THE ROLE OF VENTILATION ON THE DISPERSION OF FIRE GASES INSIDE A TUNNEL

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Abstract

Tunnel fires represent a serious threat for underground, rail and road safety, due to their potential severe consequences in terms of loss of lives, economic consequences and operational discontinuity. Given the fundamental role of tunnel ventilation in both normal and emergency conditions and the lack of any systematic analysis, a numerical analysis has been carried out in order to compare different ventilation configurations and to assess their effect on smoke and pollutants dispersion inside a tunnel for a typical fire scenario. The software Fire Dynamics Simulator (FDS), developed by NIST, was used for the modeling activity.

The present study evidenced that the use of computational fluid dynamics (CFD) models in this field can be useful especially for designing adequate ventilation systems and the necessary escape routes.

Introduction

In spite of statistics suggesting that road tunnels are inherently safer than open roads [1], catastrophic tunnel fires occurred in the recent past (Mt Blanc, Gotthard and Tauern Tunnel fires are a few examples) have highlighted the importance of the study of the fire dynamics in order to design fire safety systems with satisfactory levels of protection for users, rescuers and the tunnel itself [1].

The European Directive 2004/54/EC aimed at identifying the minimum safety requirements for road tunnels highlighted the need for risk analysis and upgrading of tunnels with unsatisfactory safety characteristics. In this context, given the impossibility to perform a high number of experiments for each tunnel configuration, a fundamental role has to be played by numerical simulations.

Tunnel ventilation plays a key role in both ordinary and emergency operations [1] and thus should be carefully analyzed: it should grant tenable conditions during normal operations as well as safe, smoke free escape routes from an hypothetic fire zone during an emergency situation, without enhancing combustion by providing oxygen to the burning materials. The design of a correctly performing ventilation system is highly dependent on the geometrical and physical configuration of the tunnel [2]. In this paper a simple tunnel configuration has been considered in order to study the performances of different ventilation systems in controlling the smoke spread and the dispersion of fire gases inside the tunnel.

Configurations of the ventilation system

The design of tunnel ventilation systems is aimed at solving two problems: dilution of pollutants inside tunnels and control of the smoke spread in case of fire [3]. To this purpose, it is possible to consider natural or mechanical systems. Natural ventilation in tunnels is achieved through the piston effect generated by moving vehicles together with meteorological conditions at the portals, so as to preserve satisfactory ventilation conditions inside the tunnel environment. On the other hand, mechanically ventilated tunnels rely on a combination of ducts and dampers to move air streams along the tunnel length; according to the layout of the ventilation system, they can be further classified in longitudinally ventilated (Long), fully-transverse (TR) or semi-transverse (ST) systems.

Longitudinally ventilated systems rely on axial fans which capture fresh air at the beginning of the tunnel and discharge heated and polluted air at the other portal. Transverse flow is created by the uniform distribution of fresh air, uniform collection of vitiated air along the length of the tunnel (semi-transverse configurations) or a combination of both (fully transverse), which help provide a consistent level of temperature and pollutants throughout the tunnel [4].

Different guidelines [3,5] provide design requirements for the ventilation of tunnels (both mono and bi-directional) of different length. For instance, natural ventilation could be enough for two-way tunnels shorter than 0.5 km, while tunnels longer than 6 km should be equipped with TR ventilation only [5]. In spite of the fact that all the aforementioned configurations could be applied, there is a small amount of systematic studies on configurations other than the longitudinal one, subject to the vast majority of tunnel fire studies [6] aimed at identifying parameters such as the critical ventilation velocity, the backlayering length [7], etc.

Given the difference among them, in this work a numerical analysis was carried out in order to compare different ventilation configurations and to assess their effect on smoke and pollutants dispersion inside a tunnel for two typical fire scenarios.

Modeling approach

The Fire Dynamics Simulator (FDS) [8], developed at NIST, is a CFD model of fire-driven fluid flow. FDS solves numerically a form of the Navier-Stokes equations appropriate for the low-speed, thermally-driven flow with an emphasis on the smoke and heat transport from fires. FDS model solves the equations for the conservation mass, species, and momentum, taking into account conductive and radiative heat fluxes. The overall computation is treated as a Large Eddy Simulation (LES). The description of the numerical schemes used for the solution all equations is described in [9]. The geometry of the domain, mesh resolution, obstacles, boundary conditions, material properties and different simulations parameters are all inputs for the simulation. In the case of tunnel fire, boundary conditions are prescribed on the walls and vents.

In order to make a significant comparison, a basic set up was selected from literature [10] and different test cases were defined by changing the ventilation configuration while keeping the same tunnel geometry (length of 180 m, height of 6 m and width of 4 m) and volumetric inflow rate of 52.5 m^3/s; two fire characteristics were investigated, one with an assigned heat release rate (fire produced by a solid fuel, as considered in [10]), the other with a burning liquid pool of a gasoline-like fuel.

The transverse configurations were obtained with 12 extraction vents along the tunnel ceiling and 12 supply vents on the tunnel wall at floor level (Fig. 1). The velocity profiles at vents for the different cases were chosen as to maintain the same volumetric inflow rate of air; the non-uniform velocity values, summarized in Table 1, were defined as suggested by Yan et al. [10] to reproduce the differences from the ideal behavior in the ducts.

Table 1. Ventilation velocities [m/s] at the tunnel openings along the ceiling.

Mechanical System Mode	Vents 1, 12	Vents 2,11	Vents 3,10	Vents 4, 9	Vents 5, 8	Vents 6, 7
Uniform (un)	3.5	3.5	3.5	3.5	3.5	3.5
Non Uniform (nn)	7.5	5.5	3.75	2	1.5	1

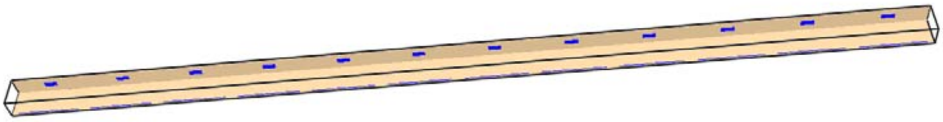

Figure 1. Sketch of the tunnel setup used in the present study.

Results and discussion

In CFD fire simulations, the grid size on the fire source should be selected referring to the criterion established by Quintiere et al. [11], corresponding in this case to cells ranging from 7 to 15 cm. Preliminary grid sensitivity tests were performed in order to verify the independence of the results from the cell size; it was found that a computational domain with cells of 10 cm or less on the fire sources and 20 cm away from it could be considered satisfactory, resulting in a computational domain with about 540 kcells (full 3D simulations).

Different ventilation configurations, with uniform and non uniform air velocities, were considered for the fire scenario in which the solid fuel combustion was represented by a prescribed HRR profile. Fig. 2 highlights the smoke patterns obtained for the investigated cases at different times, while Table 2 roughly summarizes the behavior of the smoke plumes, in terms of percentage coverage of the tunnel length, during the fire evolution. In the non ventilated configuration smoke spreads along the tunnel portals form both ends, without destratification and with long cleaning times due to the absence of the air inflow momentum that could dilute and help the smoke extraction.

Table 2. Dimension of smoke plumes (% of the total tunnel length) 50, 80, and 170 s from the beginning of the fire. The last column describes whether the tunnel is free of smoke after 500 s (320 s after the fire extinction).

Configuration	**t = 50 s**	**t = 80 s**	**t = 170 s**	**After 500 s**
1. No Ventilation	15	84	100	Upper layer only
2. Longitudinal	30	59	70	No smoke
3. ST-un extraction	14	31	30	No smoke
4. ST-nn extraction	14	47	59	Smoke
5. TR-un	12	32	47	No smoke
6. TR-nn	13	49	61	No smoke
7. ST-un supply inject.	57	99	100	No smoke
8. ST-nn supply inject.	50	87	100	Smoke

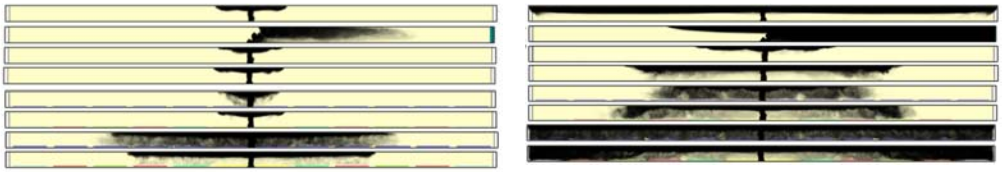

Figure 2. Smoke profiles at 50 and 170 s after the beginning of the fire for the investigated ventilation configurations (as reported, from top to down, in Table 2).

Longitudinal ventilation grants tenable, smoke free conditions upstream of the fire; downstream, the whole section becomes filled with smoke, which is quite rapidly removed once the fire is extinguished. Semi transverse configurations with exhaust vents on the tunnel ceiling grant excellent confinement and rapid dilution of smoke (ST extraction cases); on the other hand, the supply configurations (with air inlets along the walls, ST injection cases) are characterized by the worst destratification conditions due to a strong increase of mixing phenomena in the vertical direction which prevent the formation of the hot gas layer close to the tunnel ceiling. Non uniform extraction velocities – which take into consideration the deviation from the ideal situation represented by uniform velocities - are characterized by a wider smoke spread, together with more destratification in proximity of vents characterized by the highest velocities. Fully transverse configurations (TR), characterize by identical supply and exhaust velocities, behave similarly to the semi-transverse extraction cases, with increased destratification due to the increased turbulence generated by the air inflow.

Then, the performances of a subset of the previously defined ventilation conditions (NO ventilation, Longitudinal, ST-nn extract, ST-nn inject and TR-nn) were evaluated for the case of a pool fire scenario. Some burn rate profiles obtained by modeling also the liquid fuel vaporization are compared with the prescribed HRR profile used to describe the solid fuel fires in Fig. 3a, while Fig 3b represents the soot volume fraction trends (SVF) predicted along the tunnel centerline, 40 m downstream of the fire, at an height of 2.3 m. While the burn rate profiles were poorly influenced by the different ventilation conditions (also for the cases not represented in Fig. 3a), soot trends obtained for the pool fire cases are strongly affected by the inflow air presence and movement. In particular, it is possible to notice that the longitudinal ventilation mainly deflects the smoke plume, without diluting the fire gases downstream of the fire position; similar SVF levels and trends were found for the fully-transverse (TR) and the ST inject. configuration. The best performances, in terms of fast dilution and complete smoke removal, were evidenced by the ST extraction configuration because the hot smoke layer is directly exhausted from the ceiling vents, trying to prevent its interaction with the lower cold air layer. These results are confirmed also by the reduction of the visibility predicted by the model (Table 3); low visibility conditions are sometimes more critical than the presence of toxic gases inside the tunnel because they affect the possibility to quickly reach escape routes, thus exposing people to fire consequences for longer periods.

Table 3. Minimum visibility conditions reached during the fire tests for the investigated fuels and ventilation configurations (X=20, Y=0, Z=2.3); best visibility conditions are represented by the value 30 m.

	Min. Visibility [m]	
Configuration	Solid fuel	Liquid fuel
No Ventilation	30	30
Longitudinal	0.9	0.6
ST-nn extraction	18	22
ST-nn supply inject.	15	30
TR-nn	17	28

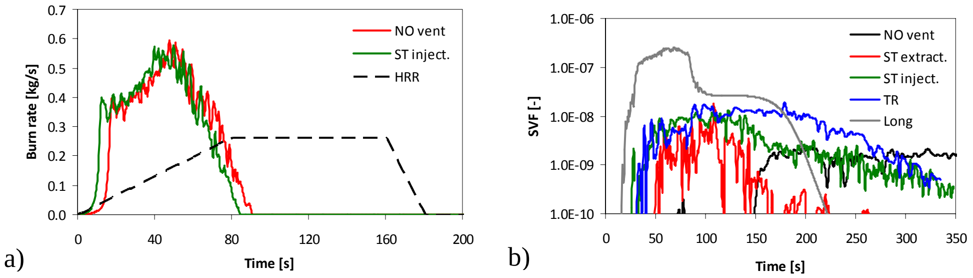

Figure 3. a) Comparison among burn rate profiles obtained for liquid fuel pool fires (solid lines) and solid fuel fires (dotted line); b) Soot volume fraction profiles detected at (X=40, Y=0, Z=2.3) for the investigated pool fire scenarios.

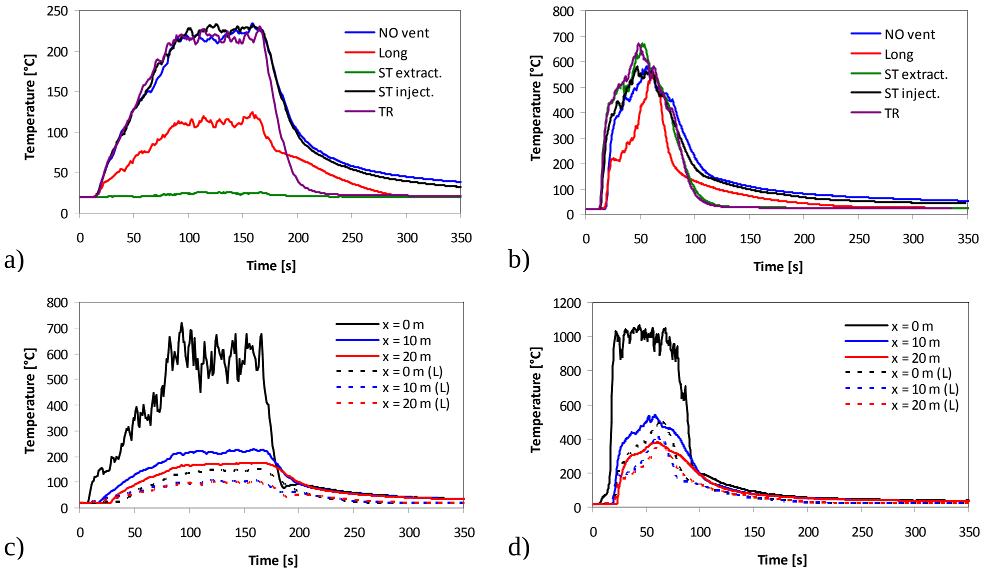

Figure 4. Temperature profiles (X=8, Y=0, Z=6) for different configurations: a) solid fuel; b) liquid fuel pool; Temperature profiles at different locations downstream of the fire (Y=0, Z=5.2) for the NO ventilation and longitudinal ventilation (L) cases: c) solid fuel; d) liquid fuel pool.

Several temperature profiles along the tunnel axis were reported in Fig. 4 to confirm the qualitative findings evidenced by the smoke contours. In particular, Fig. 4a and 4b show the temperature profiles obtained basically at the tunnel ceiling for different ventilation configurations and for the two investigated fuels. It can be noticed that the strong simplifications used to represent a fire source by means of a prescribed HRR trend (Fig. 4a) lead to relevant differences among the ventilation strategies concerning the maximum predicted temperatures; on the other hand, temperature profiles obtained for the pool fire cases (Fig. 4b) show similar trends apart from the longitudinal ventilation case, where the flame is stretched and deflected in the downstream direction.

A detailed descriptions of the pool dynamics and vaporization can affect the temperatures non only above or close to the fire source but also at a certain distance from it; Fig. 4c and Fig. 4d compare the evolution of several temperature profiles along the tunnel axis for different distances downstream of the fire. Two quite different ventilation cases, the absence of a mechanical ventilation and a longitudinal ventilation, were compared respectively. In the prescribed HRR approach (Fig. 4c), the effect of the active mechanical ventilation induces an overall reduction of the temperatures along the tunnel axis; conversely, with the pool model (Fig. 4d) the shape of the temperatures profiles is influenced by the ventilation configuration but similar peak values are reached both with and without mechanical ventilation (with the exception of X=0) in correspondence of the maximum burn rate of fuel. These results highlight the key role of the source term modeling and suggest that further studies should be dedicated to understand the effective capability of the model to predict experimental data for different fuels and fire scenarios.

Conclusions

The FDS model was used to perform a series of numerical simulations aimed at evaluating the effect of the ventilation conditions on tunnel fire dynamics and fire gases dispersion. The comparison highlighted several differences in the smoke spread dynamics, temperatures distribution and clean-up times that can be ascribed to both the different layouts of the investigated ventilation systems and the choice of the airflow input and output rates. Further investigations should be aimed at identifying the effect of different fire positions along the tunnel on the ventilation performances. Further attention could also be devoted to the study of the source term modeling which can strongly affect the fire evolution, the pollutants dispersion and the heat transfer inside the tunnel.

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