Process Safety and Environmental Protection 116 (2018) 727–736

Contents lists available at ScienceDirect

Process Safety and Environmental Protection

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

# Near-field BLEVE overpressure effects: The shock start model

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ARTICLE INFO

*Article history:*
Received 25 July 2017
Received in revised form 21 March 2018
Accepted 7 April 2018
Available online 10 April 2018

*Keywords:*
BLEVE
Explosion
Blast overpressure
Shock initiation
Risk assessment

ABSTRACT

This paper presents the results of a small scale experimental study of BLEVE overpressure effects. Testing consisted of a sealed aluminum tube (0.6 L) filled with either water or propane, being heated by a flame until the internal pressure led to catastrophic failure and explosion. Three parameters were controlled during the experiments: the failing pressure, the weakened length on the tube and the fill level. BLEVEs were obtained with tests involving water and propane. Blast gages and optical techniques were used to characterize the shock wave escaping from the failing tube. The results obtained suggest that the lead shock was primarily generated by the vapor space. Overpressure results obtained were compared with the predictions of existing models and found to be in reasonable agreement except for overpressures measured vertically above the cylinder where the overpressures were highest. A prediction model based on only vapor space characteristics was developed. Images show that the shock was fully formed at some distance away from the vessel opening and this was due to the non-ideal opening of the vessel. The model developed was based on the characteristics of the shock when fully formed away from the tube. These characteristics were defined using a combination of imaging, pressure measurements, and predictions from shock tube theory.



## 1. Introduction

A Boiling Liquid Expanding Vapor Explosion, or BLEVE, is a major hazard in the industrial landscape where storage tanks of Pressure Liquefied Gas are common. Pressure vessels are subject to various types of aggressive conditions that can weaken them and can sometimes lead to failure, e.g. corrosion, the impact of a projectile, or exposure to fire (Heymes et al., 2013).The case of fire engulfment of a vessel is investigated in this study because it is the most prevalent source of BLEVEs according to the literature (Abbasi and Abbasi, 2007; Hemmatian, 2016). In such a case the liquefied gas in the vessel is heated, increasing the pressure significantly. Pressures higher than the normal functioning pressure may be the result and the wall of the vessel is severely weakened at the top by the temperature increase due to the poor cooling properties of the vapor. An important characteristic of BLEVE accidents is that the fluid in the vessel is usually at a temperature much higher than its atmospheric boiling temperature. The combination of high pressure and weak structure leads to a crack that propagates along the length of the vessel allowing the pressurized fluid to be released. The vapor first expands violently, leading to a fast drop in pressure within the vessel where the liquid is in a superheated state and boils explosively. In some scenarios, the vessel opens fully, releasing all of its contents and leading to a BLEVE.

The consequences of such an event are blast overpressure, projection of vessel fragments, as well as possible fire and/or toxic hazards depending on the stored gas properties. A fireball, though, is not a necessary consequence of a BLEVE. It should be noted that a BLEVE is the mechanical explosion due to liquefied gas release. This study is focused on the overpressure consequences of such a phenomenon.

Overpressure prediction is a major factor in predicting BLEVE impact. The impact on the surroundings of a BLEVE generated blast needs to be understood in order to better prevent chain reaction effects and casualties. Various parameters are required to describe the full effects of overpressure: the peak overpressure of the blast, the positive overpressure impulse and its duration, the drag loading due to the dynamic pressure exerted on a structure. The wide range of prediction models currently available in the literature focus on the maximum first peak overpressure. These models also focus on the far field effects.

Various overpressure prediction models with different approaches to the BLEVE phenomenon are available. The TNT-equivalent method (Baker et al., 1977; Van den Berg and Lannoy,

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https://doi.org/10.1016/j.psep.2018.04.003

1993) is widely used for far-field overpressure prediction. It involves the calculation of the energy contained in the vessel and released in the blast. Several models are available that consider either the isentropic expansion energy (Prugh, 1991), or irreversible expansion energy (Planas-Cuchi et al., 2004), or the excess superheat energy (Casal and Salla, 2006; Genova et al., 2008). This TNT-approach is easy to implement and well validated for far-field overpressure prediction.

However, the complex opening mechanism and phase change contributions cause the TNT-equivalent model to be an overpredicting approach to near-field BLEVE blasts. Van den Berg (van den Berg et al., 2004) proposed a model based on Computational Fluid Dynamics (CFD) by calculating the evaporation rate of a vessel full of liquid. This model predicts the overpressure caused by the sudden expansion of the vessel contents. It is in better agreement with the constraints of the physical evaporation phenomenon, especially close to the vessel. Some conservative hypotheses (no vapor in the vessel, instantaneous vessel disintegration and evaporation) do not solve a few key problems of the near-field BLEVE overpressure calculations such as the contribution of the vapor expansion and the liquid boiling. Van den Berg assumes that the flash evaporation is instantaneous and that the shock is produced by the expansion of this vapor. A more recent approach (Yakush, 2016) provides a reasonable physical description of the BLEVE phenomenon with CFD modelling of the expansion wave propagation in the liquid, assuming instant equilibrium boiling when the thermodynamic conditions are reached. This model shows that the vapor generates a shock while the velocity of the boiling wave through the liquid restricts shock formation due to liquid expansion. Finally, the prediction model of Laboureur (Laboureur et al., 2015) introduced the non-ideal opening of a vessel into the prediction. This model estimated the starting shock position and overpressure and extrapolated it through distance with hemispherical decay. The starting position of the shock was assumed to be some factor times the vessel diameter which determines the overall scale of the release. The predictions were empirical, experiment based, and validated with simulations (van den Berg et al., 2004).

The issue raised by these prediction models is the definition of the contribution of each phase. Most of the energy based models consider expansion energy from the vapor space added to expansion energy from the vapor generated by the flashing fraction of liquid in order to calculate the maximum overpressure. However, some authors (Baker, 1985; Birk et al., 2007) state that only the vapor contributes to the maximum first peak overpressure. Moreover, additional phenomena such as directionality need to be taken into account in the overpressure prediction models. Empirical factors adding the effect of this phenomenon are used, based on pressure vessel bursts experiments (CCPS – American Institute of Chemical Engineers, 1994). But none have been validated for BLEVE so far.

This paper first presents results of tests involving a small scale experimental apparatus with overpressure data and high speed imaging. These results are compared to existing prediction models for validation. Finally, a physical approach to the shock start phenomenon is presented with a modelling method that does not require evaluation of the expansion energy.

## 2. Material and methods

Experiments involving small scale BLEVEs were undertaken (Birk et al., 2016). The apparatus used consisted of 6061T6 aluminum tubes, 5 cm in diameter, 30 cm long, with a wall thickness of 1.65 mm and an inner volume of 0.6L. The tubes were annealed and some aluminum was removed through machining, to produce a specific weakened length and reduced burst pressure (Fig. 1).This weakened length is referred to as a slot. The ends of the tubes were sealed with Swagelok fittings. The BLEVE case studied here was failure through exposure to fire. During testing, the tube was filled remotely with water or commercial propane (roughly 80% propane, 20% other hydrocarbons), up to a known quantity. It was then pressurized to failure through a slow heating process using a small burner placed below the tube (Fig. 2). The controlled variables of these tests were the burst pressure, and the weakened length on the tube.

Failure conditions were monitored with pressure sensors located on the filling and venting pipes, and two type K thermocouples mounted inside the tube (one in liquid and one in vapor). The monitoring sensors are sampled at 10 Hz. Blast gages (PCB 137A23 piezoelectric with a sample rate of 200 kHz) were set at various heights and angles to the slot in the tube. Three pencil type blast gages were mounted on a vertical axis above the experimental tube at distances of 0.3m, 0.4 m and 0.9 min order to observe the decay above the tube. Except in the case of the small scale results (Laboureur, 2012), previous mid-scale and large scale BLEVE experiments did not measure the overpressure above the vessel, but measured it only from the sides.

Other gages were located at 45° (down from tube top on side) and horizontal (tube side) to the tube to observe the directional influence of the opening process on the overpressure at distances varying from 0.25 m to 0.4 m.

High speed imaging was used to capture the rupture mechanism and for retroreflective shadowgraphy of the shock propagation (Hargather and Settles, 2009).Observation of the phenomenon inside the tube was done through a 38 mm quartz window constructed at one end of the tube. The imaging was carried out using two Phantom V711 high speed video cameras. The lenses used were a Nikon 105 mm (f/8) for PILS and a Tamron 300 mm (f/5.6) for the end window imaging.

Load cells were mounted under the experimental tube to measure the load on the ground generated by the BLEVE.

## 3. Experimental results

### 3.1. Summary of experiments

Twenty tests were performed with tubes filled with an average mass of 300 g of water resulting in eleven BLEVEs and nine partial failures. Over all the tests performed with water, the failure pressure ranges from 9 to 50 bar, thus the liquid volume fraction ranges from 62 to 70%, assuming equilibrium before rupture. Twelve tests were performed on tubes filled with propane resulting in ten BLEVEs. Over all the tests performed with propane, the mass of propane used per test ranges from 140 g to 156 g, the failure pressure ranges from 8 to 40 bar, thus the volume fraction of liquid ranges from 50 to 66%. The failure conditions, evaluated from the pressure sensor and thermocouple in the liquid phase for all of the cases, are summarized in the P-T diagrams shown in Fig. 3. The failure conditions for most of the tests were near equilibrium at saturation conditions. A slight offset with respect to the saturation curve is visible. It is due to fast heating and the presence of temperature stratification in the tube leading to a faster pressurization of the vapor space but a weaker explosive boiling.

### 3.2. Pressure peaks data

Measurements from all of the blast gages are summarized in Table 1, where R is the distance from the top of the tube to the sensor of the blast gage.

The influence of the direction of measurement on the maximum overpressure is clearly shown by these results. The ratio between