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NATURAL AND MECHANICAL VENTILATION CFD STUDY FOR A SUBWAY STATION/TUNNEL (ECCOMAS CFD 2010)

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Abstract. *An evaluation of natural and mechanical ventilation solutions for a specific subway station and tunnel was undertaken. The geometrical characteristics of the subway station and tunnel undermine the possibility of empirical correlation based estimates, such as those used to predict critical velocity, for flow behavior under natural or mechanical ventilation. The technical solutions were validated by CFD modeling and their comparison is provided in terms of overall safety, reliability, flexibility and maintenance costs. Aesthetics, visual impact and usability are also discussed.*

The numerical simulations were performed in the framework of the Reynolds average Navier-Stokes equations. The standard κ-ε turbulence model accounting for buoyancy effects on the kinetic energy production was used with a hybrid tetrahedral/hexahedral unstructured grid. The simulations were performed with a commercial code. The fire was modeled by a volumetric heat source term which ensured mass balance and provided reasonable solutions except for the near the fire region.

The results showed that the natural ventilation solution for this specific subway and tunnel case for smoke control is possible if a careful design of exhaust louvers is made. In the present case the prevailing winds induce a positive effect on the internal flow pattern due to the orientation, geometry of the subway station and tunnel and the characteristics of its openings. The effects of adverse wind directions are presented and discussed. A mechanical ventilation solution was achieved by implementing two ventilation shafts and six jet fans at the tunnel being the both reversible.

Natural ventilation in the present case can deliver an effective, low cost and low maintenance solution. Its main issue was found to be related to architectural integration. The mechanical ventilation solution introduced, on one hand, additional economical costs and, on the other hand, a more flexible solution for fire fighting. The investments costs were estimated to be 2 to 3 times higher for the mechanical ventilation system which also has higher operational and maintenance costs.

1 INTRODUCTION

Subway systems ensure an efficient transportation solution for large amounts of passengers to and within cities. The growing number of passengers and the increase of vehicle velocity pose new challenges in terms of fire safety. A fire incident in an underground system presents different challenges from those of common buildings such as those concerning the fire load, evacuation strategies and fire fighting.

The goal of a ventilation system for Subway stations and tunnel is to provide smoke free evacuation paths for passengers and to facilitate firefighting and firefighter access.

The most commonly used tunnel mechanical ventilation strategy is longitudinal ventilation in a push-pull strategy recurring to supply and extraction fans placed at both ends of the tunnel. The typical design criterion is the "critical velocity" which corresponds to the minimum tunnel average velocity that prevents the occurrence of the backlayering phenomenon. This strategy ensures that evacuation paths are free of hot and toxic gases.

Different critical velocity estimates for several tunnel geometries have been studied in terms of semi empirical correlations, based on fire power and tunnel geometry, that have been validated using measurements both from large and small scale experiments, see e.g. [1, 2, 3]. Nevertheless, the introduction of more complex geometries give rise to more complicated three dimensional flows that undermine the possibility of correlation based design.

Natural ventilation is also used for relatively short tunnels if sufficient tunnel height is available and smoke stratification is not impaired due to the existence of geometric particularities or significant adverse wind effects at the tunnel entrances.

Computational fluid dynamics (CFD) modeling has shown to be an increasingly valuable tool for design engineers. Several emergency ventilation strategies are possible through a better understanding of the physics of flow and smoke behavior for particular cases. The CFD simulations of tunnel fires represent a flexible and low cost solution when compared to on site testing.

Different modeling approaches have been used to simulate fire and smoke behavior in tunnels which have shown a good agreement of simulation results with experimental data.

In reference [1] the critical velocity results of small scale experiments with fires with heat release rates (HRR) from 3 kW to 45 kW showed to be well approximated by the CFD modeling approach undertaken by these authors. In reference [4] the full scale test measurements made under the EUREKA-499 project also show good results.

The reported CFD [1, 4, 5, 6] simulations differ in terms of turbulence modeling and fire modeling.

The two most important group of models used are the RANS (Reynolds Average Navier Stokes Equations) and LES (Large Eddy Simulation) model. The first group of models, being less computationally intensive, have been widely used and results obtained have proven to be in good agreement with experimental results, see [1,4]. LES simulations can be one or two orders of magnitude more time consuming, being, on the other hand, intrinsically more accurate. In reference [5] a comparison of the results obtained with the κ-ε RANS model and LES using the Smagorinsky-Lilly subgrid scale model can be found and better results from LES approach are reported. Also in reference [6] results obtained by these two models are compared and the strong mesh size dependence of the LES model is discussed.

Fire models used to simulate may take into account combustion modeling through mixture fraction transport and pre-assumed PDF (Probability Density Function) model for the interaction of turbulence and chemistry, see e.g. [6, 7], or it may be modeled by a volumetric heat source (VHS). The first modeling technique requires considerable computational effort, whereas the second provides solutions in good agreement with experimental values except for the near fire region as explained in reference [8].

A common approach to avoid the computational effort of radiation simulation is to use a reduced heat load of approximately 2/3 of the total heat load to account for radiation losses. This approximation is valid for the initial fire development stage. Radiation modeling is also addressed in references [8, 11].

The objective of this work is to present the natural and the mechanical emergency ventilation solutions for a specific subway station and tunnel and to discuss their advantages and disadvantages in terms of safety, flexibility, investment and operational costs.

2 SUBWAY STATION AND TUNNEL GEOMETRY

The studied subway station is 90 m long and 14 m wide and gives direct access to the exterior at one end (portal at the left side in figure 1) and is connected to a 150 m long tunnel. The tunnel is also opened to the exterior (right side in figure 1) and presents a slightly positive slope in that direction. This slope will lead to a 0.5 m difference in floor height from the tunnel entrance to its exit.

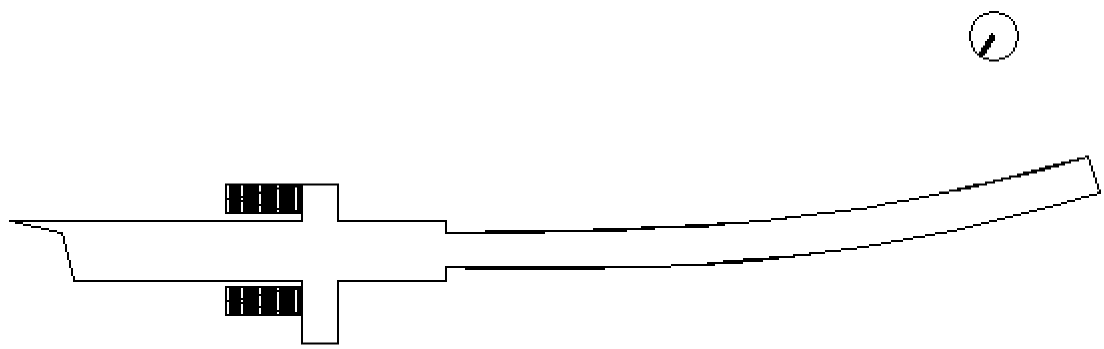

Figure 1: Subway station and tunnel geometry.

The station has two lateral independent entrances to the platforms. Passengers can also reach the platforms through the station portal. The actual ceiling heights are the following: at the station platform of 3.9 m, at the tunnel of 4.4 m and at the lateral corridors of 3 m. The lateral corridors are 14.4 m and 8 m long, respectively North and South and both 8.5 m wide.

The computational domain was extended to the exterior in order to capture the interaction of wind with the station openings and its effects on internal flow (figure 2). The tunnel opening is linked to an exterior ramp which has a 1.5 m height protection wall.

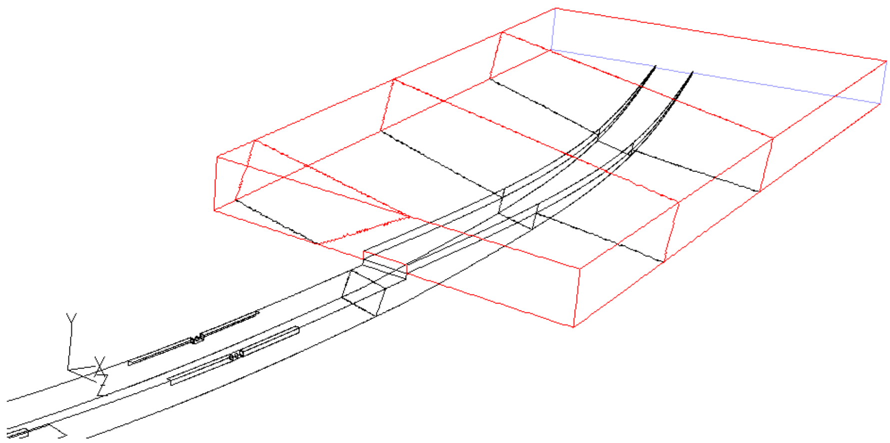

Figure 2: Tunnel entrance, exterior ramp and protection wall.

3 COMPUTATIONAL MODELING

In this work the turbulence model was the standard κ-ε accounting for the buoyancy and turbulence interaction. Fire was modeled by a volumetric heat source (VHS) ensuring the overall mass balance. Radiation modeling and simulation was not carried out and it was considered that it represented roughly 1/3 of the total estimated fire load. The remaining 2/3 of the estimated 15 MW overall fire load was considered in the simulations for the convective heat load.

Boundary conditions included velocity inlets for wind simulation and ventilation louvers. The lateral passenger exits were considered not to have relevant wind exposure and were set to null pressure gradient boundaries. For jet fans, constant volume flow rate was considered. Fully developed turbulent flow was considered for the velocity inlets and backflow boundary conditions.

Louvers were modeled by considering local head loss coefficients of k = 0.5 for the natural louvered ventilators and of k = 3 for wall mounted grilles located above the lateral accesses.

The environmental conditions were evaluated by analyzing the temperature field, meaning that the regions with temperatures above the exterior ambient temperature may be contaminated with toxic gases and/or visibility may be insufficient. This approach is valid because the contamination of fresh air resulting from turbulent mixing will cause a temperature increase. Because heat loss to the walls is neglected, temperature decrease of the smoke layer can only occur by mixture with fresh air.

The computational mesh comprised hexahedral and tetrahedral elements and was refined at the walls, jet fan shrouds and at the jet development regions. An overall of roughly 15 million cells were needed to capture the most important flow characteristics.

The same geometrical model was used, with different boundary conditions and computational mesh, for both the natural ventilation and mechanical ventilation simulations. Simulations for different mesh sizes were performed to ensure grid independence.

4 VENTILATION STRATEGIES AND FIRE SCENARIOS

In this section the studied fire scenarios and ventilation solutions adopted in accordance with passengers evacuation strategies will be presented and discussed. Figure 3 shows the modeled geometry of the station and tunnel.

The evacuation routes from the platforms lead to the corridors and stairs, and also to the station portal. The objective of both ventilation strategies is to maintain evacuation paths leading to these exits under bearable environmental conditions.

Natural ventilation of tunnels has been less studied because it is mostly used for short tunnels. The NFPA 130 (National Fire Protection Agency) standard [12] states that natural ventilation is possible for tunnels up to 200 ft (61 m) and recommends that an engineering analysis should be made if natural ventilation is to be considered for tunnels with lengths up to 1000 ft (304,8 m). In the present case the overall length is of 240 m, considering both the tunnel and station. For longer tunnels this standard recommends mechanical ventilation. This norm also establishes that evacuation times should be less than 4 minutes for the platform and less than 6 minutes for the station.

4.1 Natural ventilation strategy

For natural ventilation, openings at the station ceiling with exhaust louvers and vertical ventilation grilles above the exit corridors were considered.

The size and location of these openings were selected in order to assure that sufficient smoke is extracted to provide adequate environmental conditions during the passenger's evacuation.

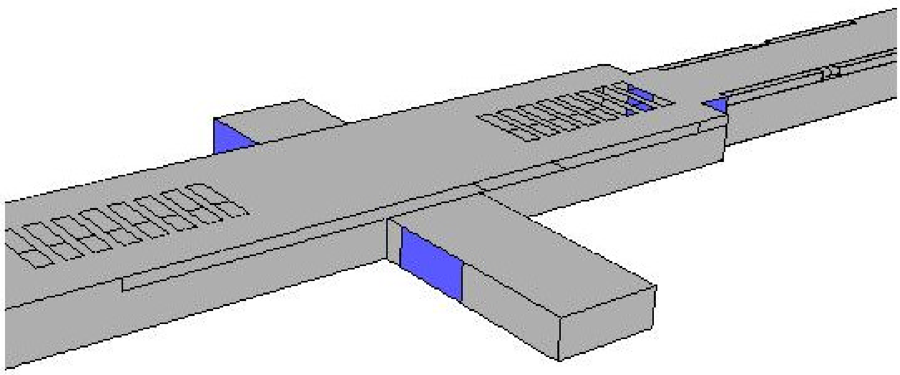

Figure 3: Subway Station and tunnel geometry details.

If a fire starts inside the station the ceiling openings will extract, due to stratification, the hot smoke, maintaining low temperatures and a low concentration of toxic gases at passenger level. The vertical ventilation grilles at the top of the exit corridors will also reduce the amount of smoke that might flow into these corridors.

In the case of a fire occurring inside the tunnel, the ceiling openings next to the tunnel will ensure that most of the smoke layer will be extracted, reducing the amount of smoke inside the station.

4.2 Mechanical ventilation strategy

For mechanical ventilation two ventilation shafts at the tunnel entrance and six jet fans distributed in three rows were considered, these can be seen in figure 4. Each ventilation shaft is able to extract 40 m^3/s (and is 65 % reversible) and each jet fan has an impulse of 250 N.

The ventilation strategy is to induce sufficient volume flow to prevent backlayering and smoke flow through evacuation routes.

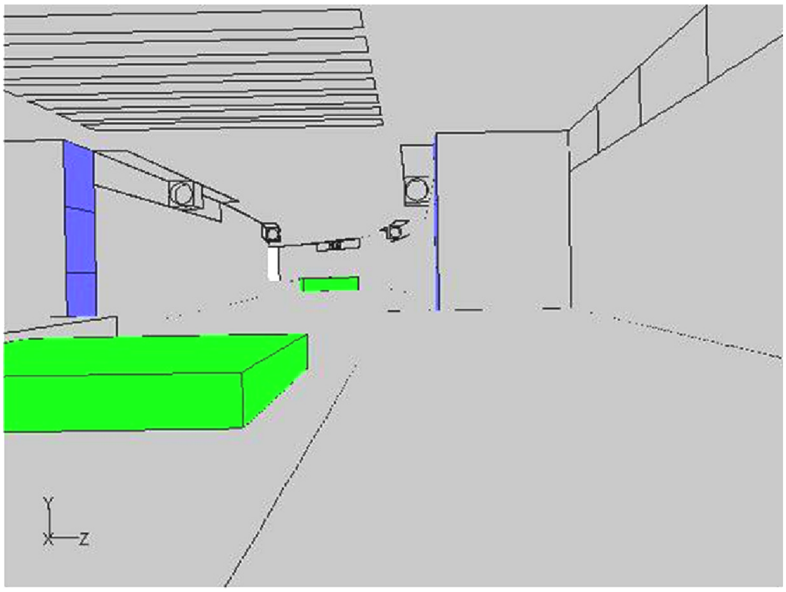

Figure 4: Station and tunnel view from the platform.

5 RESULTS AND DISCUSION

In this section the results obtained for the natural and mechanical emergency ventilation simulations are presented and discussed.

The results that will be presented are those considered to be the most critical, and that imposed the design conditions for the ventilation systems. The critical design conditions were those where emergency ventilation is made under wind conditions, particularly winds from the South and Southwest direction. For natural ventilation, wind may be able to destroy smoke stratification and force toxic gases to descend to passenger's level. In the case of mechanical ventilation the air flow velocity through the station may be reduced to a point that the backlayering phenomenon is not avoided.

A frequent wind velocity of 4.6 m/s was considered based on reference [9].

5.1 Natural ventilation results

The steady state results obtained show that for the considered fire load an overall of sixteen ceiling natural louvered ventilators are needed in order to provide enough hot smoke extraction. Figure 5 shows the obtained temperature field at the station and tunnel center plane. A slight inclination of thermal plume, caused by the fresh air entering the tunnel is reported. Nevertheless, the thermal stratification is not destroyed and high temperatures do not reach passenger level. This may be seen in figures 6 and 7, where the temperature field at a horizontal plane 1.5 m above the platform and people access corridor is shown. Temperatures of approximately 60 ºC are found at this level even for the steady state and peak heat load simulation, meaning that during passenger evacuation and initial fire growth temperatures are expected to be lower the obtained in this simulation. The results indicate that the natural ventilation strategy is able to maintain bearable conditions in terms of toxic gases concentration, visibility level and temperature.

The effectiveness of the natural ventilation solution may be better understood by analyzing the results displayed in table 1. In this table Ceiling 1 corresponds to the louvered natural ventilators placed just before the tunnel and Ceiling 2 to the ones placed next to the station portal.

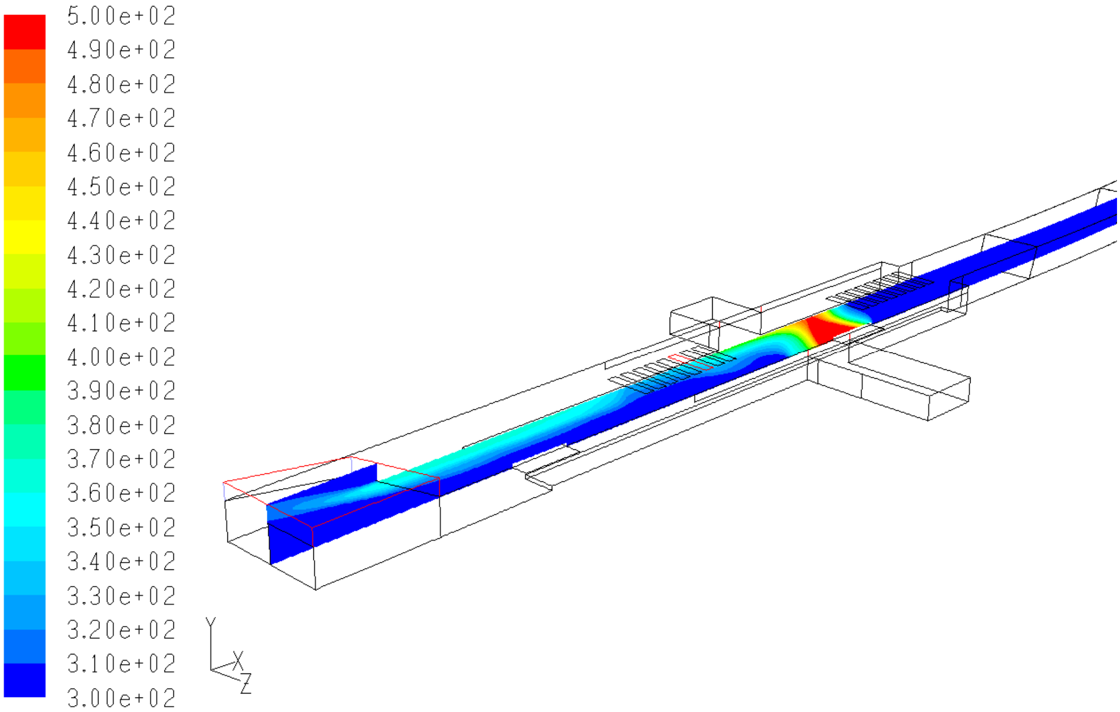

Figure 5: Temperature (Kelvin) at the central plane.

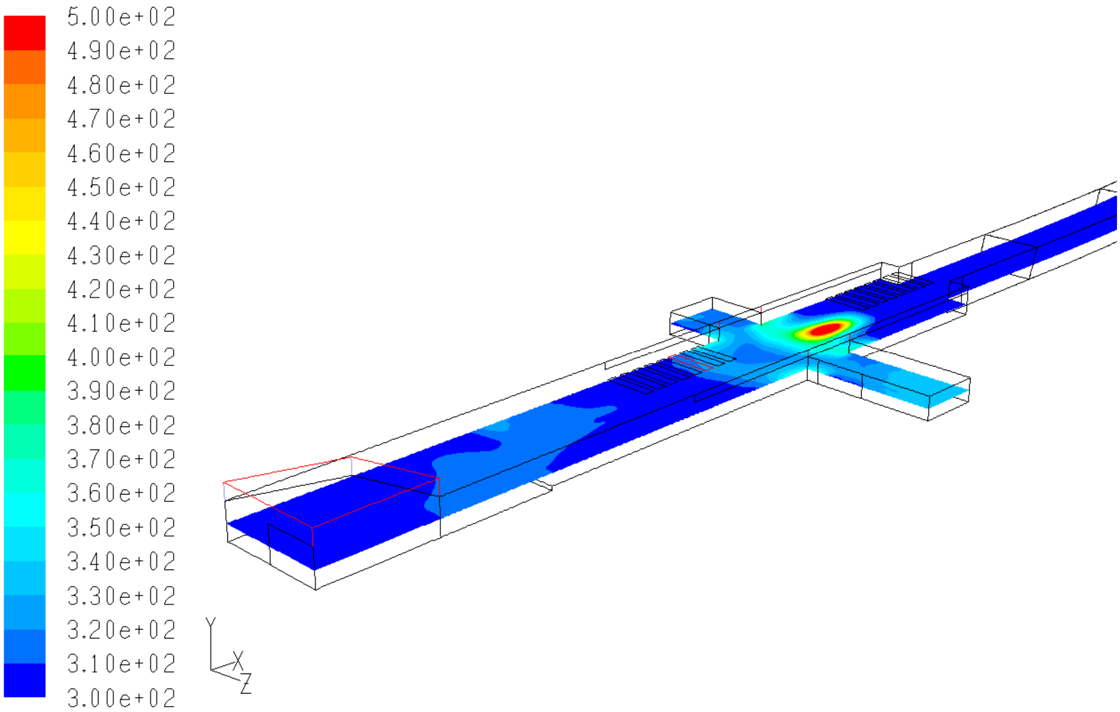

Figure 6: Temperature (Kelvin) at a plane 1.5 m above the platform.

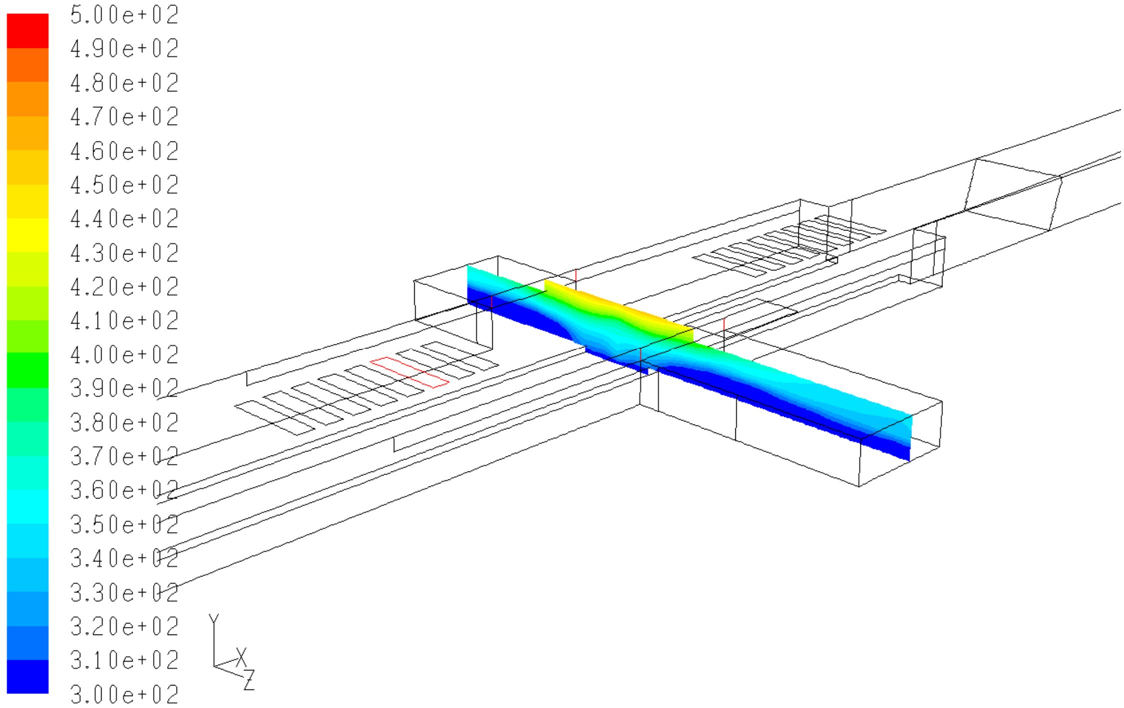

Figure 7: Temperature (Kelvin) field at the lateral accesses.

Opening	Volumetric Air Flow [m3/s]	Heat Transfer Rate [MW]
Ceiling 1	-66	-4,1
Ceiling 2	-21	-2,0
Louver 1	-14	-1,4
Louver 2	-14	-1,4

Table 1: Flow rate and heat extracted from the natural ventilation openings.

The ceiling natural ventilators are able to extract 87 m^3/s of hot smoke which corresponds to more than 60 % of the fire convective heat load. The vertical mounted grilles are able to extract a 2,8 MW of heat load and provide an important extraction point, reducing the amount of hot smoke that passes through the exit corridors.

In the present case the effect of wind on the internal flow is reduced because of its interaction with the ramp and side walls.

5.2 Mechanical ventilation results

The results obtained show that mechanical ventilation (figure 8) under wind conditions is possible and ensures that no backlayering occurs and that evacuation paths are clear of hot smoke. This indicates that toxic gas concentration and visibility levels at these routes do not constitute a major drawback for passenger evacuation. The tunnel fire scenario is shown because it corresponds to the critical design case. The ventilation strategy is to supply fresh air through the ventilation shafts and extract this air flow rate through the tunnel exit using the jet fans. The jet fans located at the middle of the tunnel are not considered, if fire is detected inside the tunnel, because of potential interaction with the thermal plume and possibility of destabilizing the thermal stratification near the fire location.

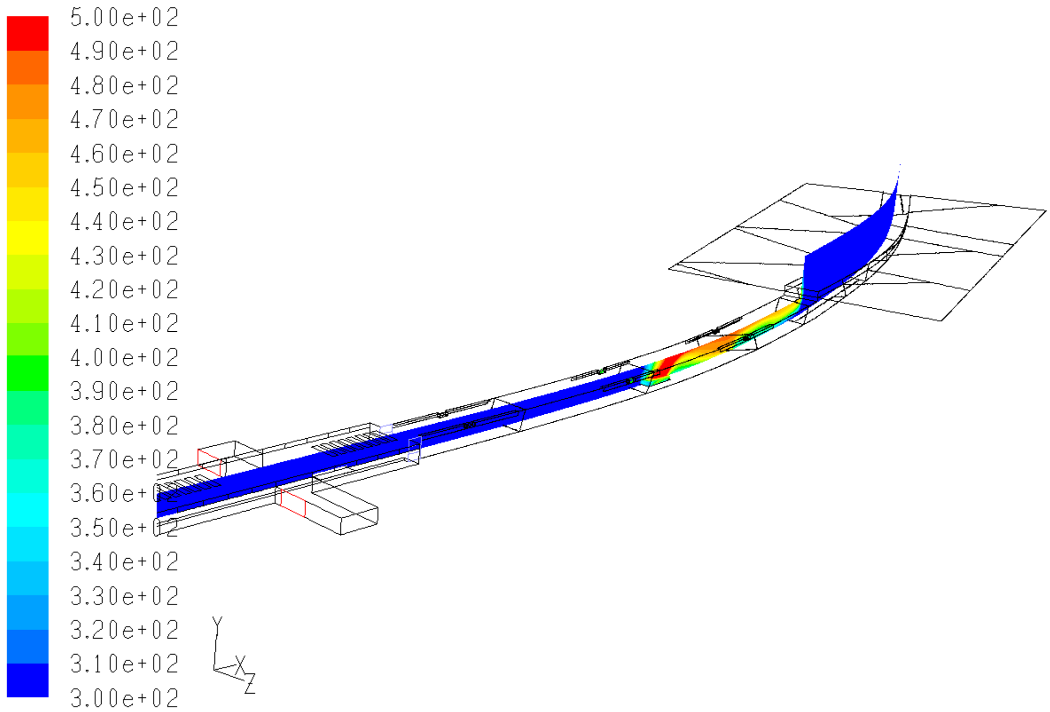

Figure 8: Temperature (Kelvin) at the central plane.

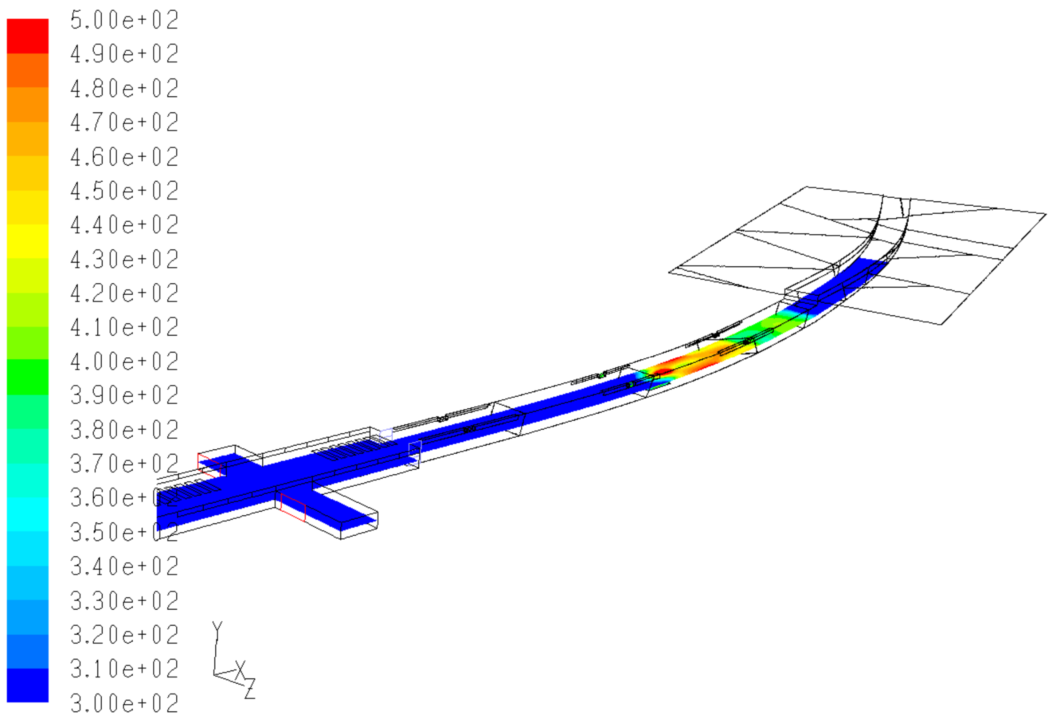

Figure 9: Temperature (Kelvin) at the central plane.

5.3 Discussion of ventilation strategies

Both natural and mechanical ventilation strategies solutions may be considered for emergency ventilation of the studied station and tunnel. Natural ventilation is a valid solution for small tunnels and stations, although it needs careful analysis due to its possible sensitivity to external wind effects.

An advantage of natural ventilation solution is that the heat release rate may be expected to be lower than in the case of mechanical ventilation because naturally ventilated fires are more susceptible to be ventilation limited than fuel controlled due to lower availability of oxygen. In well ventilated tunnels the combustion process is fuel controlled, as discussed in reference [10].

Low extraction velocities of 2 to 4 m/s at natural ventilation openings imply that natural ventilated underground spaces should have sufficient ceiling height and suitable smoke reservoirs to ensure that enough volume is available to store the large amounts of smoke produced.

Natural ventilation also uses systems, such as automatic louvers, which are simpler to control and maintain. These also avoid the need of emergency generators and their power networks. Mechanical ventilation often requires large air flow rates which means that expensive fire rated fans must be operated and maintained. On the other hand, mechanical ventilation provides a more flexible solution because hot smoke may be transported to a discharge location far from the extraction point. For underground space within cities, mechanical ventilation might be the only reasonable solution. Large natural ventilation openings may be difficult to implement because of architectural integration issues.

The presented cases corresponded to the critical design fire scenarios obtained by considering both station and tunnel fires with and without wind effect for the natural and mechanical ventilation solutions.

6 CONCLUSIONS AND FINAL REMARKS

Natural and mechanical emergency ventilation may be used for the studied station /tunnel underground space. Wind interaction with the station openings and its influence on internal flow was simulated and both solutions were validated.

The advantages of natural ventilation are low investment, operation and maintenance costs. The natural ventilation solution is, on the other hand, less flexible because extraction points must be placed near location where fire is most probable to occur. The low extraction velocities force the usage of large openings which can promote aesthetical and practical construction issues.

Mechanical emergency ventilation is the most widely used for underground spaces although it is the less cost effective. Its greatest advantage is to provide a solution which is the easier to test and the most flexible.

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