Safety of LPG Rail Transportation

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The risk due to the road and rail transportation of liquefied petroleum gas (LPG) is well known. The analysis of historical records evidences that severe scenarios have been caused by road or rail accidents involving LPG pressurized tank cars. Consolidated approaches exist for the analysis, the prevention, and the mitigation of risk due to the transportation of hazardous materials (HazMat) by road or rail. On June 29th, 2009, an extremely severe transportation accident involving LPG took place in Viareggio station (Italy). A tanker was punctured, releasing its entire content; the cloud ignited causing an extended and severe flash-fire, which set on fire several houses, causing extended damage and 31 fatalities.
The present study focused on the analysis of the consequences of the event and on the evaluation of the effectiveness of the safety barriers now present along the railway. Once the accident was simulated and the CFD model validated with the actual damage map, the same approach was used to test the effectiveness of the safety wall that has been built, after the accident, by Viareggio's municipality to protect the houses near to the railway lines.

1. Introduction

The risk due to the road and rail transportation of liquefied petroleum gas (LPG) is well known. Previous studies clearly have pointed out how this category of substances is often responsible of the highest contribution to the overall individual and societal risk due to HazMat transportation (Egidi et al. 1995, Molag 2003, Paltrinieri et al. 2009). This has been also confirmed by statistical data recorded in accident databases which showed that several among the most severe scenarios, occurred during HazMat transportation or in industrial facilities, were connected with LPG (DGAIS 2000, MHIDAS 2001, ARIA 2006, and FACTS 2006).
Consolidated approaches exist for the analysis, the prevention, and the mitigation of risk due to the transportation of hazardous materials by road or rail, both in Europe and in the USA (Pages & Hubert 1986, ACDS 1991, CCPS 1995, Uijt de Haag and Ale 1999).

As a result, specific technical standards and compulsory regulations exist to define the technical characteristics of the tank cars, which should be used for the transport of liquefied flammable gases in pressure. In Europe, the ADR (2006) and RID (2006) regulations apply.

On June 29th, 2009, an extremely severe transportation accident took place in the station of Viareggio (Italy), due to the derailment of a freight train carrying LPG. One of the tankers was punctured and released its content, which ignited resulting in an extended flash-fire, setting on fire several houses and vehicles and causing 31 fatalities.

A standard approach for consequence analysis in the framework of HazMat transportation was shown. Damage distances were calculated according to the threshold values used for in the Italian land-use planning using simplified models for consequence assessment based on point-source dispersion simulation. On the other hand, a detailed computational fluid dynamic (CFD) model was also applied, taking into account the presence of obstacles (e.g. walls, trees) and the shape of buildings around the railway lines. The results of the calculation were compared with the reported damages. The same approach was used to test the effectiveness of the safety wall that has been built, after the accident, by Viareggio's municipality to protect the houses near to the railway lines.

2. Description of the Accident

2.1 The sequence of events

The Viareggio LPG accident took place at 23:45 of June 29th, 2009. This case history is thoroughly discussed elsewhere (Brambilla 2010) and it is only briefly summarized in the following. A train carrying 14 LPG tank cars, each having a nominal capacity of about 46.7 t (about 110 m^3), heading South at a speed of 90km/h derailed before the Viareggio station, a small city on the Tirrenic coast, located about 20km North of Pisa, in Tuscany. After the derailment the first five tank wagons overturned while passing the shunts after the Viareggio station. The first car after the train engine was punctured after overturning and released its whole content. No loss of containment occurred from the other 13 tank wagons. This accident is a typical example of the hazard posed by LPG transportation by road and rail, as reported in accident databases, which have shown that flash fires, together with fireballs, are among the more severe scenarios likely to take place during the transportation of hazardous materials (DGAIS 2000, MHIDAS 2001, ARIA 2006, and FACTS 2006).

All the data reported in the followings were obtained from public information and from direct on-site inspections carried out after the accident in non-restricted areas. An official inquiry on causes and responsibilities of the accident is still undergoing.

From the available information, the release section had a release equivalent diameter comprised between 140 and 150mm. The released LPG formed a gas cloud that underwent a delayed ignition. From the available video recorded by close circuit cameras present in the area, a 3 minutes elapsed between the train passage through the Viareggio station and the flash fire. Meteorological conditions at the moment of the accident were: 23°C temperature, 94% relative humidity, stability class F, wind almost absent (on the seaside, wind at 0.7 m/s blowing towards the E-SE direction at 10 m

level was recorded). The ignition point is still uncertain and no evidence has been found concerning the possible presence of multiple ignition positions. The cloud ignition resulted in an extended flash fire, which affected the houses close to the railway area.

A detailed analysis of the consequences of the fire was carried out taking into account a systematic classification of damages, which produced an "effect matrix" used as blue line to build the damage map. Damage analysis was carried out by: i) direct inspection of non-restricted areas ii) analysis of photos and videos published on the web. In addition, minor damages, in particular to vegetation, were documented in order to understand the actual extension of the fire that followed the release. The database available was used to base the CFD simulations aimed at the prediction of accident consequences.

3. The CFD Model

A computational fluid dynamic (CFD) model was developed, taking into account the presence of obstacles (e.g. walls, trees) and the shape of buildings around the railway line.

CFD codes solve the Navier-Stokes equations together with specific model equations, such as energy balance, species diffusion, turbulence, etc.

In the present study, the ASsM (Pontiggia et al. 2009) (which is a k-ε model modified to account for the atmospheric stratification) was used to represent the effects of turbulence. This model introduces an additional source term, in the turbulent kinetic energy dissipation rate ε balance equation, to assure consistency between k-ε model predictions and Monin-Obhukov similarity theory profiles across the whole integration domain. This enables a proper representation of different stability classes, namely neutral stratification and stable stratification.

A value of $C_S = 0.978$ for modelling the logarithmic profiles close to the walls was used to ensure consistency between the logarithmic profile and the approach for representing atmospheric stability classes, while fully developed vertical profiles of velocity, temperature, turbulence intensity, and dissipation rate were used as boundary conditions at the wind inlet boundary (Pontiggia et al. 2009). Standard boundary conditions were used for all the other boundaries.

The geometry of the area of interest was imported into the CFD code from a topographical database available for the Viareggio municipality, allowing for a fast and easy geometry generation: eaves height and position were available for each building, leading to a simplified representation of the urban terrain as a combination of parallelepiped structures. Further details on the geometry importation procedure can be found in (Pontiggia et al. 2010). The domain area has been selected in order to enclose all the damage points, leading to a total domain of 350x500x45m. Because of the partially confined explosion, which occurred at a relevant distance from the release point, the garage in which the explosion took place was fully represented as a cavity in the ground. Access pads were also reproduced to investigate the behaviour of the dense cloud in correspondence of the slope and to check the capability of the simulation code to forecast a gas infiltration large enough to justify the inner gas explosion.

Containment walls present along the railway were added to the imported geometry, as well as the footbridge. Trees were also added in the most densely packed zone. Tank wagons (apart from the punctured one) and train engine were modelled as boxes 16m long, 3m wide and 3m high. The punctured tank wagon was reproduced with a higher level of detail. A cylindrical tank and wheel-axes encumbrance were represented. Roadbed was also reproduced, imposing standard slope and width.

From the punctured tank a flashing liquid was assumed to enter the atmosphere, leading to the formation of a gas jet (from the flash fraction) and of an evaporating pool (from the liquid rainout). Gas inlet surface (into the integration domain) was obtained on the lateral surface of the cylindrical tank, at its axial end, facing downward and impinging the ground, in agreement with reported tank damage and with the tank position after the accident. A triangular unstructured grid was imposed over the buildings, with a characteristic length of one half of the smaller edge up to a maximum of 1m. A 0.05m triangular grid was imposed on the gas inlet surface, while a 0.2m grid was used at the ground near the source, in order to describe pool evaporation. A size function was set with a growth factor of 1.2 and a size limit of 20m, leading to a tetrahedral unstructured grid of about 8 millions elements.

4. CFD Results and Discussion

Figure 1a shows the predicted LFL and UFL boundaries at 300s. It is worthwhile stressing that the model results are "true predictions", that is, no model parameters were tuned on the observed damages. This strongly supports the reliability of the CFD model used in the present study. Figure 1b shows the model predictions at 300s in the presence of the new safety wall that has been built (height about 2.5 m, dashed line on the right side of the railway line), after the accident, by Viareggio's municipality to protect the houses near to the railway line. Unfortunately, the simulation shows the ineffectiveness of the wall as the damage areas in the presence of the wall and without are almost superimposed.
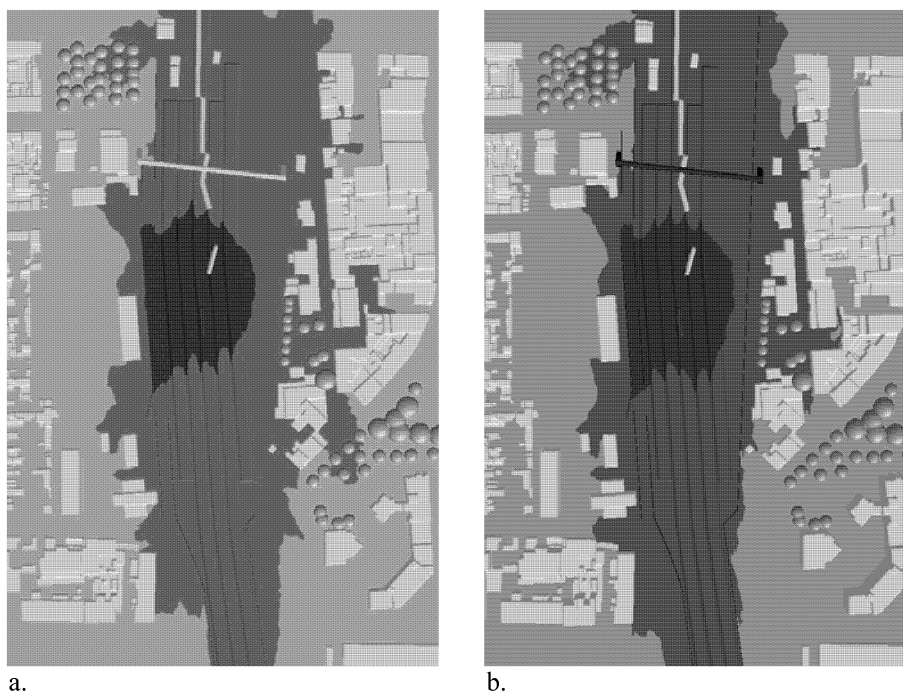
a.   b.

Figure 1 a. Predicted extension of flammability limits 300s after the release; b. Predicted extension of flammability limits 300s after the release in the presence of the new wall. Dark grey: concentrations at ground level above UFL. Grey: concentration at ground level above LFL.

5. Conclusions

In the present study, the consequences of the Viareggio accident were analyzed in detail implementing an advanced CFD dispersion model. The CFD model embedded a previously developed turbulence model able to reproduce atmospheric stratification, without loosing the robustness and the low-CPU requirements of the standard k-ε model. The model was applied in order to test the effectiveness of the safety wall installed by the Municipality of Viareggio after the accident, evidencing a poor mitigation effect on the same type of accidental dispersion.

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