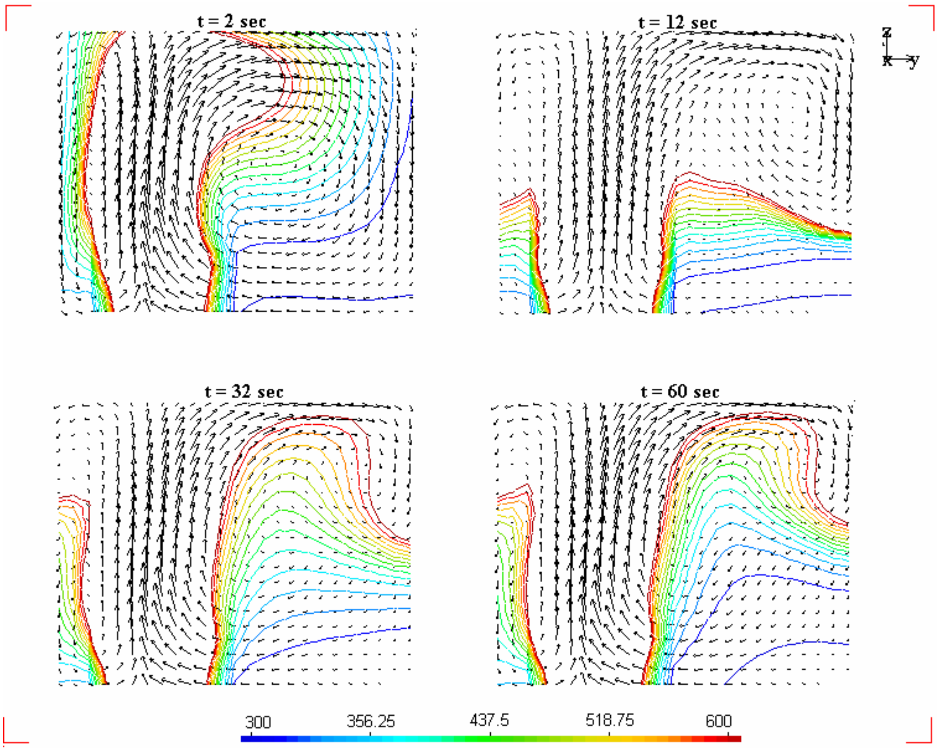

Figure 3: Contour plot of Temperature [K] and vectors plot on transverse section passing through fire source at various time instants

4 PERFORMANCE EVALUATION OF THE VENTILATION SYSTEM

The maximum temperature and its distribution depend upon the interaction among the longitudinal and the semi-transverse ventilation. While the longitudinal draught prevents smoke back layering, transverse vent extract out the high temperature layer near ceiling and prevent the smoke entrainment. The result of operating the ventilation with different longitudinal draught blowing from right to left end is presented in Figures 4 and 5.

Previous work by Heseldon [21] on methods to prevent smoke back layering put forward a non-dimensional parameter, commonly known as the critical velocity. The critical velocity predicts the minimum longitudinal velocity to prevent smoke backlayering. Further studies[18] relate the critical velocity with the heat release rate and the tunnel geometry through empirical relations (3.1 – 3.4). At low release rate, the critical velocity varies with 1/3rd power of heat release rate but remained constant after a certain fire size.

$$V^*(0) = 0.40*(0.20)^{\frac{-1}{3}}*(Q^*)^{\frac{1}{3}} \qquad Q^* < 0.20 \qquad (3.1)$$

$$V^*(0) = 0.40 \qquad Q^* > 0.20 \qquad (3.2)$$

$$V^* = \frac{V}{2}*(g*H_D)^{\frac{1}{2}} \qquad (3.3)$$

$$Q^* = \frac{Q}{\rho*C_P*T_0*(g*H_D^{\ 5})^{\frac{1}{2}}} \qquad (3.4)$$

The Equations (3.1-3.4) are valid in the case of road tunnels without station, i.e. for tunnels with constant cross section area and no opening in between. In the current case, the non-dimensional heat release rate (Q*) is greater than 0.20. The computed value of critical velocity is 0.4m/s. However, the results shown in Figure 2 indicated that the longitudinal speed of 0.5m/s have only marginal effect on fire. The nearest exhaust opening at the subway passage, rather than the longitudinal draught, influences the fire spread. The present results show the necessity of the presence of transverse ventilation strategy to fulfill the requirement of safe evacuation.

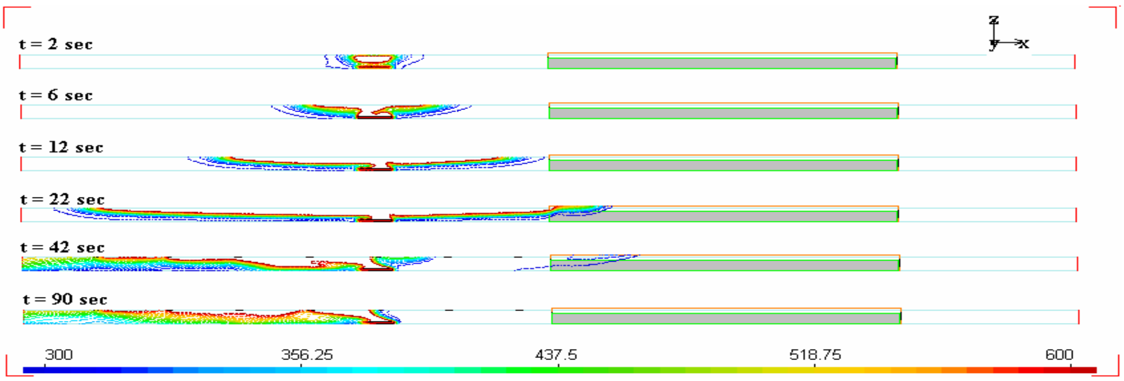

Figure 4: Contour plot of Temperature [K] on section passing through source at various instants for longitudinal speed of 0.5m/s

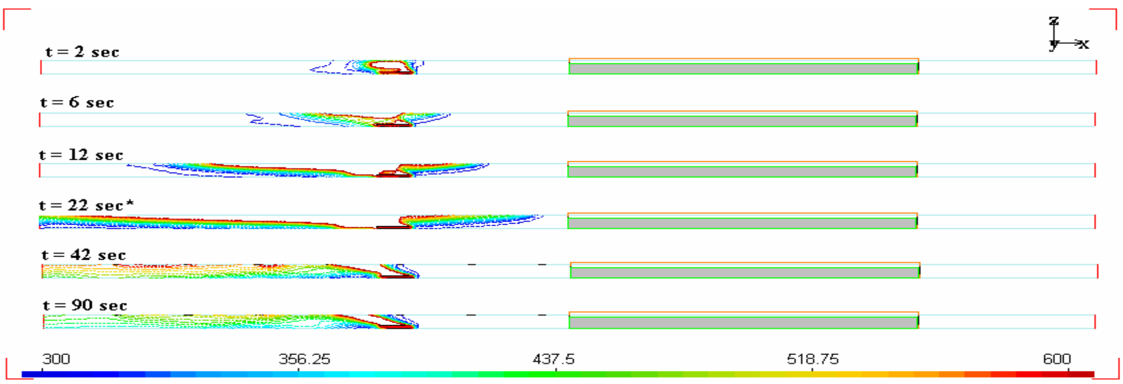

Figure 5: Contour plot of Temperature [K] on section passing through source at various instants for longitudinal speed of 1.5m/s

4.1 SURVIVABILITY CRITERION

The performance of a ventilation system can also be evaluated in terms of probability of survival of passengers in the case of a fire. There are two common criterions [22] to predict the probability of survival. (i) The tenable limit of temperature is identified as 180°C. (ii) The toxic gas concentration [CO] should be less than 3000 ppm. Under these criterions, following two conditions have been identified (i) $T < 453$ K (ii) $\frac{11}{78}[Yp] < 0.003$ (CO < 3000 ppm).

The figure 6 and figure 7 gives the comparative representation of performance of ventilation system with different longitudinal draught coupled with semi-transverse ventilation.

1. With draught=0.5m/s, the effect of transverse ventilation is dominant. The high temperature layer has extended up to the vent-A. The maximum temperature value near the tunnel ceiling is found to be 1516K. The smoke layer is in accordance with temperature. With in 60 sec, the maximum value of the mass fraction of CO and CO_2 is found to be 0.132 and 0.494 respectively at the ceiling.
2. An increased draught of 1.5m/s shifted the peak temperature downstream, the interaction between longitudinal and transverse ventilation is more coupled. The untenable temperature layer has propagated to the tunnel end A. At 60 sec, the maximum value of the mass fraction of CO and CO_2 is found to be 0.114 and 0.445. It maintains a clear smoke layer at the top till 60s.
3. For draught=3.0 m/s, the longitudinal ventilation dominated and the peak temperature is further shifted downstream closer to vent D. The high temperature layer is spread up to tunnel exit but it is the smoke propagation, which looks more fatal. Figure 10 shows that within 60 s the complete tunnel length downstream fire is stuffed with CO beyond unacceptable limit. The transverse vents removed the hot air accumulated near the ceiling and the highest temperature is maintained in the layer below the ceiling. As described above, the maximum value of temperature, CO and CO_2 further decreased by increasing the draught. The maximum temperature at the ceiling is found to be 751K. The maximum value of the mass-fraction of CO and CO_2 is observed as 0.067 and 0.27 respectively.

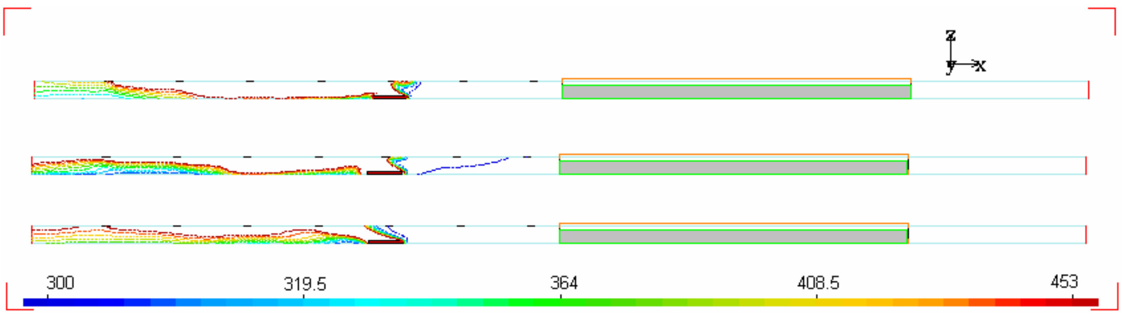

Figure 6: Contour plot of temperature [K] on section passing through center of tunnel at t=60s (a) for draught=0.5m/s (b) for draught=1.5m/s (c) for draught=3.0m/s

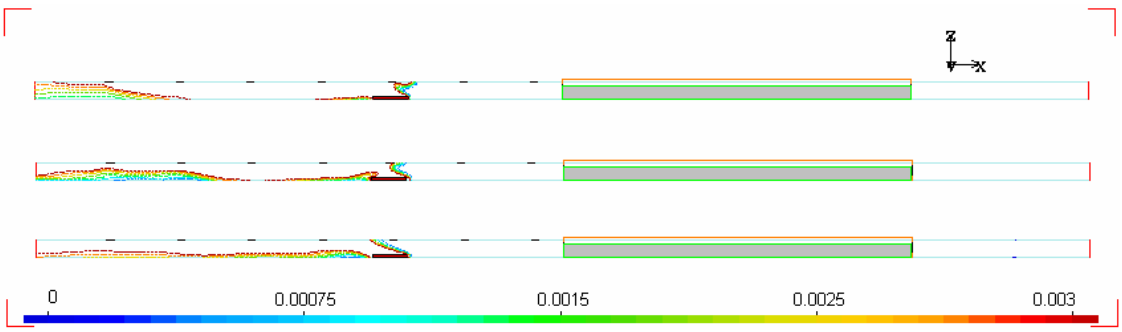

Figure 7: Contour plot of 11/78[Yp] CO on section passing through center of tunnel at t=120s (a) for draught=0.5m/s (b) for draught=1.5m/s (c) for draught=3.0m/s

5. CONCLUSION

Various studies with different combinations of longitudinal and semi transverse ventilation systems have been performed to analyze a crucial fire scenarios for a generic two-lane rail tunnel with a station. The results put forward following points

1. It is found that the longitudinal ventilation alone proves inadequate to control the movement of hot gases and the locating transverse vents at regular distances is more effective.
2. The adopted evacuation strategy in the presence of longitudinal and semi transverse ventilation works well. The safety officers must put on the jet fan to have a longitudinal draught away from the station. The transverse vents between fire site and tunnel-end, away from station, must be put on in extraction mode.
3. The longitudinal draught must not exceed a certain range, as the movement of smoke reduced its temperature and the buoyancy effects and may result in de-stratification of smoke downstream fire.
4. During a tunnel fire, passengers' behavior is least expected to be regulated by guidelines. Presence of emergency exit points inside the tunnel could be life saving for people who moved downstream.
5. To check the upper bound of ventilation, the ventilation performance is evaluated under high heat flux and fully developed fire. However, in reality, the fire development is gradual. A better understanding of time dependent evolution of fire may help in more realistic modeling of the fire problem.

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NOMENCLATURE:

ρ - Density
u - Speed
U_t - Maximum Trains speed
U - Velocity Vector
p - Pressure
τ – $\mu\gamma^* - \left(\frac{2}{3}\mu - \kappa\right)(\nabla . U)\delta$, Viscous tensor
γ^* – $\nabla U + (\nabla U)^T$, The rate-of-strain (or rate-of-deformation)
μ - Effective Viscosity
κ - Dilatational Viscosity (=0 according to stokes)
δ - Unit Tensor

S_U	-	Source term for momentum equation
T	-	temperature
Cp	-	specific heat at constant pressure
q	-	heat flux vector
K	-	thermal conductivity
S_T	-	Source Term for energy equation
T_0	-	Reference Temperature = 298K
H_D	-	Hydraulic diameter
g	-	Gravity vector=9.81m/s^2
V	-	Longitudinal draught in m/s
Q	-	Heat release rate in W
Q^*	-	Non dimensional heat release rate
V^*	-	Non dimensional draught

LIST OF FIGURES: