Simulation of the LPG release, dispersion, and explosion in the Viareggio railway accident

Sara Brambilla, Roberto Totaro, Davide Manca
Dipartimento di Chimica, Materiali e Ingegneria Chimica “G. Natta”
Politecnico di Milano – P.zza Leonardo da Vinci, 32 MILANO, ITALY

The manuscript analyzes the accident that occurred in the railway station of Viareggio (Italy) on June 2009. A freight train carrying LPG went off the rails and five out of fourteen wagons derailed and overturned. A hole formed in the first tank car due to the impact with a signaling stake. The pressurized LPG was released as a two-phase jet: the liquid phase formed a boiling pool on the ballast while the dense gas dispersed in the atmosphere. The dense cloud spread and moved towards the neighboring houses. Afterwards, the cloud was ignited and exploded. The overpressure destroyed some residential buildings in the area closest to the explosion epicenter, while glasses were shattered in a larger area. Thirty-one people died and a number of residents were injured due to the fires that engulfed the surrounding houses. Starting from the data related to the tank cars, meteorological data, pictures of the site after the accident, aerial photos, witnesses of both civilians, and rescue teams, the manuscript reconstructs the dynamics of the accident by means of a dedicated software.

1. Qualitative description of the accident

On June 29th, 2009 at 11:48 pm a train loaded with LPG went off the rails while it was crossing the station of Viareggio (Italy). A tank wagon was damaged and the released LPG spread around, finally exploded, and burnt out. Thirty-one people died and more than thirty people were seriously injured. The train transported 14 cars with a nominal capacity of 110 m^3, each loaded with 45 t of LPG. When the train came in the Viareggio station, the front axle of the first wagon broke and the wagon went off the rails. The first car detached from the tractor, overturned, and dragged nine more cars off the rails. Of the nine derailed wagons, only the first four overturned.
The first wagon, which derailed and overturned, was dragged on the ballast, and crashed into a stake that was embedded in the ground. The impact of the tank with the stake produced a longitudinal crack in the metal vessel about 40-50 cm long and a few centimeters wide. When the axle failed, it plowed the ground, sheared several sleepers, and raised a heap of pebbles on the ballast. The drivers felt a strong jerk on the traction; they went to the window and saw the first tank car gone off the rails. The drivers applied immediately the emergency brakes and they could smell the gas. They had enough time to collect the carriage sheets, jump off the train, and run away trampling on the LPG pools on the ballast. Eventually, the drivers took shelter behind a party wall of

the station and immediately after occurred the explosions and the fires (Dellacasa, 2009).

1.1 Consequences of the derailment

The pressurized LPG in the first car was released by the hole, and started spreading and evaporating on the ballast. The surrounding population could hear a loud noise like a gas emitted by a valve. The summer night was rather hot and the people, who lived in the houses overlooking the station, went to the open windows to see what was going on. They could see a white and short cloud of gas that was moving towards their houses. Some people flew to the top storey of the building although many houses were two-storied; some decided to pick up some personal belongings but this choice was lethal; some smelt the gas and run away from home.

The dense gas cloud moved radially from the derailed tank mainly across the railway line, due to the rather calm weather conditions. It is worth noting that there was not any safety distance between the railway and the next houses, being the distance between the line and the nearest house as short as 10.44 m.

Some witnesses reported that there were two/three explosions. It is not clear whether the first ignition source was inside the ballast or among the surrounding houses. However, when the ignition occurred, besides triggering an explosion, it propagated a fire to the flammable portion of the cloud. It is also difficult to get a clear idea about the elapsed time between the crack opening and the first explosion. Some witnesses reported 2 min others 5 min. The intense emotional agitation of residents in those moments did not allow analyzing objectively the course of events.

Eventually, the dense and short gas cloud could find an easy way towards Ponchielli Street, which is a narrow and long street that is parallel to the railway line and comprises more than forty-two storied houses. A rather loose cement fence divided Ponchielli Street from the station and the gas cloud went through it. Finally, the LPG cloud, helped also by the hot night that saw a number of windows left open, entered the ground floors and basements and accumulated until an ignition source made it exploding and/or burning.

Five houses collapsed due to inner explosions. Almost all the remaining houses of Ponchielli Street burned due to the following fires that engulfed also other areas surrounding the station. The pool fire, produced by the spreading of LPG released by the punctured wagon, could be noticed far away and exceeded the electric grid with flame lengths as high as 20-25 m. Fourteen people died immediately: some under the collapse of buildings; some due to the toxic substances released by the fire of their houses; some were literally run over by the flame radiation. The fatalities rose to 22 people the day of the state funerals. Finally, there were 31 fatalities (one woman had a heart attack) and the last person died exactly two months after the accident. There were two children among the victims and more than thirty people were seriously injured. About 1100 people had to evacuate their homes for safety reasons either due to unsafe buildings or to areas exposed to further risks. As a matter of facts, the firefighters had to remove the LPG load from the derailed wagons that withstood the accidental event. The overall damages that involved the population and the infrastructures were valued 32 M€. The consequences of the accident would have been even worse if the stationmaster had not stopped two passenger trains that were arriving in Viareggio a few minutes later. Nonetheless, the Viareggio accident is the worst railway accident that ever happened in Italy as far as the transportation of dangerous goods is concerned. The Viareggio event is also the worst accident ever occurred in Italy with reference to LPG production and transportation.

2. Accident modeling

To investigate quantitatively what happened on June, 29th, 2009 in Viareggio, it is necessary to model the sequence of events that starting from the tank cars overturning led to the explosion and the burn down of some houses, cars, and people. The phenomena to be modeled are:

- the release of liquid propane from the crack in the tank car;
- the flash of the liquid jet in the atmosphere;
- the spreading and boiling of the LPG pool on the ballast;
- the dispersion of vapors emitted from the tank car and of those evaporated by the pool;
- the dilution of the gas cloud in presence of obstacles such as the permeable fence at the railroad borders, and the houses on the cloud path;
- the ignition of gas pockets inside the houses and the magnitude of the consequent explosion;
- the ignition of the liquid pool, and the consequent pool fire.

The following sections discuss how to model these phenomena and quantify the accidental consequences.

2.1 The release phase

The carrier can be sketched as a horizontal cylinder 15.95 m long and 3.04 m large. As reported above, the derailed and punctured tank car was carrying 45 t of LPG at 15 bar. Since the hole was in the bottom part of the derailed car, the release was liquid. During the discharge, no air could enter in the car, consequently a fraction of the liquid evaporated to preserve the internal pressure. The evaporation subtracted energy to the liquid fraction that cooled down (see Figure 1 for the symbology).

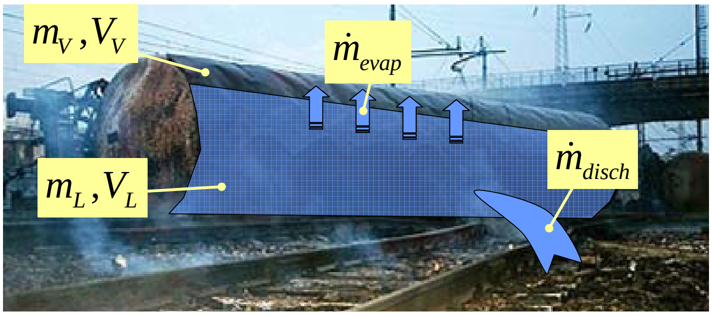

Figure 1. Illustration of the terms and the symbols used to model the car dynamics

The liquid mass ($\dot{m}_L$) inside the tank car changed due to both the evaporation and the discharge from the hole, whilst the vapor mass ($\dot{m}_V$) changed due to the evaporation only. The energy balance can be written by assuming that the system is adiabatic, *i.e.*

there is no heat exchange with the environment, a reasonable hypothesis due to the short time required to discharge all the liquid in the damaged car. The evaluation of the dynamics of the LPG inside the car, in terms of liquid and vapor masses, and temperature, calls for the solution of the following ordinary differential equation (ODE) system:

$$\begin{cases} \dfrac{dm_L}{dt} = -\dot{m}_{disch} \big/ \left(1 - \rho_V / \rho_L\right) \\ \dfrac{dm_v}{dt} = -\dfrac{dm_L}{dt} \dfrac{\rho_V}{\rho_L} \\ \dfrac{dT}{dt} = -\dfrac{\dot{m}_{evap} \Delta H_{ev}}{m_L cp_L + m_V cp_V} \end{cases} \tag{1}$$

where the evaporation rate ($\dot{m}_{evap}$) was derived imposing the volume conservation. The discharge rate ($\dot{m}_{disch}$) can be evaluated as (van der Bosch and Duijm, 2005):

$$\dot{m}_{disch} = \rho_L A_h c_D \sqrt{2\left(P - P_a\right) \big/ \rho_L + 2gh_L} \tag{2}$$

where P is the pressure of the gaseous phase over the liquid, *i.e.* 15 bar. From the images of the crack, it seems that the effective hole dimensions were 40×2.5 cm that is a hole area, A_h, of 100 cm^2. This value is also in line with the aforementioned estimations from experts that reported hole areas of 90–220 cm^2. The discharge coefficient (c_D) value is 0.62, representative of a hole with sharp and irregular edges.

Figure 2 shows the decrease of the liquid mass in time and the corresponding discharge rate, by assuming that the pool ignition occurred once the liquid release was over. It follows that the 45 t of LPG were released in 193 s, *i.e.* 3 min and 13 s. After this time, only gas was emitted.

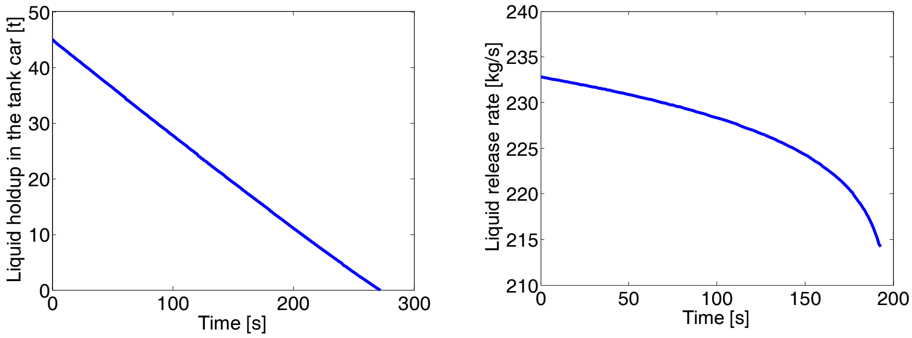

Figure 2. Discharge of the liquid mass from the tank car (on the left) and the corresponding liquid release rate (on the right)

2.2 Flash of the liquid jet in the atmosphere

Once at ambient conditions, the liquid jet flashed and produced a two-phase jet. According to Hanna and Drivas (1987), the fraction of vapor can be evaluated as: $x_V = cp_L \left(T - T_{eb}\right) \big/ \Delta H_{ev}$, where T is the temperature of the jet and $T_{eb} = 231.1\text{K}$ is evaluated by assuming pure propane since the real composition is unknown. Since the temperature changed during the discharge, the vapor and liquid fractions changed accordingly.

2.3 Formation of the liquid pool

Since the crack in the tank car was close to the ground, the liquid jet impacted directly on the ballast and did not have the time and space required to break up into drops (as it happens after a typical flight in air). Therefore, the liquid fraction spread on the ground and formed a pool.

The spreading of the LPG on the ballast, its evaporation, and delayed ignition were simulated with AXIM™, a software tool for the simulation of chemical accidents (Brambilla and Manca, 2009). This simulator can account for the time-dependent release rates and temperatures. In addition, it is possible to simulate a pool-fire triggered at any arbitrary time after the beginning of the release.

By assuming that the pool was free to spread and expand, AXIM™ determined that, in case of ignition after 5 min from the beginning of the release, the pool reached a diameter of ~24 m, whilst the flame reached a maximum drag diameter of ~27 m and a height of ~46 m (see Figure 3).

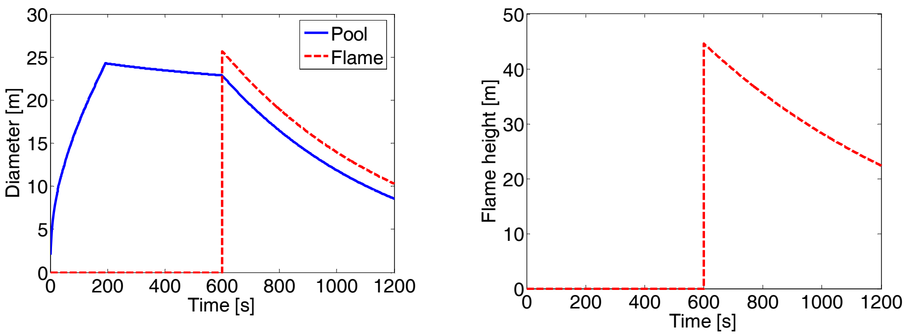

Figure 3. Pool and flame diameters (on the left) and pool fire height (on the right)

2.4 Dense gas dispersion

To simulate the dispersion of the dense gas flashed from the liquid jet emitted by the tank, it is necessary to account for the following phenomena: the gravitational slumping, due to the high density of the gas cloud; the entrainment of fresh air that dilutes and heats up the cloud; the change of the cloud temperature due to heat exchange with the ground; the motion of the cloud with the local wind. We do not account for the heat exchange with the ground. In addition, since we were in calm weather conditions, the motion of the cloud is negligible respect to the gravity slumping.

We simulated the gas dispersion on the railroad and then through the rows of buildings with AXIM™. The dense gas cloud is modeled with the shallow water equations. In particular, the model of TWODEE (Hankin and Britter, 1999) was adapted to simulate congested environments, *i.e.* to account for the presence of buildings and/or other manmade obstacles (*e.g.*, the process units of a plant). Figure 4 shows the dispersion of the cloud in the area close to the accident and its spreading over the buildings and in the street canyons. It is possible to notice that the cloud arrived at the closest building after ~13 s, then to the second rows of buildings at ~23 s. It reached the buildings on the west side of the cloud after ~93 s.

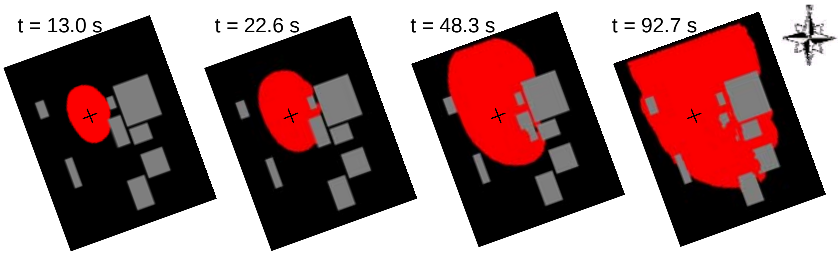

Figure 4. Dispersion of the dense gas cloud at different times (only the locations with concentration between the upper and lower flammability limit are reported)

2.5 Explosion

The evidence tells us that the explosions occurred within the houses. The dense gas model discussed in the previous section cannot simulate the penetration into buildings. Consequently, we cannot determine the amount of LPG that permeated into the houses and then exploded. In addition, since there were no explosions external to the houses, conventional methods as the TNT equivalent method or the multienergy method (Lees, 2004; Mercx and Duijm, 2005) do not apply to the case study.

3. Conclusions

The dynamic analysis of the Viareggio accident showed how vast and fast were the emission and dispersion of the LPG cloud towards the surrounding houses. It took less than 100 s for the dense-gas cloud to reach the furthest house that eventually exploded. Such a short time inhibits any emergency-response activities aimed at reducing the accidental outcomes. Conversely, only some kinds of countermeasures, designed and installed *a priori* (*e.g.* protective barriers), can reduce the impact of the accident.

References

Brambilla S., D. Manca, “Accidents Involving Liquids: a Step Ahead in Modeling Pool Spreading, Evaporation and Burning”, Journal of Hazardous Materials, 161, 1265–1280, 2009

Dellacasa E., Corriere della Sera (Italian newspaper) 1-Jul-2009, p. 3, 2009

Hanna S.R., Drivas P.J., “Guidelines for use of Vapor Cloud Dispersion Models”, American Institute of Chemical Engineers, New York (NY – USA), 1987

Hankin R.K.S., R.E. Britter, “TWODEE: the Health and Safety Laboratory’s Shallow Layer Model for Heavy Gas Dispersion. Part 1. Mathematical Basis and Physical Assumptions”, Journal of Hazardous Materials, A66, 211–226, 1999

Lees F.P., “Loss Prevention in the Process Industries”, Third Edition, Elsevier, Oxford, 2004

Mercx W.P.M., Duijm N.J., “Vapor Cloud Explosion”, in Methods for the Calculation of Physical Effects due to Releases of Hazardous Materials (Liquid and Gases), TNO, 2005

van der Bosch C.J.H., N.J. Duijm, “Outflow and Spray Release”, in Methods for the Calculation of Physical Effects due to Releases of Hazardous Materials (Liquid and Gases), TNO, 2005