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Risk reduction in road and rail LPG transportation by passive fire protection

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ABSTRACT

The potential reduction of risk in LPG (Liquefied Petroleum Gas) road transport due to the adoption of passive fire protections was investigated. Experimental data available for small scale vessels fully engulfed by a fire were extended to real scale road and rail tankers through a finite elements model. The results of mathematical simulations of real scale fire engulfment scenarios that may follow accidents involving LPG tankers proved the effectiveness of the thermal protections in preventing the "fired" BLEVE (Boiling Liquid Expanding Vapour Explosion) scenario. The presence of a thermal coating greatly increases the "time to failure", providing a time lapse that in the European experience may be considered sufficient to allow the start of effective mitigation actions by fire brigades. The results obtained were used to calculate the expected reduction of individual and societal risk due to LPG transportation in real case scenarios. The analysis confirmed that the introduction of passive fire protections turns out in a significant reduction of risk, up to an order of magnitude in the case of individual risk and of about 50% if the expectation value is considered. Thus, the adoption of passive fire protections, not compulsory in European regulations, may be an effective technical measure for risk reduction, and may contribute to achieve the control of "major accidents hazards" cited by the European legislation.

1. Introduction

All over the world, and particularly in industrialized countries, the transport of hazardous materials has till years a continuously increasing trend. Together with the volumes of chemicals shipped from one site to another, also the awareness of public of the risk posed by these activities has grown [1–4]. Public concern is focused mainly on road and rail transport, since the routes used for road and rail transportation of hazardous substances necessarily come closer and sometimes also cross densely populated areas. Accidental releases of flammable and toxic material from road or rail tankers were the initiating event of accidents with multiple fatalities [5,6]. The development and assessment of preventive and protective measures for risk reduction in the transport of hazardous materials (hazmat) is thus an actual theme, also emphasized by the results of some comprehensive quantified risk analysis studies of areas where a high concentration of sites handling and storing hazardous substances is present. These studies pointed out that often hazmat transport activities give a major contribution to the overall risk, thus evidencing that a relevant risk reduction may be achieved acting on hazmat transport [7–9].

The present study focuses in detail on LPG transportation by road, which is extremely intense among Europe. It is well known that, due to the inherent properties of LPG, an accidental spill may lead to severe fire and explosion scenarios having the potential to cause injuries and fatalities also among the off-road population. Among them, one of the more severe is the BLEVE, which consists in an instantaneous catastrophic rupture of a tank containing the pressurized liquefied gas, which instantly vaporizes and expands, originating a blast that is often followed by a fireball due to LPG ignition [10–16]. Further details on BLEVEs, fireballs and their consequences are reported elsewhere [17–22].

In the present context, it is important to recall that two types of BLEVEs are usually defined: "fired" BLEVE and "unfired" or "cold" BLEVE. The first is thermally induced, and usually occurs when a tank is impinged or engulfed by an external fire, as a jet fire or a pool fire. Fire exposure causes a temperature increase of the tank wall and a consequent reduction of its mechanical resistance. At the same time, the increase of the internal pressure (due to the temperature increase of the fluid inside the tank) causes an increase of the stresses acting on the vessel shell, which may loose its integrity leading to a catastrophic rupture [16]. The "cold" BLEVE is a BLEVE not thermally induced. "Cold" BLEVEs may be caused by a violent

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Table 1
Hazmat transportation: number of "fired" and "cold" BLEVEs recorded in past accident data concerning the road and rail LPG transport.

	No. of events		
	"Fired" BLEVEs	"Cold" BLEVEs	Total
Rail transport	32	5	38
Road transport	6	1	6
Total	38 (86.4%)	6 (13.6%)	44 (100.0%)

impact on the tank during a traffic accident or by the tank sudden failure due to a material defect or to overfilling [19]. Table 1 shows the observed distribution of "fired" and "cold" BLEVEs of LPG road and rail tankers, obtained from the analysis of several transport accident reports [23–27]. As shown in the table, more than 85% of BLEVEs recorded in past accidents are thermally induced. As a consequence, the prevention of "fired" BLEVEs may lead to a relevant reduction of the risk related to LPG transportation.

It is well known that "fired" BLEVE may be prevented increasing the "time to BLEVE" (that is the time interval between the beginning of fire and the catastrophic failure of the tank), thus allowing for external protection actions by emergency teams. Passive protections as pressure relief valves and thermal coatings are known to be effective measures to avoid "fired" BLEVEs [28]. In North America specific transport regulations have been adopted, requiring road and rail tankers carrying flammable liquefied gases to be equipped with pressure relief valves. In addition, rail tankers have to be also thermally insulated. In Hong Kong road tankers should be equipped with both thermal coating and pressure relief valves [29]. However, such protective measures are not compulsory in Europe, where no passive fire protection of LPG tankers is presently required by ADR and RID regulations [30,31] that define the standards required respectively for the road and rail LPG tankers. Moreover, a specific and systematic assessment of the potential effect of these passive protection systems on the reduction of the risk related to flammable liquefied gas transportation is still missing.

The aim of the present study is to investigate the effectiveness of passive protections of tankers in the reduction of the overall risk due to LPG road and rail transportation. In a first part of the study (Section 2), a detailed model of the behaviour of road and rail tankers engulfed in fire was developed and validated. The effect of the thermal protection on the "time to BLEVE" was analyzed. In the second part of the study (Section 3), the results obtained were used to investigate the extent of the risk reduction due to the reduction of the probability of the "fired" BLEVE scenario following the adoption of passive tank protections. Several case-studies derived from actual LPG road transportation scenarios in Europe were analyzed, and a Transport Risk Analysis (TRA) was performed to evidence the risk reduction due to the adoption of thermal coatings.

2. Analysis of the expected perfomances of passive fire-protection systems

2.1. Expected performances of passive fire protections

It is well known that passive fire protection of tanks, containing liquefied pressurized gas, is applied to mitigate the effect of the fire on the vessel shell, mainly aiming to avoid the tank failure and to prevent BLEVEs. BLEVE prevention may be obtained by the combination of two possible effects of passive protections [32,33]:

(1) reduction of the vessel wall temperature, usually obtained by the installation of a heat resistant coating;
(2) limitation of the vessel internal pressure by the control of the vapour pressure increase due to the raise of the liquid temperature, usually obtained by the installation of a pressure relief device.

An intense work was devoted in past years to the assessment of the performances of such devices in the protection of tanks present in fixed installations. Technical standards and data of bonfire tests are available in the technical literature concerning the use and the optimal specifications for both coating and PRVs in fixed tanks [34–39]. However, less attention was dedicated to the analysis of the performances of such devices in the specific accidental scenarios that may take place during the road and rail transportation of LPG. It is well known that in road and rail accidents severe fire engulfment or impingement may take place, while external cooling due to rescue teams or fire brigades may be widely delayed with respect to fixed installations [40]. Moreover, experimental tests addressing these specific scenarios were mostly carried out at a laboratory [32] or pilot scale [29,34,35,41–45]. Thus, in the present study, experimental data reported in the literature were

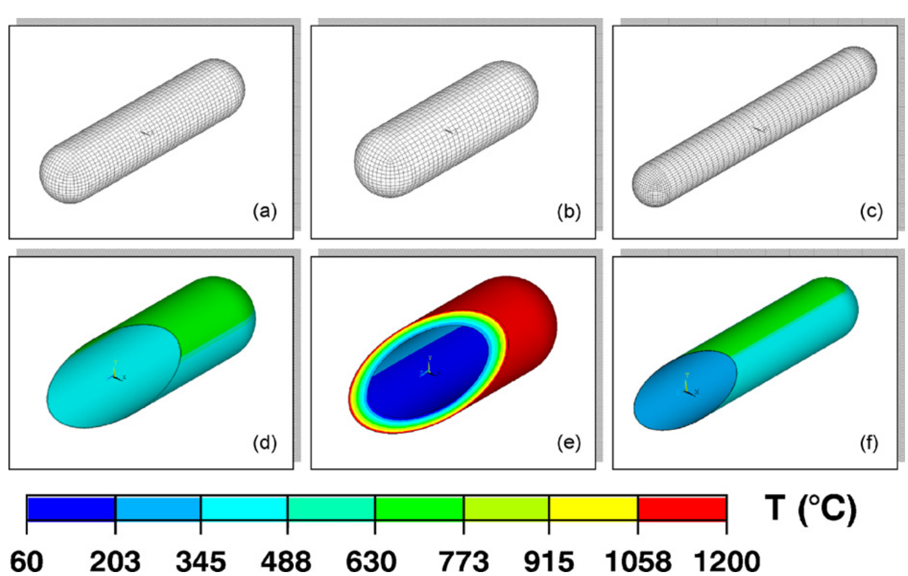

Fig. 1. Details on the geometry and mesh used for the validation of FEM with experimental results for tests: (a) BF1—4 m^3 tank; (b) BF2—4.85 m^3 tank; (c) BF3—120 m^3 tank. Temperature maps (T, in °C) calculated at the end of simulation runs are also reported: (d) test BF1; (e) test BF2; (f) test BF3.