Large eddy simulation of a tunnel fire

N. PERES[a], **R. HOWARD**[b]

a. Laboratoire de Modélisation en Mécanique et Procédés Propres, UMR 6181 CNRS - Université Paul Cézanne -Aix-Marseille III
b. EDF R&D, MFEE Department, 6 quai Watier, 78401 Chatou Cedex, France

Résumé :

Une simulation des grandes échelles (LES) est utilisée dans le cadre d'une étude dédiée aux incendies dans les tunnels routiers. Le feu est modélisé comme une entrée de préchauffage de carburant injectée pour produire la même énergie que celle produite par le feu (en supposant que tout le carburant est brûlé). Les effets de rayonnement sont pris en compte à travers un modèle simplifié conçu pour représenter le transfert d'énergie des produits issus de la combustion vers les murs du tunnel beaucoup plus froids. Les résultats sont validés par comparaison avec des essais expérimentaux effectués dans le tunnel Ofenegg. Un bon accord qualitatif et quantitatif est obtenu entre les deux approches. Après avoir validé les résultats, une série d'autres analyses sont menées, portant notamment sur la présence de voitures à l'intérieur du tunnel et sur la stratification et la convection des produits de la réaction de combustion à la sortie du tunnel. Une autre étude est également réalisée pour identifier le potentiel pour la survie de l'homme dans le tunnel lors de l'incendie. Il est constaté que la survie de l'homme est renforcée par la présence de voitures à l'intérieur du tunnel. Les résultats montrent finalement la forte potentialité de la méthode LES utilisée ici pour la simulation et la prévision des incendies de tunnel routier.

Abstract :

In this work a method known as large eddy simulation (LES) is tested to evaluate how appropriate it is to study fires in a road tunnel. The fire surface is modelled as an inlet of preheated fuel injected at a rate designed to produce the same energy as that produced by the fire (assuming all the fuel is burnt). The effects of radiation are included using a simplified model. This model is designed to represent the transfer of energy from the hot combustion reaction products to the much colder tunnel walls. The results are validated by comparison with experimental tests carried out in the Ofenegg tunnel. This comparison shows that the simulations have good quantitative and qualitative agreement with the experiment. Having validated the results, a series of further analyses are carried out which include: the presence of cars inside the tunnel and the stratification and convection of the combustion reaction products to the exit of the tunnel. A further study is also carried out to identify the potential for human survival in the tunnel during the fire. It is found that human survival is enhanced by the presence of cars inside the tunnel. The results of this work show that, provided sufficient care is taken in incorporating the appropriate physics, the LES method has a lot of potential in the simulation and prediction of road tunnel fires.

Keywords : **tunnel fires, combustion, LES**

1 Introduction

Accidental fires in road tunnels are a well known problem for road safety throughout the world. More particularly, in Europe, one of the more tragic incidents involving 39 deaths occurred in 1999 in the Mont-Blanc tunnel which connects France and Italy.
The current study is a contribution to the research and development for the prevention, safety and supression of these sorts of fires.
Accidental tunnel fire problems can be considered as time evolving unsteady turbulent flows which incorporate a very complex combination of physical effects. The main features are therefore related to the stratification and convection of the tunnel gases due to combustion process and subsequent heat generation. A comprehensive review on the fluid mechanics of fires in general given by [1].
In this review the physics involved in the fluid mechanics of fires is discussed with an emphasis on the multi-physical coupling between the flow momentum and the gas scalar fields, combustion chemistry and radiation. The main features of this discussion examine the links between buoyancy and large density gradients, the effect of combustion chemistry on the flow turbulence and radiation/turbulence coupling and the corresponding effects involved with soot.

In a review of the computational fluid dynamics of compartment fires [2] there is a discussion of the gradual evolution from RANS methods to LES for fire simulation. The potential difficulties regarding both subgrid models and the implementation of combustion models in LES are discussed. The need to take into account radiation and soot formation is also highlighted. The major key aspects of the physics of tunnel fires are discussed in [3]. The observation of fire pulsation in particular is mentioned. This unsteady behaviour is clearly an important feature of a real fire. However it is unlikely that steady state methods are able to take into account such behaviour.

The Ofenegg tunnel [4], [5] is a well defined experimental test case involving a tunnel fire. The tunnel is 190 m long and has one end blocked. The fire is approximately one third of the tunnel length away from the blocked end. Numerical simulations of the problem [6], [7] demonstrated several difficulties in simulating the evolution of the fire using 2-equation model turbulence modelling approaches. These studies demonstrated that no single approach was able to reproduce the temperature distribution at different positions in the tunnel and the velocity behaviour near the tunnel exit. The unsteadiness of the flow field and the complex local exchanges involved present a challenge for a turbulence modelling approach derived from time averaged statistical turbulence theory. A turbulence modelling approach using large eddy simulation (LES) is therefore a particularly appropriate method to use. There have been a series of reviews that provide some detail on the current state of large eddy simulation of combustion and fire these include [8], [9], [10] and [11]. From these reviews it can be seen that many different approaches to combustion modelling for LES have been attempted and it there is still no overall consensus. A new method has been investigated and the model used here is an extension of the eddy dissipation concept model (EDCM) of Magnussen [12, 13] for LES.

This paper makes use of the Ofenegg tunnel fire test case to study large eddy simulation of tunnel fires. The first part of the work discusses the fundamental equations that are solved, turbulent subgrid modelling in large eddy simulation, the combustion model for large eddy simulation and the radiation modelling.

This background is followed by a description of the physical parameters of the numerical simulations. The results obtained are compared with the experimental data obtained in the tests of the Ofenegg tunnel, followed by a study of the influence of the presence of obstacles inside the tunnel and a qualitative representation of the critical areas to human survival. Conclusions that can be drawn from the results are given in the final section.

2 Background equations and theory

2.1 Low Mach number compressibility

The low Mach number form of the Navier-Stokes equations used here [14] is based on a redefinition of the pressure in the momentum and temperature equations. The pressure is divided into two parts such that $p(x,t) = p0(t) + p1(x,t)$ where $p0$ is a purely time dependent, thermodynamic pressure for the temperature equation and $p1$ is a spatial and time dependent hydrodynamic pressure for the momentum equation. This decoupling of the pressure prevents thermodynamic effects from interfering with the pressure in the momentum equation and so it can be solved using a conventional incompressible flow approach with a pressure update. The momentum equation is

$$\frac{\partial(\overline{u}_i)}{\partial t} + \frac{\partial\left(\overline{u}_i\overline{u}_j\right)}{\partial x_j} = -\frac{1}{\rho}\frac{\partial p_1}{\partial x_i} + g_i + \frac{\partial}{\partial x_j}\left[2\left(\nu+\nu_t\right)\overline{S}_{ij}\right] \tag{1}$$

where $\overline{S}_{ij} = \frac{1}{2}\left(\frac{\partial \overline{u}_i}{\partial x_j} + \frac{\partial \overline{u}_j}{\partial x_i}\right)$ and ν_t is the turbulent viscosity (see section 2.2). The temperature equation incorporates the thermodynamic pressure and is independent of the hydrodynamic pressure component (p1)

$$\frac{\partial\overline{T}}{\partial t} + \frac{\partial}{\partial x_j}\left(\overline{u}_j\overline{T}\right) = \frac{\partial}{\partial x_j}\left[\left(\nu+\nu_t\right)\frac{\partial\overline{T}}{\partial x_j}\right] + \frac{1}{\rho c_p}\left[\frac{\partial p_0}{\partial t} + \omega_T H - Q_{rad}\right] \tag{2}$$

where c_p is the specific heat capacity (J/kg.K), H the enthalpy of reaction (J/Kg), ω_t the reaction rate ($kgs^{-1}m^{-3}$) and Q_{rad} represent the transfer of energy from the hot combustion reaction products to the colder tunnel walls. The groups of m scalar concentration equations for the mass fraction Y of each species are

$$\frac{\partial\overline{Y}_m}{\partial t} + \frac{\partial}{\partial x_j}\left(\overline{u}_j\overline{Y}_m\right) = \frac{1}{\rho}\left[\frac{\partial}{\partial x_j}\left(\left[\frac{\mu}{Sc_m} + \frac{\mu_t}{Sc_{mt}}\right]\frac{\partial\overline{Y}_m}{\partial x_j}\right) + \omega_T st_m\right] \tag{3}$$

The parameters Sc_m e Sc_{mt} are the Schmidt and turbulent Schmidt numbers for the species m where $Sc_m = \mu/\mu_m$ e $Sc_{mt} = \mu_t/\mu_{mt}$ (μ_m e μ_{mt} are the molecular diffusivity and turbulent diffusivity of species m). Here the values used are Sc_m=0.7 e Sc_{mt}=0.7. This assumption has been shown to be appropriate by [15]. The stoichiometry ratio is given by st_m.

2.2 Subgrid modelling

The subgrid turbulence model studied is a modified Smagorinsky model called the WALE model(wall-adapting local eddy viscosity). The basic details of the implementation are given below. Firstly the Smagorinsky model [16]

$$\nu_t = (C_s\Delta)^2|S| \tag{4}$$

where $|S| = \sqrt{2S_{ij}S_{ij}}$, Δ is the LES filter width (i.e. the grid size), C_s a model constant (generally taken to be Cs=0.18) and $S_{ij} = \frac{1}{2}\left(\frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_j}\right)$.
The large eddy simulation subgrid model used, as mentioned above, is the wall-adapting local eddy viscosity (WALE) modification of the Smagorinsky model [17] given by:

$$\nu_t = (C_w\Delta)^2 \frac{(s_{ij}^d s_{ij}^d)^{3/2}}{(S_{ij}S_{ij})^{5/2} + s_{ij}^d s_{ij}^d)^{5/4})} \tag{5}$$

where $s_{ij}^d = \frac{1}{2}(g_{ij}^2 + g_{ji}^2) - \frac{1}{3}\delta_{ij}g_{kk}^2$ and $g_{ij}^2 = g_{ik}g_{kj}$, $g_{ij} = \partial u_i/\partial x_j$ and C_w is a model constant (taken to be Cw=0.5). The model is a significant improvement over the classic Smagorinsky model and adjusts implicitly according to the local turbulence levels as walls are approached (instead of many models where there is explicit dependence on wall distance).

2.3 Combustion model

To reproduce the combustion process a simple one step reaction is modelled in terms of the mass fractions of fuel and air with implicit modelling of the products

$$Y_P = 1 - (Y_f + Y_0) \tag{6}$$

This means that only two species need to be modelled which helps to reduce the complexity. This reaction is implemented in order to allow for both premixed and diffusion flames. This is achieved using the following expression for the reaction rate

$$\omega_T = \frac{\omega_A\omega_{EDCM}}{\omega_A + \omega_{EDCM}} \tag{7}$$

The Arrhenius reaction rate for this type of situation is

$$\omega_A = A_A\rho^2 Y_f Y_{ar} exp\left(-E_a/RT\right) \tag{8}$$

where A_A is the frequency in the Arrhenius law, E_a the activation energy and R the universal gas constant. For the propane reaction the values used are A_A=10^{10}(m^3/(kg.s)) and $E_{a/R}$ = 18400 K. The turbulent reaction rate based on the formulation EDCM (Eddy Dissipation Concept Model) is given by:

$$\omega_{EDCM} = AC_\mu\rho^2\frac{\tilde{k}}{\tilde{\mu}_t}min\left(Y_f, Y_{ar}/st_{ar}\right) \tag{9}$$

with A a dimensionless turbulent combustion model constant A=4 and st_{ar} the stoichiometric ration of air st_{ar} = 17. The value of the dimensionless constant C_μ used was 0.0002.

2.4 Radiation model

The model used to incorporate the transfer of energy from the hot combustion reaction products gases to the colder tunnel walls is copied from the optically thin radiation transfer model of [18] which is also detailed on the website [19]. In this approach radiation losses Q_{rad} are modelled based on the the local temperature T, a reference temperature (the ambient background temperature, T_b) and the emissivity of the gases present. The approach used here is slightly modified and only considers the radiation losses due to an estimation of the product gases according to the relation

$$Q_{rad} = 4Y_p\sigma P_{th}a_p\left(T^4 - T_b^4\right) \tag{10}$$

where Y_p is a scalar representing the mass fraction of the combined products present, σ is the Steffan-Boltzmann constant 5,669$\times 10^{-08}$ (W/m^2K^4), a_p is the total emissivity of the product gases which are assumed to be made up of water, carbon dioxide and carbon monoxide with

$$a_p = \frac{4}{7}a_{p(H_2O)} + \frac{3}{14}\left(a_{p(CO)} + a_{p(CO_2)}\right) \tag{11}$$

The emissivity of each gas varies with temperature according to the expressions detailed in [18] and the [19].

3 Numerical method and domain of calculation

The code used is called Trio-U and is developed at the Commisariat à l' Energie atomique, Grenoble, France. Much additional useful information regarding the code can be found in [20] and [21]. The code is written in c++ and has been developed for both structured hexahedral and non-structured tetrahedral grids. In this study only the structured hexahedral approach is studied. The numerical method used is a second order staggered grid central difference scheme in space and a third order Runge-Kutta scheme in time. In this approach normal velocities are modelled at the face centres and pressure and all other scalar quantities at the element centres. The divergence condition for the pressure update is carried out using an iterative conjugate gradient method. The time step size is chosen to preserve a unity CFL constraint.
The box dimensions for the tunnel domain are 190 x 6 x 4.25 (m in the x, y and z directions). The base grid resolution used is 190 x 21 x 21 cells in the streamwise (x), streamnormal (y) and spanwise (z) directions. In order to assess the effect of different resolutions a series of tests are carried out with a variety of grids in each direction. In each case the simulations are run for the full 120 seconds and statistical samples are obtained by averaging the instantaneous quantities over the last 20 seconds of each simulation. These tests led to the most appropriate mesh for the simulation of the several cases considered in this study. The figure 1 shows the cross section of the Ofenegg tunnel as well as the geometry simulated and the position of the fire source.

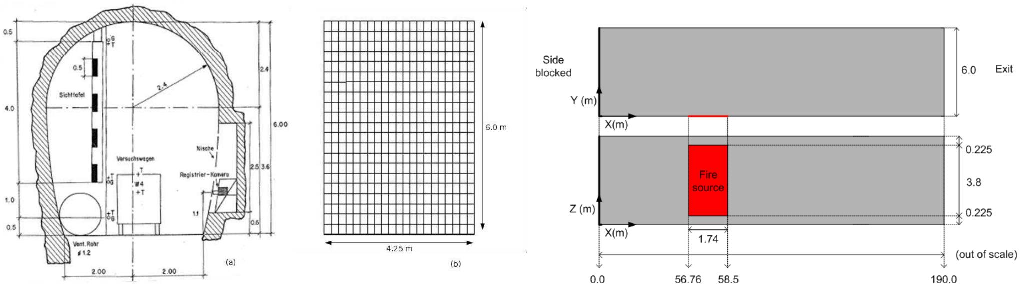

Figure 1: Schematic representation of the Ofenegg tunnel [4].

4 Results

In the experiments carried out in the Offenegg tunnel the fire was produced by burning a reservoir of liquid fuel. The quantity burned produced an average heat release of approximately 17.8 MW. The fire source in this study is is modelled as an inlet of gaseous fuel to be burnt in a combustion reaction. The velocity of this inlet is chosen to allow sufficient fuel to enter into the domain to produce the desired heat release when it is consumed during combustion.

4.1 Study of the Ofenegg tunnel tests

To improve the outflow behavior an outlet zone is generated in which the domain is extended by 5 m in the vertical, side and axial directions. The tunnel walls are assumed to have the conductivity of stone to allow for conductive heat losses, with the conductivity of stone (K=1.4 W/m.K, ρ=2300 kg/m^3, c_p=880 J/kg.K) at ambient temperature.

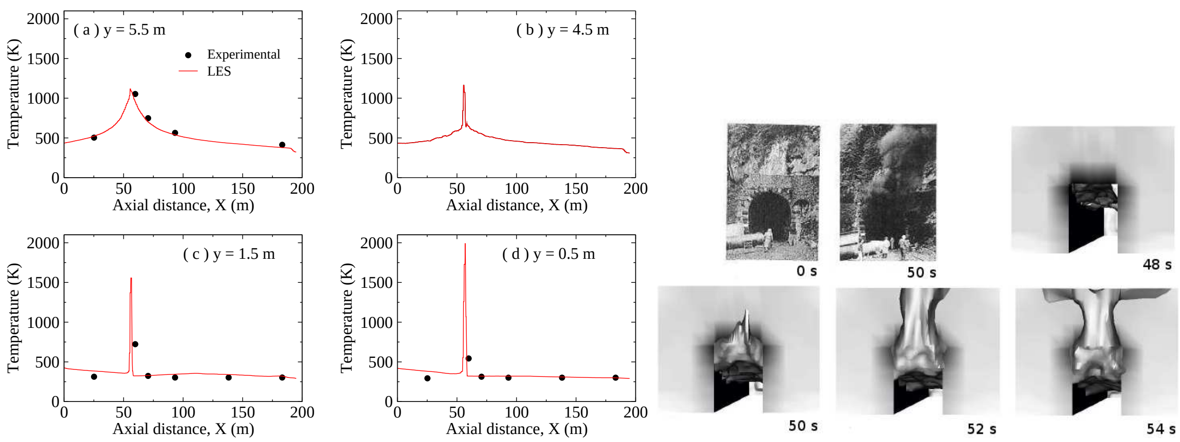

Figure 2: Temperature profiles: a) y=5.5 m; b) y= 4.5 m; c) y=1.5m; d) y=0.5 m. Smoke at the tunnel exit.

Figure 2 shows the temperature profiles after 120 s. The profiles cover the length of the tunnel and are shown for different heights. These results show good overall agreement both in the vicinity of the fire source and near the tunnel exit. The experimental study included photographic evidence which can be used for qualitative comparison of the behaviour of the smoke produced in the fire. Figure 2 shows several photographs one of which shows the smoke leaving the tunnel after 50 s. In order to provide some qualitative comparison surfaces of the products are shown at the same time. The experimental photograph shows a fairly weak flow of smoke out of the tunnel indicating the smoke has only just begun leaving the tunnel in a similar way to the LES.

4.2 Presence of cars inside the tunnel

During the tests in the Ofenegg tunnel, were placed three cars inside the tunnel at 4.5, 10 and 30 meters downstream from the fire source. In figure 3 the temperature and velocity fields are represented considering two cases: the first (3a)) does not take into account the presence of vehicles inside the tunnel, the second (3b)) takes into account the presence of three cars. As shown the presence of cars leads a significant change in the intensity of the cold air flow coming from outside.

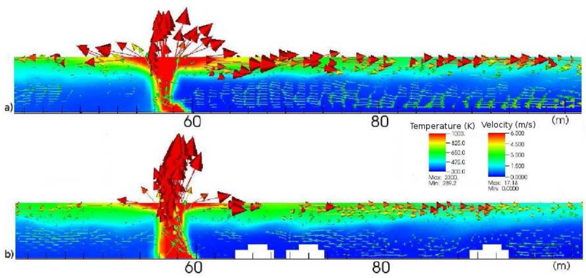

Figure 3: Temperature and velocity fields after 118 s: a) without cars, b) with cars.

4.3 Survivability

This section is presented in a qualitative way, which aims to study the critical areas to human survival, based on the criteria described in [5]. This study is purely qualitative since the combustion model used (section 2.3) simulates the combustion process in a simple one step, and the fact that this study did not include the formation of soot. The conditions under which survival should be possible are CO concentrations less than 2000 parts per million for more than 1 minute, O_2 concentrations less than 16% during 1 minute and air temperatures below 80-180 ^oC for a short time. In the figure 4 the black regions correspond to where survival is possible. The gray and white regions correspond to regions where survival is not probable.

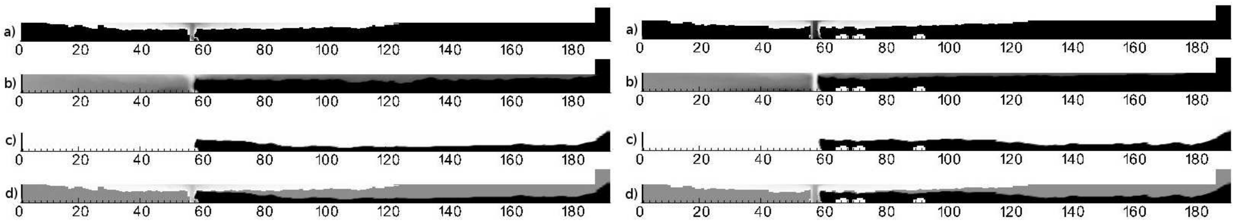

Figure 4: Regions where the survival is possible, without cars inside the tunnel and with cars inside the tunnel: a) temperature criterion, b) concentration of O_2 criterion, c) CO, d) all the criteria.

5 Conclusions

This study shows that the combustion model in conjunction with the simplified model of radiation used, produce results in good qualititative and quantitative agreement with available experimental data. The analysis of the exit of the tunnel confirms that the system can reproduce the stratification process, it is however noted the necessity to introduce a model for the soot formation in future works.

The study of the presence of cars inside the tunnel shows local changes in the flow field. This study together with the study of human survival, shows that the presence of obstacles inside the tunnel should not be neglected, since the regions where the human survival it is possible can be increased with their presence.

Evaluation of survivability criteria indicate that after 120 s a region in between the fire and the opening remains under survivable conditions however the route to the exit is blocked by a region in which survival may only be possible for short periods suggesting breathing apparatus should be used by rescue workers.

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