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Study of a Nimble Model to Evaluate the Effects of a Gasoline Fire in a Road Tunnel

Carlo Sala Cattaneo[a], Silvia Tavelli[a], Marco Derudi[a], Renato Rota[a], Massimo Raboni[b], Vincenzo Torretta[b], Sabrina Copelli[*b]

[a]Politecnico di Milano - Dip. di Chimica, Materiali e Ingegneria Chimica “G. Natta” Via Mancinelli 7 - 20131 Milano - Italy
[b]Università degli Studi dell’Insubria - Dip. di Scienza e Alta Tecnologia Via G.B. Vico 46 - 21100 Varese - Italy
sabrina.copelli@uninsubria.it

Since the beginning of modern industry, the need to move large quantity of raw materials and products has increased continuously, matching with the improvement of the transport routes, especially public roads. With more and more trucks on world’s streets, the number of accidents has increased together with the risk connected to side events derived from the transport of hazardous materials such as fuels, acids, toxic wastes and so on. In a world where there is an increasing attention to safety, transport of hazardous materials has become one important aspect to evaluate. In order to reduce the risk, a proper choice of the transport route and a reliable simulation of the consequences of possible accidents is needed.
To estimate the consequences of an accident involving flammable materials, mathematical models developed in the frame of the Computational Fluid Dynamics (CFD) are able to provide a detailed description of temperatures and species concentrations but, since they are very demanding in terms of both CPU-time and analyst skill, they are not often used for a screening evaluation of the magnitude of the consequences of an accident (as required by an ordinary shipping operation).
Aim of this work is to develop a simplified mathematical model able to evaluate the effects of an accident involving the spill of a fuel (in this case study, gasoline) from a tanker in a road tunnel with a subsequent fire. The simplified model should be able to produce results comparable with those obtained using CFD models with much less CPU-time, in order to be easily implemented in a risk analysis software. To achieve this purpose, a set of differential equations has been written to describe the main phenomena involved in a tunnel fire accident; moreover, all space-time correlations have been sundered to obtain a set of equations easily solvable, therefore avoiding the time-consuming operations due to multiple numerical resolutions. The results obtained for the investigated case study using the simplified model are in fairly good agreement with those obtained from a dedicated CFD model.

1. Introduction

Since the dawn of the industrial age, the need of moving goods has only increased, shifting from simple raw materials as silk, cotton, wood, stone etc. to different, highly specialized products as hydrazine, acetylene and pharmaceutical products. Even if the first and safest way to move huge amounts of goods was using railway (Ryland, 1999), the increasing number and conditions of public roads shifted attention to the use of trucks to reach places not yet connected (or not connectable) with the railroad system, especially when, in 1896, Daimler built the first truck.
With more and more cars and people and trucks on the roads, goods transport became a serious, and sometimes dangerous, affair (Oggero et al., 2006). In Italy, since the IV Conference of the Automobil Club (held in Genoa in 1933) the problem of moving dangerous material has been taken into account by experts but we have to wait until 1968 to have the first regulation for the transport of dangerous materials by road, the so-called ADR (UNECE, 2013). Particularly, since the sixties, these rules have been modified and improved at the same rate with which safety rules improved. Obviously, as the attention to safety increased, the same happened to the safety related to transport on public roads, especially after the disaster of Monte Bianco in 1999, where a truck full of flour and margarine caught fire, leading to a 53-

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hours long fire, to serious damage of the tunnel ceiling, and to the death of 39 persons (Miclea et al., 2007). From this example, it is easy to understand why the attention on this subject cannot be lowered but, at the same time, it is not possible to avoid the using of public roads to deliver goods to industries. So, what are the options? How could the risk be estimated?

As it is well known, risk is a combination of probability and magnitude of an accident. While the former could be calculated using statistical data, the latter should take into account the specific route of the truck, the presence of bridges, towns and tunnels, the different kind of goods moved, etc.

This work focuses on accidents occurring in road tunnels to evaluate three different critical effects: walls temperature increase due to the fire, which could lead to structural damages and subsequent collapse; air temperature inside the tunnel; and the effect of irradiation on a specific target (e.g. a human body). In order to evaluate all these specific features, Computational Fluid Dynamics (CFD) may come to aid (Benucci and Uguccioni, 2010; Tavelli et al., 2013), but its complexity and accuracy, which are its best qualities in occurred-accident analysis, could be too time and resource consuming to estimate the magnitude of a will-be scenario.

Therefore, in order to reduce the required resources, both in terms of CPU-time ad analyst skill, a simplified mathematical model has been developed (see Section 2). This model has been designed to be nimble and easy to use, while retaining a fair reliability. To validate this model, a case study involving the loss of gasoline in a tunnel with a consequent fire has been studied (see Section 3). The results obtained with the simplified model have been compared with the results obtained using FDS (McGrattan et al., 2010), a well-know CFD software that is usually used to obtain realistic reconstructions of a accidents involving confined fires, and they are discussed in Section 4.

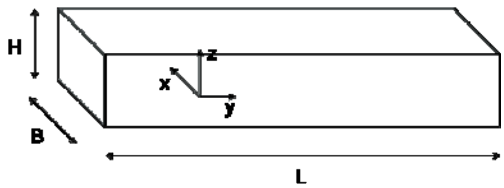


Figure 1: Sketch of the tunnel design

2. Mathematical Model

In the following it will be described a simplified mathematical model that can be used to evaluate the magnitude of a very common accidental scenario: the spill of a fuel (in this case, gasoline) from a truck that has suffered an overturning into a road tunnel.

Particularly, in order to keep the model as simple as possible, the following assumptions have been retained:

- the heat source is a circular pool fire originated in the middle of the tunnel (which means that the computational domain is symmetric);
- the pool is located at a distance Y (m) from the tunnel entrance;
- the flame can be considered as a tilted cylinder of radius $R(t)$;
- for what concerns the effect of the radiant heat generated by the flame on the temperature of tunnel walls, a simple point source model is used (that is, the heat source is located in the ideal centre of the flame and it radiates in all directions);
- for what concerns the effect of the radiant heat on a generic target (e.g. a human body placed at a certain distance from the flame), a solid flame model is used;
- tunnel ventilation velocity prevents backlayering of the smoke upstream of the fire source;
- the tunnel has been hypothesized as empty and with a square section, as sketched in Figure 1;
- the most relevant direction is considered to be the longitudinal one (indicated in the following as y). Temperature gradients in the other two dimensions (x and z) will be neglected.

In order to estimate the power radiated by the fire, some geometrical considerations on the flame are required. First, the spill of fuel from a hole in the tank truck generates a gasoline pool whose radius $R(t)$ can be calculated using Equation 1 (Lees, 1996):

$$R(t) \approx \left(\frac{4{,}32gQ}{3\pi}\right)^{\frac{1}{4}} \cdot t^{\frac{3}{4}} \tag{1}$$

where g the gravitational acceleration (m^2/s), Q the volumetric flow rate exiting from the hole in the truck structure (m^3/s) and t is the time (s).
Similarly, representing the flame as a tilted cylinder, it is possible to evaluate its tilt angle, θ, with respect to the vertical direction using Equation 2 (Lees, 1996):

$$\theta = \arcsin\left(0.7 \cdot u*^{-0.49}\right) \tag{2}$$

where:

$$u* = u \Big/ \left(gmD/\rho_a\right)^{\frac{1}{3}} \tag{3}$$

is the dimensionless air velocity, u is the air velocity in the tunnel (m/s), m is the mass burning rate (kg/m^2 s), D is the flame diameter (m) and ρ_a is the density of the ambient air (kg/m^3).
Similarly, the flame length L (in the tilted direction) can be calculated using the modified Thomas' correlation (Lees, 1996):

$$\frac{L}{D} = 55 \cdot \left(\frac{m}{\rho_a \cdot \sqrt{gD}}\right)^{0.67} \cdot u^{-0.21} \tag{4}$$

Finally, it is possible to evaluate the heat radiated by the flame, W_{rad} (W), using the following equation:

$$W_{rad} = m \cdot A_{pool} \cdot \Delta h_{comb} \cdot \eta \tag{5}$$

where A_{pool} is the free pool surface (m^2), Δh_{comb} is the combustion enthalpy (J/kg) and η is the fraction of heat effectively radiated by the flame (for a gasoline pool of about 3 m of diameter, as in this case study, such a value is equal to about 0.31).

2.1 Temperatures of the walls

In order to estimate the temperatures of the walls at a given (x,y,z) coordinate along the tunnel, it is necessary to calculate the heat radiation, I_i (W/m^2), using Equation 6:

$$I_i = \frac{W_{rad}}{4\pi \cdot r_i(x,y,z)^2} \cdot \tau \tag{6}$$

where $\tau = -exp(-\kappa\ r_i(x,y,z))$ is the atmospheric transmittivity, κ is an attenuation factor (in this case equal to 0.007 1/m) and $r_i(x,y,z)$ is the distance of the surface element i located at coordinate (x,y,z).
Since y is the prevalent direction, as previously mentioned, walls temperatures increase approaching the heat source and they decrease moving away from it. To account for this phenomenon, several values of I_i have been calculated, one for every ideal wall element in which we can split the walls. On the other hand, wall distances along x and z axes are constants, since the tunnel section does not change with y.
Now, it is possible to estimate the neat heat radiated to a single wall element by taking into account the radiation contribution due to the heat source, the incident radiation coming from all the other wall elements in the tunnel (which emit heat because they are at a certain temperature) and the radiation emitted by the surface element itself.
The resulting equation is:

$$I_{neat,i}(y) = I_i(y) + \sigma \cdot \sum_{j=1}^{n} F_{j\to i}(y) \cdot \left[T_j^4(y) - T_a^4(y)\right] - \sigma \cdot \sum_{j=1}^{n} F_{i\to j}(y) \cdot \left[T_i^4(y) - T_a^4(y)\right] \tag{7}$$

where σ is the Stephan-Boltzmann constant ($W/m^2\ K^4$), $F_{j\to i}$ is the view factor of element j with respect to the element i (dimensionless), $T_{i/j}$ is the temperature of the surface element i/j (K), T_a is the air temperature (K) and the summations (index j) are extended to all the elements of all the walls (n elements).
According to the hypothesis that there is a prevalent dimension along which the tunnel develops (its length), the tunnel can be considered as a closed cavity where the heat loss by the entrance and the exit are neglected (this is a conservative hypothesis that implies an overestimation of the wall temperatures). In this case, it is possible to compute the time evolution of the walls temperatures (having a density ρ_s, kg/m^3) solving the following system of differential equations:

$$\rho_s \cdot dy \cdot \frac{dT_i(y)}{dt} = I_i(y) + \sigma \cdot \sum_{j=1}^{n} F_{j\to i}(y) \cdot \left[T_j^4(y) - T_i^4(y)\right] \tag{8}$$

It should be noted that this equation considers that the temperature of each single wall element can change only because of the effect of the heat radiated by the flame and by the other walls elements (heat conduction inside the material of the walls is disregarded).

2.2 Air Temperature

The temperature of the air along the tunnel length is not constant and its variation as a function of y can be determined using an energy balance equation on each single elemental volume of gallery (that is, a volume $dV=B\,H\,dy$, see Figure 1) placed along y.

$$B \cdot H \cdot dy \cdot \frac{d}{dt}\left[\rho_a\big|_{T_a(y)} \cdot c_{p,a}\big|_{T_a(y)} \cdot T_a(y)\right] = \dot{H}_{a,IN}(y) - \dot{H}_{a,OUT}(y) + \dot{H}_{smoke}(y) \tag{9}$$

where: B is the tunnel width (m), H is the tunnel height (m), dy is the infinitesimal length (m) along y direction, $c_{p,a}$ is the specific heat of the air calculated at the temperature $T_a(y)$ in the element and $H_{a,IN/a,OUT/smoke}$ are the enthalpic fluxes of air and smoke, which can be calculated as:

$$\dot{H}_{a,IN}(y) = u \cdot B \cdot H \cdot \rho_a\big|_{T_a(y)} \cdot c_{p,a}\big|_{T_a(y)} \cdot \left(T_{a,IN}(y) - T_{rif}\right) \tag{10}$$

$$\dot{H}_{a,OUT}(y) = u \cdot B \cdot H \cdot \rho_a\big|_{T_a(y)} \cdot c_{p,a}\big|_{T_a(y)} \cdot \left(T_a(y) - T_{rif}\right) \tag{11}$$

$$\dot{H}_{smoke}(y) = \begin{cases} 0 \quad if \quad -1.5\ \ m \le y \le 1.5\ \ m \\ m \cdot \dfrac{\pi D^2}{4} \cdot c_{p,smoke} \cdot \left(T_{smoke} - T_{rif}\right) \quad if \quad y < -1.5\ \ m\ \ and\ \ y > 1.5\ \ m \end{cases} \tag{12}$$

where $T_{a,IN}$ is the temperature of the air entering the generic element (K), T_{rif} is the reference temperature (K), $c_{p,smoke}$ is specific heat of the smoke develops by the flame (J/kg K) and T_{smoke} is the fumes temperature (K). According to this equation, the temperature of the air is mainly determined by the hot fumes enthalpy.

2.3 Target radiation

In order to evaluate the effect of the heat radiating a vertical target (such as a human body), the flame has been considered as a solid cylinder tilted in the airflow direction.

According to this hypothesis, given a generic vertical target placed downwind at a distance s (m) from the centre of the flame base, the emissive power of the flame can be calculated using Equation 13 (Lees, 1996):

$$I(s) = \alpha \cdot \tau \cdot F_{flame} \cdot \left(T_{flame}^4 - T_a^4(y)\right) \tag{13}$$

where α is the absorbance of the target, T_{flame} is temperature of the flame (for a gasoline flame a typical value is 1240 K) and F_{flame} is the view factor of the flame with respect to the target, that is:

$$F_{flame} = \frac{2}{\pi} \cdot \sin^{-1}\left(\frac{R}{R + (s-R)\cdot\cos\theta}\right) \cdot \left[\sin\theta + \sin\left[\tan^{-1}\left(\frac{1}{(s-R)\cdot\cos\theta} - \tan\theta\right)\right]\right] \tag{14}$$

3. Case Study and Simplified Model Results

The case study assumes that a tank truck carrying 1500 L of gasoline, has been overturned 50 m after the entrance of a tunnel. The tunnel is 300 m long (L), 10 m wide (B) and with a height (H) of 5 meters. The impact with the ground has caused a crack of 250 cm^2 and a leakage of gasoline with a volumetric flow rate equal to about 0.25 m^3/s. The resulting radius of the gasoline pool can be estimated using Equation 1.

Through the mathematical model presented in Section 2, it is possible to evaluate the effects of the fire onto: 1) the structural stability of ceiling and walls (using equations reported in subsection 2.1); 2) the increase of the air temperature inside the tunnel (using Equation (9)); and 3) the radiation effects onto a vertical target (representing a human body) placed into the gallery at a given distance downwind from the centre of the pool fire. Particularly, for what concern the determination of the ceiling and wall temperatures, it is possible to observe that a maximum temperature value of about 210 °C and 160 °C, can be reached in correspondence of about 50 m from the entrance ($y=0$), that is at the ideal centre of the tilted flame (see

Figure 2). Before and after $y=0$, both ceiling and walls temperatures tend to decrease rapidly approaching the air temperature (about 20 °C before and 80 °C after).

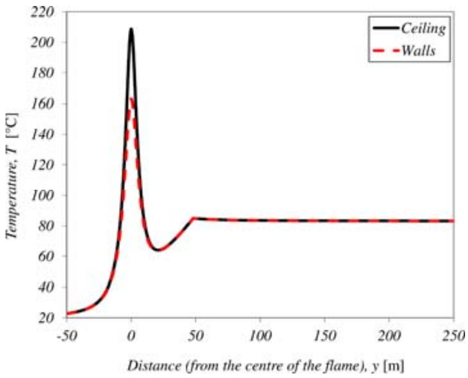


Figure 2: Ceiling and walls temperatures as a function of tunnel length and at time equal to 1000 s (maximum value). Simplified model simulation

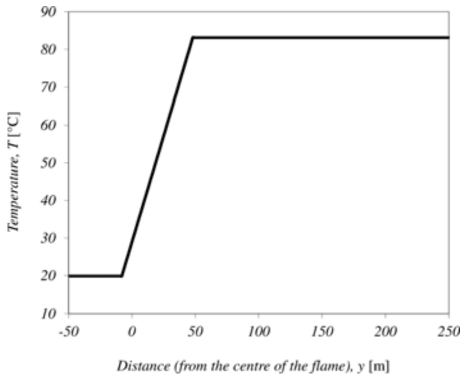


Figure 3: Air temperatures as a function of tunnel length and at time equal to 1000 s (maximum value). Simplified model simulation

On the contrary, observing the trend of the air temperature reported in Figure 3, it is possible to notice that the maximum value is reached in correspondence of 40 m after the flame centre but, when moving towards the gallery exit, the temperature remains at a constant value of 80 °C because no backlayering of the cold air downstream of the fire source has been considered.

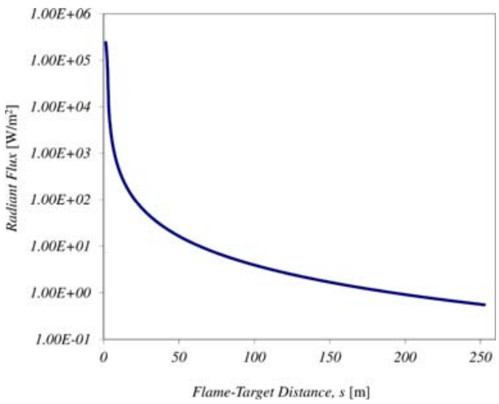


Figure 4: Effects of the heat radiated by flame onto a vertical downwind target. Simplified model

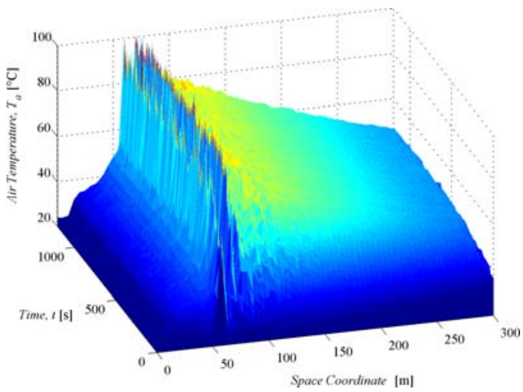


Figure 5: Air temperatures as a function of tunnel length and time. FDS simulation

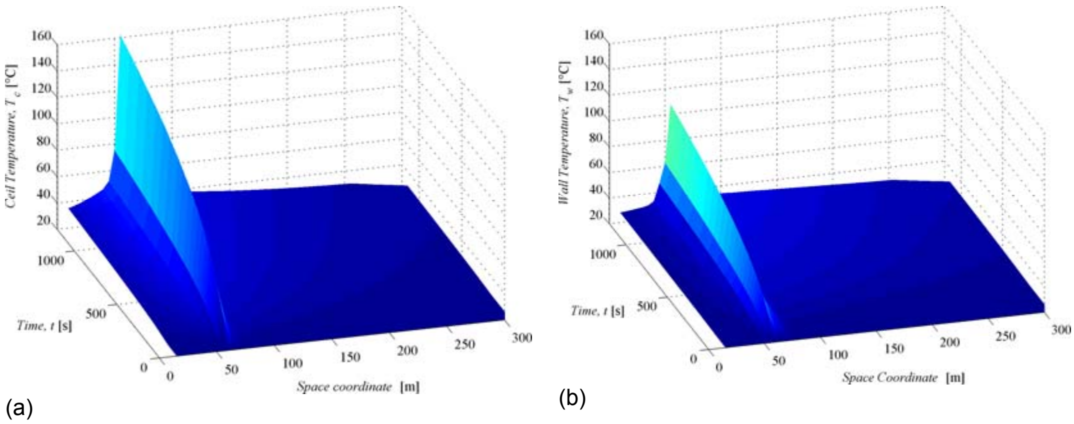
Finally, the heat radiated by the flame to a vertical target representing a human body has been estimated, as shown in Figure 4. Knowing that a human body can sustain without pain a heat radiation of about 8.2E+02 W/m^2 for 120 s (HSL, 2004), it is possible to estimate a safety distance from the flame equal to about 15 m.

4. CFD Results and comparison with the simplified model

On the following the results concerning CFD simulations for ceiling, walls and air temperatures obtained using FDS software are reported.

For what concerns the air temperature inside the tunnel, it is possible to notice a peak around 75 - 80 m from the entrance (see Figure 5), after that the temperature gently decreases until a final value of about 40 °C. This is in fairly agreement with the results of the simplified model reported in Figure 3.

As it is possible to observe from Figure 6, both ceiling (a) and walls (b) temperatures profiles are quite similar to those obtained using the simplified model. Particularly, FDS predicts maximum temperature values of about 160 °C (ceiling) and 100 °C (walls) that are about 50 °C lower than those estimated by the simplified model.



(a) (b)

Figure 6: Ceiling (a) and walls (b) temperatures as a function of tunnel length and time. FDS simulation

5. Conclusions

In this work, a nimble model has been developed in order to simulate the consequences of a tunnel pool fire in terms of wall temperatures, air temperature, and radiation on a specific target (e.g., a human body). Results obtained by the simplified model have been compared with other model results computed using FDS obtaining a fair agreement (which is completely acceptable considering that the final aim is a quick evaluation of the magnitude of the risk). Therefore, the developed simplified model can be employed as a screening tool to evaluate the magnitude of a pool fire in a road tunnel with short computational times, as required by decision support system software for reducing risk in hazardous material transport routing.

References

Benucci S., Uguccioni G., 2010, Fire hazard calculations for hydrocarbon pool fires -application of "Fire Dynamics Simulator - FDS" to the risk assessment of an Oil extraction platform, Chemical Engineering Transactions, 19, 291-296.

HSL (Health & Safety Laboratory), 2004, Human vulnerability to thermal radiation offshore, Report HSL/2004/04, Harpur Hill, UK.

Lees F.P, 1996, 2nd Ed., Loss prevention in the process industries: hazard identification, assessment, and control. Butterworth-Heinemann, Oxford, UK.

McGrattan K., Hostikka S., Floyd J., Baum H., Rehm R., Mell W., McDermott R., 2010, Fire Dynamics Simulator (Version 5). Technical Reference Guide, NIST Special Publication 1018-15, US Government Printing Office, Washington, USA.

Miclea, P.C., Chow, W.K., Chien, S.-W., Li, J., Kashef, A.H., Kai, K., 2007, International tunnel fire-safety design practices, ASHRAE Journal, 49 (8), 50-60.

Oggero A., Darbra R.M., Muñoz M., Planas E., Casal J., 2006, A survey of accidents occurring during the transport of hazardous substances by road and rail, Journal of Hazardous Materials, 133, 1-7.

Ryland D., 1999, Regulating the transboundary movement of hazardous waste in Europe: a legislative study, The Journal of Legislative Study, 5(1), 102-134.

Tavelli S., Derudi M., Cuoci A., Frassoldati A., 2013, Numerical analysis of pool fire consequences in confined environments, Chemical Engineering Transactions, 31, 127-132.

UNECE, 2013, European Agreement concerning the International Carriage of Dangerous Goods by Road <www.unece.org/trans/danger/publi/adr/adr_e.html> accessed 07.12.2013.