On a New One-dimensional Model to describe Tunnel Fires

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Abstract

We present a model derived to describe tunnel fires. The model originates in a compressible description of the air in the tunnel. It takes into account the strong buoyancy forces and at the same time the small Mach-number of the airflow. We comment on the derivation, on analytical results and on numerical simulations of the model.

Introduction

Due to some serious fire events in rail and road tunnels in the last few years there is a increased interest in the description, the modelling and the simulation of such events. There are many articles discussing this argument [BR,H,KZ,Pu,PaSa,PoSh]. The description of such a complex gas dynamic process in a tunnel is known to be a challenging issue. In the last decades and years many different approaches and models have been chosen. A good overview on the state of art is given in [GJL] and [P].

The so called zone models are mainly used for the description of fires in buildings and seme not to be adapted for tunnel fires, where the flow is partly self-induced by buoyancy forces. The most sofisticated models are based on a fluid mechanic description via the the Navier Stokes equations. In this context standard CFD tools are used (e.g. FLUENT in [SBR]). On the other hand expensive test programs like the *Memorial Tunnel Fire Ventilation Test Program (MTFVTP)* have been done and have been used to develop CFD tools especially for tunnel fire applications (e.g. SOLVENT in [LSHRKP]). However, the full description of a tunnel fire with resonalbe effort is still an open problem. Especially the following points create serious problems in this context:

- All (2 or 3-dimensional) CFD simulations are extremely time consuming.
- The description of turbulence is a well known problem.
- Characteristic velocities in the tunnel are of the order of $0 - 10$ m/s, i.e. one has to model a Low–Mach number flow.
- Characteristic temperature differences in the tunnel due to heat sources are large, i.e. one has to model large density and temperature gradients.

Let us mention that incompressible models as standard approach for small Mach-number flows are not appropriate to include big temperature differences. The standard Boussinesq approximation cannot be used in this context [GJL].

Therefore there is tendency to look for simpler models which are able to describe the main features of the flow in the tunnel. A step in this direction is the commercial tool SPRINT [RBB], which is based on a one-dimensional description of the tunnel. The model we are going to present here fits into the same class. First we briefly present the model. Then we discuss the existing analysis of the model and finally we report on numerical results obtained by the model.

The model

The model we are going to study here was derived in [**?**]. We use a one-dimensional approach, where all quantities are averaged quantities over the cross-section of the tunnel. Due to the expected small Mach-number in the compressible 1-d Navier-Stokes equations an asymptotics in the small Mach number is performed. The pressure comes out to be the sum of a constant leading order pressure and a pressure correction. Let ρ, u, p be the density, velocity and the pressure-correction of the flow in the tunnel, respectively. x and t denote the (one-dimensional) space and the time. The governing scaled equations are given by

$$\begin{aligned} \rho_t + u\rho_x &= -\rho q, && (1)\\ u_x &= q && (2)\\ u_t + uu_x + \frac{1}{\rho}p_x &= -p_{dv}\frac{u|u|}{2} - f_d \sin\alpha && (3) \end{aligned}$$

with $q = q(x,t)$ as time and space dependent (scaled) heat source. The quantities $p_{dv} = p_{dv}(x)$ and $\alpha = \alpha(x)$ are the space dependent pressure loss coefficient and the slope profile of the tunnel.

The temperature is given by

$$T = \frac{p_0}{\rho} \tag{4}$$

with p_0 as given constant leading order pressure (say $1bar$ at seelevel, see [GStr]).

As far as boundary data is concerned we prescribe Dirichlet data for the pressure-correction p at the entrance and the exit

$$p(t,0) = p_0, \qquad p(t,1) = p_1, \quad \forall t > 0. \tag{5}$$

Moreover we use homogenous Neumann conditions for the velocity

$$u_x(t,0) = u_x(t,1) = 0, \quad \forall t > 0. \tag{6}$$

For the densitiy we assume standard inflow boundary conditions

$$\rho(t,0) = \rho_0 \text{ if } u(t,0) > 0, \qquad \rho(t,1) = \rho_1 \text{ if } u(t,1) < 0, \quad \forall t > 0. \tag{7}$$

Initial data are prescribed for the density and the velocity

$$u(0,x) = u_0(x), \qquad \rho(0,x) = \rho_0(x), \quad \forall x \in [0,1]. \tag{8}$$

Thus, the model consists of the equations (1)-(3), the boundary conditions (5)-(7) and the initial conditions (8). To our knowledge this is the first 1-d model in this context derived from basic underlying fluidmechanic equations.

Especially for numerical reasons it is convenient to rewrite the model in the following way. The equation (2) is substituted by the x- derived velocity equation (3),

$$\begin{aligned} \rho_t + u\rho_x &= -\rho q, & (9)\\ (\frac{1}{\rho}p_x)_x &= -p_{dv} q|u| - q_x u - q^2 - q_t - f_d \cos\alpha\, \alpha_x & (10)\\ u_t + uq + \frac{1}{\rho}p_x &= -p_{dv}\frac{u|u|}{2} - f_d \sin\alpha. & (11) \end{aligned}$$

In this way it is easier to fullfill all the boundary conditions (especially the Dirichlet conditions for the pressure). In fact, this system is the starting point for the numerical investigations ([GStr]).

Analytical results

The analysis of the model (1)-(3) with boundary conditions (5)-(7) and initial conditions (8) has three main directions.

- The stationary problem.
- The transient problem.
- Stability analysis of the stationary solutions in the transient problem.

The stationary problem was studied extensively in [G]. In the case of no fire $q = 0$ it comes out, that – depending on the parameters and the on boundary data – exactly one, no or exactely two non-vacuum solutions are possible. We focus on non-vacuum solutions in order to avoid solution where the density vanishes locally which is not relevant in our application. In case of heat sources – depending on their position and on the slope profile – even more possibilities arise. Realistic examples with three and more solutions can be constructed. Cleary, an important question is the stability of these solutions as solutions of the transient problem. Preliminary results on this problem will be published in [GSte]. There also a global existence result for solutions of the transient problem will be presented.

Numerical results

As already mentioned the numerical investigations of this model were done on the alternative formulation (9)-(11). We use a finite difference method in order to solve the equations. After solving the continuity equation by an upwind scheme and the elliptic equation for the pressure-correction we use an explicit scheme for the velocity equation. The method comes out to be stable and numerically robust.

The following cases have been investigated.

- A tunnel fire test performed on 28 april 2001 on the highway A22 (Brennerautobahn) close to Franzensfeste/Fortezza in Italy with a fire of about

$20MW$ was simulated. At least qualitatively there was a good agreement between the results of the experiment and the dynamic of the hot air obtained by the simulation. The quantitative comparison was possible only partially due to a lack of data from the test (see [GStr] for details).

- A tunnel experiment done on 25 june 1999 in the Elbtunnel in Hamburg in Germany was simulated. In this test no fire was involved but a special fire fighting equippment (Turbolöscher) was used (see [GPTM] for details). Here the simulation gave a very good agreement even quantitatively with the test results. In addition, the model allowed to predict the dynamic of the hot air in case of fire in Elbtunnel.
- Airflow measurments in April 1998 in the Vereina rail tunnel between Selfranga and Sagliani in eastern Switzerland relate the varying atmospheric pressure difference to the airflow velocity in the tunnel (see [BDS]). Our model ist able to reproduce these data. In addition predictions for the case with fire is possible. This is of particular interest, since this tunnel (like many tunnel in the alps) has a slope profile such that the highest point lies in the tunnel.

The results are promising and we plan to further investigate and to validate our model using other existing real test results.

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