Process Safety and Environmental Protection 113 (2018) 242–254

Contents lists available at ScienceDirect

Process Safety and Environmental Protection

journal homepage: www.elsevier.com/locate/psep

Dynamic response of a tank containing liquefied gas under pressure exposed to a fire: A simplified model

Roberto Bubbico*, **Barbara Mazzarotta**

Department of Chemical, Materials and Environmental Engineering, "Sapienza" University of Rome, Via Eudossiana 18, 00184, Rome, Italy

A R T I C L E I N F O

Article history:
Received 13 July 2017
Received in revised form 17 October 2017
Accepted 19 October 2017
Available online 27 October 2017

Keywords:
BLEVE
Mathematical modelling
Pressure liquefied gases
Accident prevention
Hazardous materials

A B S T R A C T

A simplified mathematical model representing the dynamic response of a tank containing a pressurized liquefied gas exposed to an external heat source, is presented. This scenario is of great practical interest in the process industry because it can result in the catastrophic failure of the tank with the explosive vaporization of the stored material (Boiling-Liquid Expanding-Vapour Explosion, BLEVE).

The model has been validated against experimental data available in the literature and then applied to a number of reference cases, to assess the influence of the main parameters involved in the phenomenon on the evolution of the accident. This approach can be very helpful in various applications, such as risk analysis, where a large number of different scenarios must be simulated and/or the most critical conditions must be quickly identified. It has been found that the temperature of the tank wall in contact with the vapour phase is the most critical parameter. The time-to-failure of the tank is mainly affected by the received heat flux, while the time for the first opening of the pressure relief valve is very sensitive to both the initial storage temperature conditions and the heat input.

1. Introduction

A BLEVE (Boiling-Liquid Expanding-Vapour Explosion) represents one of the most dangerous accidents which can occur during handling or storage of a low-boiling liquid. It arises from the instantaneous vaporization of the liquid and subsequent explosive expansion of the generated vapour, after the initial liquid is suddenly exposed to a non-equilibrium thermodynamic condition. In most of the cases this means that the liquid is at a temperature higher than its boiling temperature at the newly established pressure. The expansion of the vapour produced by the evaporation can be so fast that a pressure wave is generated, possibly causing damages to people, structures and facilities. This physical explosion can occur with any type of liquid; however, if a hazardous material is involved in the accident, additional dangerous scenarios can follow: a fire (e.g. a fireball, flash fire, etc.) for a flammable material, and a toxic cloud dispersion for toxic chemicals. Furthermore, since the vaporizing liquid is generally initially hold in some kind of containment system (storage tank, process equipment, etc.), and the non-equilibrium conditions are caused by the catastrophic failure of the container, the explosive flashing will also be accompanied by the launching of the container fragments, which represent an additional serious hazard.

Given the large impact area usually associated with this type of accident, many studies have been conducted to estimate the consequences of such an event, and non-exhaustive lists of references can be found in CCPS (2010, 2000), Crowl and Louvar (2011), and Mannan (2012). Comparatively less effort has been devoted to studying the dynamics of the accident before the occurrence of the explosion, whereas this knowledge would be very useful in the selection of the most adequate strategies to prevent this scenario from occurring or, at least, to reduce the amount of energy possibly dissipated in the explosive phenomenon after the failure of the containment vessel.

Even though many different causes may lead to the failure of the tank containing the superheated liquid (corrosion, mechanical or weld

* Corresponding author.
E-mail address: roberto.bubbico@uniroma1.it (R. Bubbico).
https://doi.org/10.1016/j.psep.2017.10.016

defects, external impact, etc.), in practice this accident is frequently associated with the exposure of the vessel to an external fire. Based on this reason, most of the literature studies make reference to this type of scenario.

Because of the complexity and the costs of a specific experimental facility, rather few experimental data are available in the literature, most of them dating back to the end of the 1980s (Aydemir et al., 1988; Droste and Schoen, 1988; Moodie et al., 1988; Schoen and Droste, 1988; Townsend et al., 1974). More recently, Birk et al. have been investigating different aspects of this phenomenon (Birk, 1995; Birk and Cunningham, 1996; Birk et al., 2006), while other studies focused on mitigation methods to prevent, or delay, the occurrence of the tank failure (Landucci et al., 2009a; Shebeko et al., 1996; Shebeko et al., 2000). Even though many important aspects and effects have been highlighted by this field experience, due to the complexity and the risks associated with the management of the experimental setup, the amount of available data is referred to a reduced number of operating conditions, and consequently, the results cannot be easily extended to different cases.

Mathematical modelling is easier to undertake and, actually, some models have been proposed over the years. These models aim at calculating the trend of the main parameters involved in the accident, such as the tank pressure, the temperatures of the liquid and the vapour phases inside the tank, the temperature of the tank wall and a few others. In most cases these parameters are calculated only for a limited number of key locations (*nodes*) inside the tank, such as for the bulk liquid and vapour phases (*lumped-parameter* models), while specific circumstances, such as thermal stratification, temperature gradients over the vessel wall, or the actual operation of the relief device, which will greatly complicate the model, are usually neglected (Chen and Lin, 1999; Salzano et al., 2003; Shebeko et al., 2000). However, this allows to reduce the calculation time and the need for the knowledge of a number of additional parameters, in many cases without introducing significant errors with respect to the experimental data. In order to get a more accurate prediction of the parameters of interest at any location in the tank, without introducing too many simplifying hypotheses, more detailed analyses have been proposed in the recent years, often based on a CFD approach, devoted either to predict the trend of the main parameters characterizing the fluid phases within the tank (Gong et al., 2004; Hadjisophocleous et al., 1990; Landucci et al., 2016; Lin et al., 2010) or to the calculation of the properties of the tank wall and/or of the thermal coating, if present (Landucci et al., 2009a, 2009b). Up to now, this type of approach definitely represents the best method to adequately characterize the dynamic response of a tank containing a liquefied gas exposed to an external fire. On the other hand, it is still very time consuming, it requires the availability of trained personnel to get meaningful numerical results, and the results obtained are referred to a few specific configurations of the studied system only (e.g. for a specific fire exposure, liquid level, etc.). Conversely, in a number of applications, the initial and the boundary conditions (degree of fire engulfment, type and duration of external fire, fill level, initial temperature and pressure, etc.) are not always preliminarily and clearly defined, or may vary with time; nonetheless, a quick understanding of the tank behaviour is still required for any possible conditions. This is the case, for example, in risk analysis where all the possible accidental scenarios must be taken into consideration, and the evolution of each of them must be assessed, thus requiring a significant amount of calculations to be carried out. In these cases a quick, but still reliable, estimate of the tank dynamics is desirable, even if the accuracy of the prediction may not be the best possible; to this aim, a less refined yet quicker model, such as a lumped-parameter model can perform quite well.

In the present paper, a simplified mathematical model describing the phenomena associated with the exposure of a tank containing a liquefied gas to an external fire is presented: first the results have been validated against experimental data reported in the literature; then, rather than comparing the results for different tank geometries and/or stored materials, as already done in the literature, the model has been applied to a single system configuration, but with different initial and boundary conditions, to assess the influence of the main characteristic parameters on the overall evolution of the accidental event.

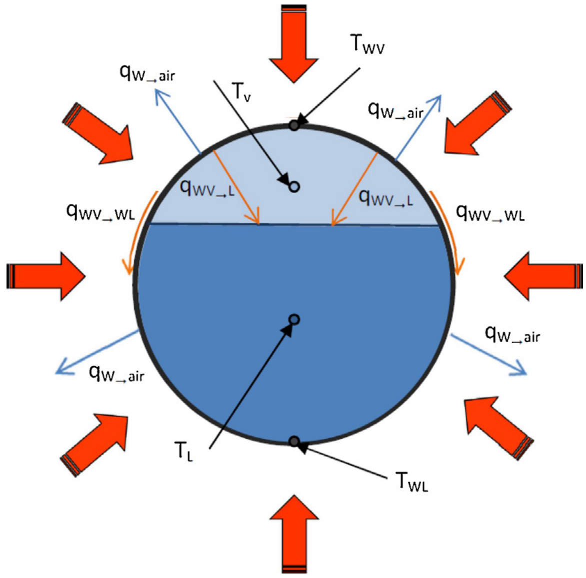

Fig. 1 – 2-dimensional picture of the tank engulfed in an external fire. The temperature nodes are highlighted.

2. Model description

Before illustrating the set-up mathematical model, a brief description of the main issues involved in the phenomenon and included in the model, will be given here.

A tank can be affected by a fire in different ways, depending on both the fire and the tank conditions: a pool fire can be fully or partially engulfing the tank, it can be located at different distances from the tank, and therefore radiating only towards a limited tank shell area, it can be a local jet fire, and so on; the tank can be open or closed (i.e. with or without a pressure safety valve), protected/unprotected (i.e. with/without thermal insulation or water spray), etc.

As stated above, in the following, reference will be made to a single system configuration: a cylindrical horizontal tank containing propane, with no thermal insulation, fully engulfed in an external pool fire, and provided with a pressure relief valve (PRV). Under these conditions, heat is homogeneously transferred from the hot combustion gases (flame) to the external surface of the tank, both by radiation and by convection (Fig. 1). After conduction through the metal vessel wall, the heat is transferred from the inner tank wall surface to the tank contents in different ways: the vapour will be heated from the tank wall in contact with the vapour by convection and, depending on the temperature reached by the metal shell, by radiation; the liquid will be heated from the tank wall in contact with the liquid by convection and boiling and from the tank wall in contact with the vapour by radiation. The temperature increase of the liquid, through its vapour pressure, will generate an increase of the tank pressure, which will finally reach the PRV set pressure. PRV activation will release a given mass flow rate of material, hopefully keeping the tank pressure under control. At the same time, the temperature increase of the vessel wall will cause a significant reduction of the metal's yield and tensile strengths, so that, if the vessel wall is not able to withstand the internal pressure any longer, a catastrophic failure of the tank can occur. When the wall temperature increase is very high, maybe just only locally, the tank