INITIAL ASSESSMENT OF THE IMPACT OF JET FLAME HAZARD FROM HYDROGEN CARS IN ROAD TUNNELS AND THE IMPLICATION ON HYDROGEN CAR DESIGN

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ABSTRACT

Underground or partial underground tunnels form a very important part of modern road transportation systems. As the development of hydrogen cars advancing into the markets, it is unavoidable in the near future that hydrogen cars would become the users of ordinary road tunnels. This paper discusses potential fire scenarios and fire hazards of hydrogen cars in road tunnels and implications on the fire safety measures and ventilation systems in existing tunnels. The information needed for carry out risk assessment of hydrogen cars in road tunnels are discussed. hydrogen has a low ignition energy, and wide flammable range suggesting that leaks have a high probability of ignition and result hydrogen flame. CFD simulations of hydrogen fires in a full scale 5m by 5m square cross-section tunnel were carried out. The effect of the ventilation on controlling the backlayering and the downstream flame are discussed.

1.0 INTRODUCTION

It can be seen now that hydrogen as fuel will be first introduced into the transportation systems. Hydrogen is a very clean fuel and ideal for transportation systems either for direct use in internal combustion engines or for fuel cells to power electrically driven vehicles. Combustion of hydrogen can produce very low emissions of nitrogen oxide together with some water vapour. In fuel cells it only produces water vapour and so far as is known there are no fuel-related health effects. Markets for hydrogen fuel already exist in road transport and a number of development vehicles have been built by the major motor manufacturers to demonstrate their potential and to gain operational experience. Global energy companies are tackling the infrastructure requirements for a substantial hydrogen production and distribution system.

When hydrogen economy takes off, hydrogen cars would be regular users of urban transportation systems. Underground or partial underground tunnels form a very important part of modern road transportation infrastructure. The use of underground space became more and more important all over the world. The volume of tunnelling construction [1] is expected to be around 2,100 km in Europe and 2,350 km in Asian in next 10 to 15 years. The hydrogen economy is predicted to arrive in a similar time scale which is in 15 to 20 years. The sustainability of tunnelling activities requires consideration of impacts of hydrogen cars as the future users of the existing tunnels and new tunnels to be constructed.

Ventilation systems play an important role in fire safety management of existing long road tunnels. In most existing long tunnels, a longitudinal or transversal ventilation system is used to supply air to control smoke movement and to create a safe route, clear of smoke, for people to escape the tunnel and for fire fighters to gain access to sources of fire. For years, the ventilation system has been considered to be an effective and practical measure to control small fires in tunnels. However the series of catastrophic tunnel fires that have occurred since 1999 has raised serious questions about the capability of the ventilation system alone to provide a comprehensive fire safety system in tunnels facing increasing traffic load. The appearance of hydrogen cars in tunnel would no doubt cause more concerns in the safety of the tunnels.

Because of the very confined space and low ceiling height, a fire in tunnel has always had much more serious consequence comparing to the fire in open air. To carry out design of new tunnels and risk assessment of the existing tunnels, it is essential to establish possible fire scenarios and fire dynamic data of hydrogen cars in tunnel. The hydrogen car is still in early development stage. It is not possible to establish the fire scenarios of hydrogen car in tunnel through experimental tests at this stage. The objective of this paper is to carry out a general discussion of the fire hazards of hydrogen cars in tunnels and use CFD simulations to assess the implication hydrogen fire on the tunnel ventilation systems.

2.0 TUNNEL VENTILATION SYSTEMS AND SAFETY MANAGEMENT

Historically the mechanical ventilation systems in the long tunnels were mainly designed for providing fresh air into the tunnel and remove pollutants out the tunnel. Only in recent years, the mechanical ventilation systems were considered seriously as measures of controlling the smoke flow movement during a fire and were used to create smoke free zones to aid the evacuation of personnel in tunnels. Nowadays the ventilation systems became an important part of emergency safety procedures.

There are mainly three types of tunnel ventilation systems namely: transverse ventilation, longitudinal ventilation and semi-transverse ventilation.

In fully transverse ventilation systems, the fresh air is channeled by fresh air ducts and is supplied to the tunnel through vents at regular intervals along the tunnel length. The pollutants are extracted through exhaust vents and channeled away by the exhaust ducts.

In the semi-transverse ventilation, the fresh air is supplied through vents at regular interval; however the exhaust air is extracted through a few large vents located in the main portals or the ventilation shafts.

In the longitudinal ventilation systems, the fresh air is supplied in one end of the tunnel portal and is forced along the tunnel by pressure differences or by aid of jet fans mounted on the tunnel roof. The systems are mainly used in high traffic density tunnel with uni-directional traffic.

All of those three ventilation systems are commonly used in road tunnels. Some of the tunnels have both longitudinal ventilation and transverse ventilation in different sections. When operated in the emergency mode, the transverse ventilation systems are aimed at the maximum extraction of the smoke from the tunnel and the longitudinal system is operated at the critical ventilation velocity that prevents the smoke flow travel against the ventilation and forces the smoke move one direction only, therefore create a clear pass for evacuation and for fire fighters to access the fire seat. Figure 1 demonstrates a tunnel fire under influence of transverse ventilation system and Figure 2 shows the smoke flow in the tunnel controlled by the longitudinal ventilation.

Some modern tunnels are also equipped with water sprinklers fire suppression systems to cool down the area round a fire. The sprinkler systems are commonly installed in long tunnels in Japan and also equipped with intelligent fire detection systems. In European, only a very few tunnels have installed water sprinklers. For fire detection, tunnels usually equipped with temperature sensors, smoke detectors, carbon monoxide (CO) monitor and closed circuit television systems (CCTV).

There are many different hazards inside road tunnels. However the fire initiated by broken down vehicles could be the most dangerous one with serious consequences. The safety level in a tunnel depends on the infrastructure, tunnel operation procedures, drivers' behaviour, emergency services and conditions of vehicles. The safety systems and emergency response plans were usually formed in the design stage. When in operation, those safety considerations and plans are embodied in procedures and management. Risk assessment should be carried out regularly as routines of the safety management.

The design of the emergency ventilation systems are based on the possible fire load of one or several accident scenario. The fire behaviour, duration and the fire load (heat release rate) of a burning passenger car and a HGV in tunnel environment have been established through a series of experimental tests [2-4]. To carry out risk assessment of transporting hydrogen car through the tunnel, it is essential to obtain data on the fire behaviour, duration and the fire load of a hydrogen car.

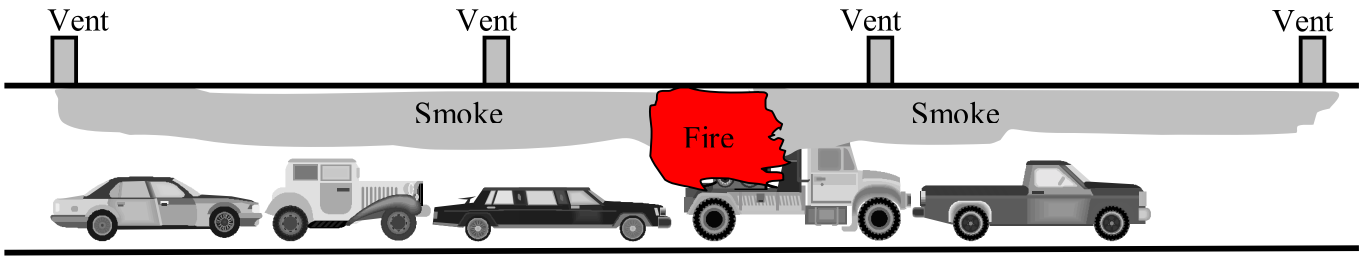

Figure 1: A tunnel fire and smoke flow under influence of transverse ventilation .

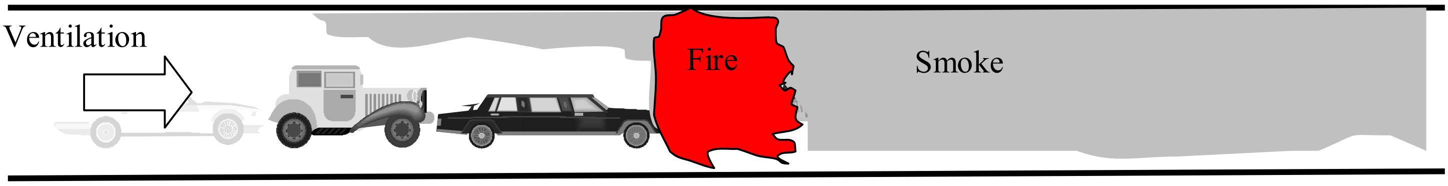

Figure 2: A tunnel fire and smoke flow under influence of longitudinal ventilation.

3.0 CHARACTERISTICS OF HYDROGEN CAR FIRE

Technical data of hydrogen cars are needed to establish the characteristics of the car fire. The characteristics of the fire are largely determined by the method of hydrogen fuel storage on board. In this paper, the discussion is concentrated on cars carrying hydrogen compressed gas bottles. Those types of hydrogen cars have been demonstrated in show cases. A few demonstration hydrogen refuelling station for cars and buses were built to provide hydrogen in compressed gas form, such as the station constructed by Norsk Hydros in Reykjavik and stations by Mitsubishi Kakoki Kaisha. Although there is very little information available at this moment on hydrogen car fire, a video produced by Swain [5] has demonstrated some of the characteristic features of fuel leak and ignition of a hydrogen car and a gasoline car in open air. Figure 3 shows one of the well known footage of a hydrogen car and a gasoline car fire in open air in 1 minute after the ignition. It showed that the hydrogen car generated vertical high velocity jet flames with very long flame length and high flame temperature. The body of the hydrogen car was not ignited and flame last only a few minutes. In contrast, the leak from gasoline car formed a pool fire; the flame engulfed the body of the car and substantial smoke generated from the burning car. Those footages have leaded to the conclusion that a hydrogen car is less hazardous than a gasoline car in open air. However consequences of a vehicle fire became much dangerous inside a tunnel due to the confined space and limited tunnel height. It is necessary to carry out analysis and to predict the fire scenarios of a hydrogen car inside tunnel.

The flame length and duration of the jet flame generated from the fuel leak would depend on the conditions and the load of the fuel tanks. Currently hydrogen stored on board on a fuel cell vehicle is mainly in high pressure compressed gas form. The storage pressure were found to be 250, 350 and 450 bars. The common storage capacity of hydrogen on board a fuel cell vehicle is approximate 3 kg, this could be a few times higher if high storage pressure is used. One of the most important characteristics of the hydrogen car fire is that the fuel released rate would be much higher than other types of vehicles and also the gas release velocity is very high. A study in stability of hydrogen flame by Wu et al [6] showed that for a 10 mm diameter nozzle, the velocity could easily reach from 200 m/s up to 860 m/s when the jet reached supersonic flow condition. For a larger release nozzle, velocity would lower accordingly. This study selected two scenarios with realistic hydrogen release conditions. In the first fire scenario, the hydrogen is released at rate of 0.1 kg/s and at velocity 10 m/s. This would results a 6MW hydrogen fire which would last about 10 minutes. In the second scenario, hydrogen is released at rate of 0.5 kg/s and velocity of 50 m/s, which would result 30 MW fire for a shorter duration.

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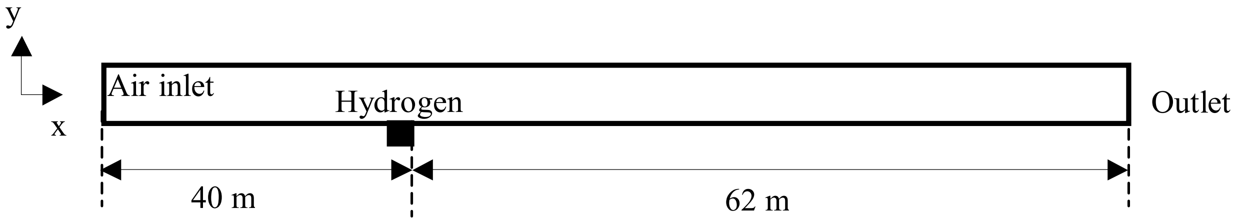
Figure 3. Photo of a hydrogen car and a gasoline car fire 1 minute after the ignition. (Produced by Swain, M. R. [5]).

4.0 CFD SIMULATIONS OF HYDROGEN CAR FIRES INSIDE TUNNELS UNDER LONGITUDINAL VENTILATION.

The tunnel studied has a length 102 m and a 5 m by 5 m square cross-section. The hydrogen release source is 40 m away from the inlet and that gives 40 m upstream and 62 m downstream. The first plane of the longitudinal domain was set to be the inlet of the ventilation flow and the last plane was set as the output of the smoke flow to the exhaust. The wall of the tunnel was set to be a solid containing 1 cell.

Three-dimensional simulations of smoke flow in the tunnels have been carried out using FLUENT code. The mixture fraction/ PDF approach has been used to model the combustion process. The standard k-ε turbulence model was used to model the flow inside the tunnels due to its simplicity and effectiveness. The standard k-ε turbulence model (Launder and Spalding,[7]) includes basic modifications for buoyancy based on Ljuboja and Rodi [8] in the k-ε equation. The standard k-ε model is a two equation eddy viscosity turbulence model which transport equations for two variables: k the turbulence energy, and ε the rate of viscous dissipation of turbulence energy. $C_{3\varepsilon}$ is used to take account of the buoyancy effects in transport equations for k and ε. Woodburn and Britter [9] used $C_{3\varepsilon}$ equal to 0.20 and showed that the inclusion of the modified buoyancy gave better predictions between the measured and predicted results. The present study tested the influence of the value of $C_{\varepsilon 3}$ in the prediction of backlayering and found that $C_{\varepsilon 3} = 0.25$ was optimal. The ventilation flow has been modelled by setting the flow of air at the tunnel inlet uniformly through out the whole cross-sectional area. The tunnel wall was modelled as insulation wall therefore no heat loss was considered. In the simulations it is assumed that the flow is symmetrical about the tunnel vertical mid-plane.

(a)Front View of the Tunnel



(b) Internal Cross-section of the Tunnel

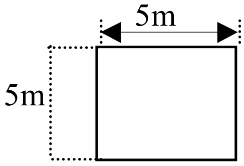


Figure 4: The tunnel geometry and boundary conditions of the CFD case.

5.0 DISCUSSIONS

The temperature and hydrogen distributions inside the tunnel are shown in the Figure 5 for the 6 MW hydrogen fire under 2.5 m/s ventilation velocity and in the Figure 6 for the 30 MW hydrogen fire under 2.5 m/s ventilation.

5.1 Critical Velocity

The values of the air velocities required to control the smoke movement in horizontal tunnels have been studied both experimentally and theoretically in a previous study by Wu & Bakar[10]. Both the experimental work and CFD simulations suggested that at low rates of heat release the critical velocity vary as the one-third power of the heat release rate, however at higher rates of heat release the dependence on the heat release rate falls off rapidly. And eventually the critical velocity becomes independent of the heat release rate. Therefore for any specific tunnel there is a super-critical velocity, which could control the smoke, moving downstream only regardless what the magnitude of the heat output from the fire is. For the 5m by 5m square cross-section tunnel, the super-critical ventilation velocity is about 2.5 m/s. In the CFD simulations, the ventilation velocity was set at 2.5 m/s.

The CFD results showed that the ventilation can fully eliminate the backlayering in the situation of 6 MW hydrogen fire at hydrogen release velocity 10 m/s. For the 30 MW fire, the ventilation flow didn't eliminate the backlayering, however the length of the backlayering was controlled within the length of three tunnel height. The CFD results showed that the flame and the flow features for 6 MW fire are different from the ones of 30MW fire. For the 6MW fire, the flame features are similar to the ones observed in previous studies by Wu & Bakar [9]. The flame length was short and located in lower part of tunnel. However for the 30MW fire, flame reached the tunnel ceiling and spread under ceiling for a long distance (45 m). This might be resulted from the deficit air supply for the fire which will be discussed later in this session.

One of advantage of hydrogen cars over the gasoline cars is that burning hydrogen is very clean, therefore much less smoke is produced from burning vehicle and this would aid the evacuation inside the tunnel in the event of fire. Therefore the short backlayering in the 30MW fire would not cause any problem for access to the fire seat and evacuation of personnel.

5.2 Jet flame Hazards

The simulation demonstrated that the hydrogen flames inside the tunnel have features of jet flames. The flame length generated from the fuel leak would depend on the conditions of the release. The long reaching hydrogen jet directly impinged the ceiling as shown in Figure 5 for the 30 MW fire. The impinging flow then would spread under the ceiling and considerable amount of hydrogen spread under the ceiling in downstream as shown in Figure 6(c) and reacting flow stretched 45 m long (9 tunnel height length). Obviously the impingement of high temperature flow could pose serious hazard on the tunnel equipment and structures along the ceiling. Hydrogen flame has very high temperature; the adiabatic flame temperature of a stoichiometric hydrogen in air is 2321 k. Equipment and sensors in the tunnel ceiling would not survive even for a very short exposure time. This ceiling flow could spread rapidly and reach long distance in a very short time space. This hot ceiling flow could act as ignition source and ignite fuel vapour and surface on its pass and generate smoky combustion flow under the ceiling. The jet flame resulted from a hydrogen car may not be a problem in open air, however when it occurs inside road tunnel, it could be a serious hazard.

5.3 Hydrogen Flame Features inside Tunnel

Hydrogen flame inside the tunnel has the feature of long reaching flame in downstream. This feature is unique for hydrogen fuel. For other types of fuels, the flame length is short and usually within two tunnel height downstream. This could be contributed by the nature of hydrogen. Hydrogen combustion demand highest amount oxygen per unit fuel by mass. Comparing with most of common hydrocarbon fuels, hydrogen needs four times air for per unit fuel. Therefore the hydrogen combustion reactions are controlled by the oxygen supply process. For most of tunnel, the ventilation system has limited and fixed air supply. Therefore it is possible to have oxygen deficit hydrogen fire inside the tunnel when the hydrogen release rate is high. For the 30MW fire, the oxygen deficiency caused the hydrogen spread downstream under the ceiling for a long distance and the reacting flow produced high temperature under the ceiling. There is no oxygen deficiency in the 5MW fire.

5.4 Implication of Oxygen Deficit Hydrogen Fire inside Tunnel

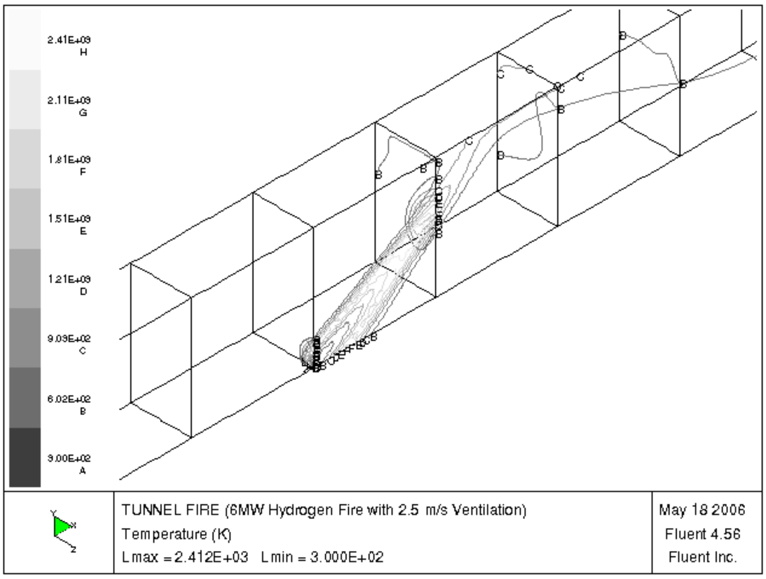
Figure 6(c) showed that there were hydrogen present in long distance downstream of the fire in oxygen deficit hydrogen fire inside tunnel. This would have more serious implication in tunnel ventilation systems. These oxygen deficit high temperature flows have a risk of develop into flash over if oxygen is supplied from other sources. For ventilation ducts with extraction mode, there might be a risk of transferring the oxygen deficit hydrogen fire into ventilation ducts.

6.0 CONCLUSIONS

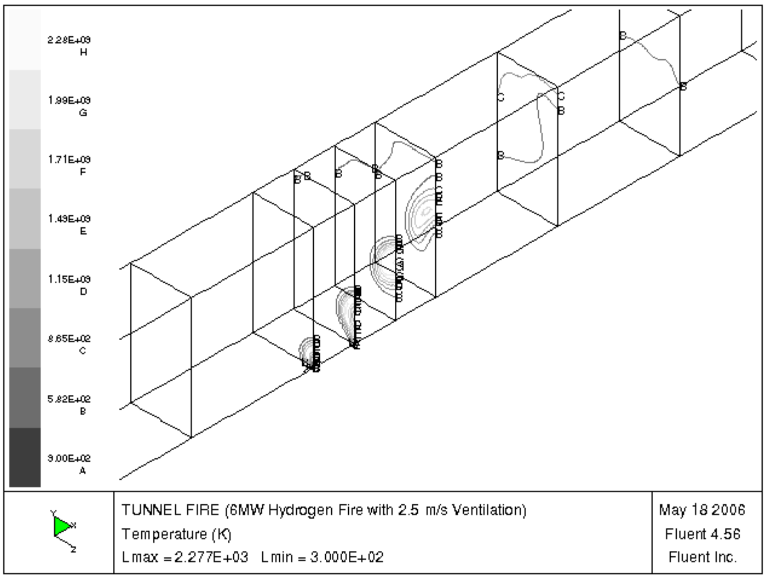
The initial assessment of the fire hazards and fire scenarios associated with allowing hydrogen cars to use the existing tunnel were carried out. The CFD simulations were carried out for two fire scenarios. It was shown that the super-critical ventilation velocity can completely eliminate the backlayering in normal hydrogen release rate or keep the backlayering under control in very high release rate. It was shown that jet flame hazard could be unique for hydrogen cars. For high release rate, the flame inside the tunnel might be in the status of oxygen deficit. This would result impingement of hydrogen jet flame on the tunnel ceiling and produce high temperature ceiling flow reaching substantial distance and damage tunnel infrastructures. The oxygen deficit hydrogen fire also pose flashover hazard inside tunnel and ventilation ducts.

REFERENCES.

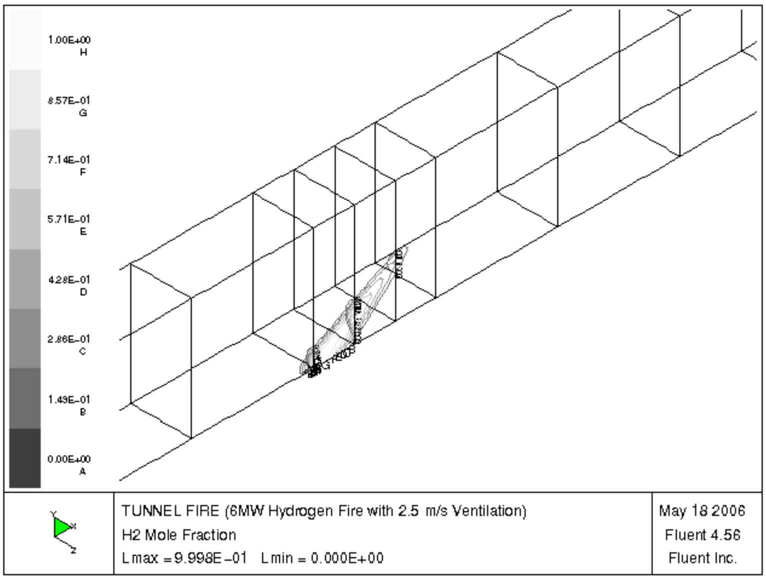
1. Haack, A., Tunnels: Challenges of Today and Tomorrow, Proceedings of 1st International Symposium of Safe and Reliable Tunnels, 4-6 February 2004, Prague, pp. 5-9.
2. French, S. E., EUREKA 499 – HGV Fire Test Summary Report, Proceedings of International Conference of Fires in Tunnels, Boras, October 10-11 1994, pp63-85.
3. Memorial Tunnel Fire Ventilation Test Program, Comprehensive Test Report by Parsons Brinckerhoff, 1996.
4. Summary of Large Scale Fire Tests in the Runehamar Tunnel in Norway, edited by Brekelman, J., TNO Building and Construction Research, the Netherlands.
5. Swain, M. R., Fuel Leak Simulation, Proceedings of the 2001 DOE Hydrogen Program Review, NREL/CP-570-30535.
6. Wu, Y., Al-Rahbi, I. S. and Kalghatgi, G. T., "Effect Of Carbon Dioxide, Argon and Hydrocarbon Fuels on the Stability Of Hydrogen Jet Flames", the International Conference on Hydrogen Safety, 8-10 September 2005 , Pisa.
7. Launder, B. E. and Spalding, D. B., (1974), "The Numerical Computation of Turbulent Flows", J. for Computer Methods in Applied Mechanics and Engineering, Vol. 3. pp 269 - 289.
8. Ljuboja, M. and Rodi, W., (1980), "Calculation of Turbulent Wall Jets with an Algebraic Reynolds Stress Models", J. of Fluids Engineering, Trans. of ASME .
9. Woodburn, P.J and Britter, R.E, (1996), "CFD Simulation of a Tunnel Fire - Part 2", Fire Safety Journal, Vol 26, pp 63-.90.
10. Wu, Y. and Bakar, M. Z. A., "Control of smoke flow in tunnel fires using longitudinal ventilation systems – a study of the critical velocity", *Fire Safety Journal* , 35 (2000) pp 363-390.



(a)
Temperature contours on the tunnel symmetrical plan and cross-sections

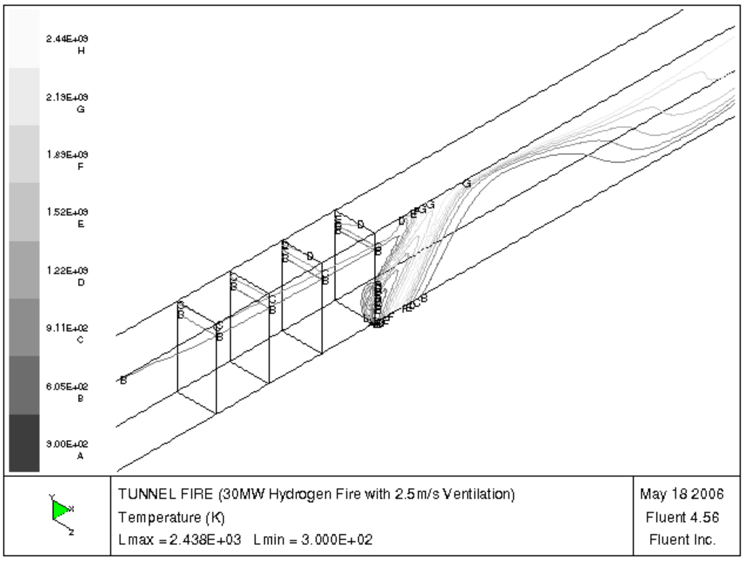


(b)
Temperature contours on tunnel cross-sections



(c)
Hydrogen mole fraction contours on the symmetrical plan

Figure 5: temperature and hydrogen mole fraction distribution inside the tunnel with a 6 MW hydrogen fire and 2.5 m/s ventilation.



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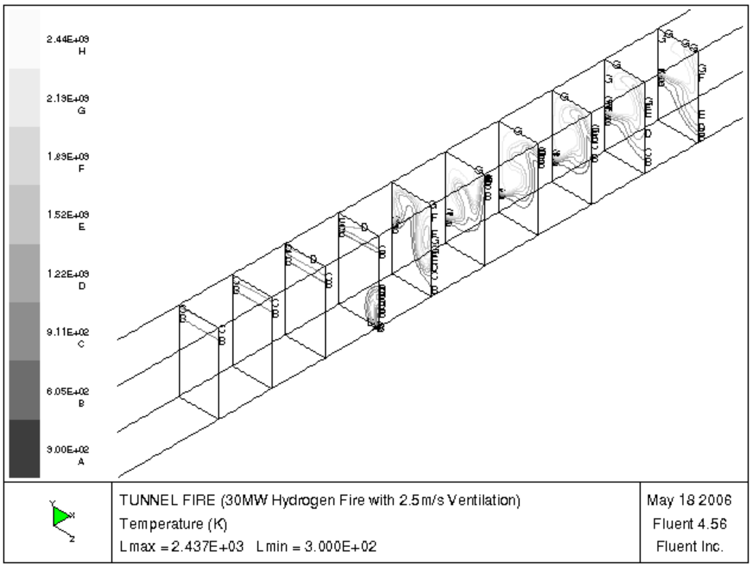
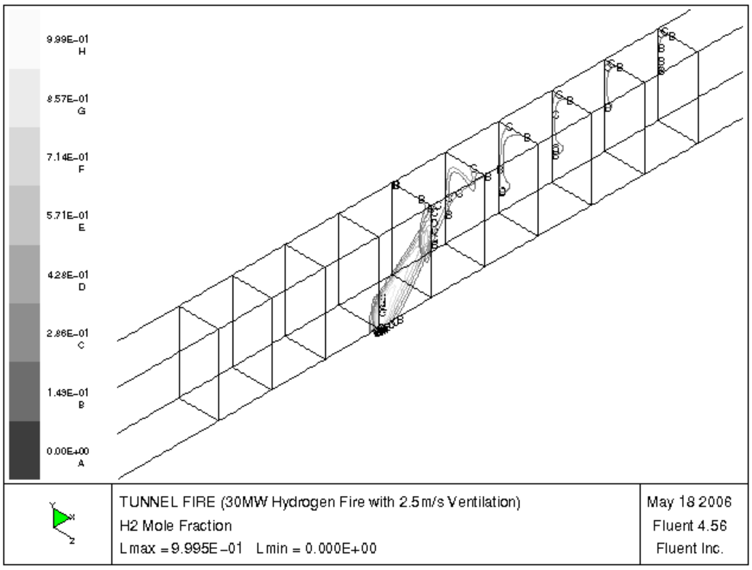


(b)
Temperature contours on tunnel cross-sections



(c)
Hydrogen mole fraction contours on the tunnel cross-sections

Figure 6: temperature and hydrogen mole fraction distribution inside the tunnel with a 30 MW hydrogen fire and 2.5 m/s ventilation.