

Analysis of Boiling Liquid Expanding Vapour Explosion (BLEVE) Due To Loss of Containment for Liquefied Petroleum Gas (LPG) Road Tankers

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ABSTRACT: *Transport of fuel is essential to ensure supplies are delivered as per requested by the industrial sites or other demands. Numerous accidents have been reported and recorded in which loss of containment of hazardous chemicals occurred and led to disastrous outcomes. This paper presents the analysis of Boiling Liquid Expanding Vapour Explosion (BLEVE) due to loss of containment for Liquefied Petroleum Gas (LPG) road tankers. The main objective of this paper is to evaluate the potential consequences resulting from overpressure blast and thermal radiation of tankers carrying LPG to the people and the surrounding. The aim is also to compare the outcomes obtained from PHAST software simulator 8.11 with that of established mathematical model. Malaysia North-south Expressway (NSE) was selected as the location of the incident. The volume, weather parameters and properties of LPG were identified. It was found that the effect of BLEVE on people and structures was catastrophic. The results obtained from the mathematical model were similar with that modelled using PHAST software simulator.*

Keywords: BLEVE, Fireball, Loss of Containment, LPG, Road Tanker

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1.0 INTRODUCTION

The transport of hazardous materials has gained a momentum and become a significant subject especially in industrialized countries due to high usage of these materials. These materials can be in the form of flammable liquids and solids, oxidizing substances, hazardous wastes and explosives gases (Erkut & Verter, 1998). Fuel transport dominates a great portion of transport hazardous materials for the last couple of years (Elaldi, 2011). Due to loss of containment, the occurrence of several severe accidents and the rates of explosions and fire incidents has increased (Zengin *et al.*, 2015). Consequently, it leads to loss of human lives, general environment damages and economic losses. Loss of containment in transporting fuel continues to happen, since avoiding them is practically impossible. Therefore, an attention has been devoted to different aspects related to the transport of fuel mainly by road.

Lack of awareness about the potential hazard of failure to anticipate the consequences of these accidents and inadequate warning from the authorities are some of the factors that led to this type of incident (Chakrabarti & Parikh, 2013). The communications on the consequence of this incident are not properly deliberated to either the operator of the tanker as well as the people. If the consequences on hazards of the loss of containment to the people and the surrounding are properly communicated, in time and fast emergency evacuation can be done during the incident. Lack of understanding of the hazards are exhibited when people are found to stay close to the affected area. Proper escape routes especially along the expressway were not clearly identified leading to high population density at scene. Comprehensive analysis of the consequences can only be performed if the hazards of loss of containment are fully understood and the contributing failure events were properly identified.

Generally, accidents start with an incident that is a result of the loss of containment (Crowl & Louvar, 2001). Loss of containment is defined as uncontrolled or unplanned release of material or energy involving catastrophic

events. The consequences of loss of containment rely on the chemical properties of the materials released and the operating conditions, such as temperature, pressure or concentration, type of material released, the amount released and its population density. The dispersion will also depend on the environmental characteristics at the time and location of the incident, as well as the condition of weather at the time of occurrence of the incident (Ambituuni *et al.*, 2015).

The main objective of this paper is to evaluate BLEVE consequences due to loss of containment from an LPG road tanker. The outcomes will include the potential number of injuries and loss of property resulting from the accidents as described by Erkut & Verter (1998). The analysis will be performed via two different methods namely mathematical calculation using TNT equivalence models and BLEVE function under Standalone tool in PHAST software. PHAST is a powerful tool that has been used to analyse and evaluate consequences from various scenarios (Dharmavaram & Klein, 2010). The outcomes include analysis that covers possible incident from the point of discharge and the extent of dispersion (Wang *et al.*, 2017).

Consequences obtained from the two methods will be compared to provide information to the body of knowledge on the loss of containment from road tankers. Thus, companies and regulators would be able to use such analysis, details and information to ensure failures that can lead to loss of containment can be prevented in the future (Lisbona *et al.*, 2012).

2.0 METHOD

The research was designed to assess the potential catastrophic events that will happen during LPG road tanker accidents. The motivation was initiated based on various accidents involving road tankers carrying hazardous materials such as fuel and chemicals. Recorded incidents that involved transportation of hazardous materials include acid spill from a road tanker due to a road collision at KM251.6 North-South Expressway (NSE) in 2017 (Brown, 2017), blast and fire of a fuel road tanker at KM 51 Bintulu-Miri Coastal Road that led to one injury (Toyat, 2019) and the most recent one occurred at KM372 NSE where a road tanker and a lorry collided causing fire and explosion on the tanker and fatality to the tanker's driver (Kaur, 2019). Therefore, the set-up of this work was based on the worst-case scenario, *i.e.* the possible largest volume of fuel transported.

The most common size of road tankers used in Malaysia ranges from 20000 L to 45000 L. A quantitative analysis work conducted by Abdul Rashid *et al.* (2011) used a 34500 L LPG road tanker as subject. The mass of fuel, operating conditions and weather parameters must be taken into consideration to perform the analyses (Planas *et al.*, 2015). Specific model was chosen to predict the outcome of the LPG road tanker accident involving explosion and fire due to the high energy flux stored under high pressure (Malviya & Rushaid, 2018). Since this paper relied on software simulator and mathematical method, some of the chemical and physical properties were used as those available in the database. Some significant data required to represent the condition at site, *e.g.* meteorological data, were needed to run the PHAST software and analyse the results.

2.1 Identify and Describe Scenarios of Accident

It is quite challenging to identify exactly the causes and the sequences of the events. There are various occurrences that can lead to fire and explosion of LPG road tanker, *e.g.* tire failure, road conditions or collision with another vehicle. For instance, in this project, it was assumed that the LPG tanker collided with another car on the North South Expressway, Kuala Lumpur, Malaysia. There are two possible scenarios that can occur as follows:

- This accident leads to a catastrophic rupture on the vessel of the road tanker. Subsequently, the fuel was released instantaneously to atmosphere and creates a vapour cloud. As a result, the fuel catches an ignition source that lead to boiling liquid expanding vapour explosion (BLEVE) fire ball or vapour cloud explosion as shown in Fig. 1.
- The tanker tipped over and it caught external fire led to overpressure effect within the vessel. This led to possible BLEVE scenario.

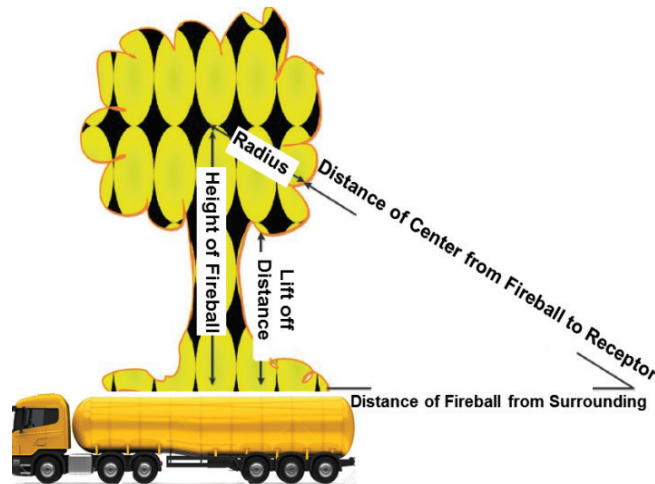


Figure 1 Fireball during explosion of LPG tanker (Bariha *et al.*, 2016)

2.2 Data collection

The data collected for this study came from various sources and all are secondary data. The schematic diagram of the road tanker was adapted from Hahn (2018). Various constraints were identified, *i.e.* no standards for road tankers configuration. The size used by companies could vary from one to the other. Thus, the characteristics of truck tanker were adopted from previous accidents and research papers (Hahn, 2018; Harper & Liccione, 1995; & Planas *et al.*, 2015). The physical properties of the road tanker and those of the LPG were obtained from literatures (Hahn, 2018; Harper & Liccione, 1995; & Planas *et al.*, 2015). The property of fuel used will be solely based on propane (C_3H_8). It is hypothetically predicted that different type of fuel might portray different fire and explosion profile. All data used in this study is presented in Table 1 and Table 2, respectively.

The data for the surrounding conditions were collected from various resources. For instance, wind speed, humidity, solar radiation and elevation values were obtained from the Malaysian Meteorological Department (2018). The value was the average data for Kuala Lumpur (Malaysia Meteorological Department, 2018) and is shown in Table 3. Furthermore, the weather conditions might vary within the span of the year. Thus, the impacts posed in this work might not accurately represent similar incident at another time and site. Lastly, the density of population at the time of accident was assumed to be based on worst case scenario; thus, the predicted injury and fatality can be differed. Statistical evaluation was not used as the determined quality assurance of the model as the actual data was not available to evaluate the best of fits of the two models. The discussion will evolve about how the two models deviate from each other.

2.3 Identification of the Outcomes

A variety of potential outcomes of accident scenarios were envisaged in the modelling stage. The outcomes depend on the conditions of the release, *e.g.* pressure and temperature. In the case of BLEVE for the LPG road tanker, the LPG is stored under high pressure and has high fuel reactivity. There is a high probability for BLEVE to occur in the case when the tanker was exposed to external fire. BLEVE scenario would produce a thermal radiation from fireball and overpressure blast from the explosion. Fig. 2 is the schematic drawing of a common road tanker with a vessel dimensions of approximately 12 m by 2.6 m. The design pressure for the vessel is 15.5 bar with 2 built-in safety valves. The detail design features are presented in Table 1.

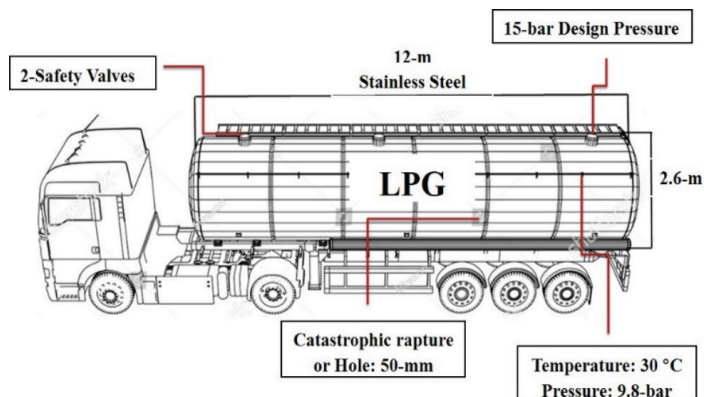


Figure 2 Schematic diagram of the road tanker

Table 1 Characteristics of road tanker involved in accident

Parameter	Value
Volume/Capacity (L)	42000
Length (m)	12
Diameter (m)	2.6
Pressure (bar)	9.8
Design Pressure (bar)	15.5

Table 2 shows the properties of the LPG transported by the road tanker shown in Fig. 2. Here, the data were obtained from the literature and the tanker was presumably carrying only propane on board.

Table 2 Physical properties of LPG

Parameter	Value
Chemical formula	C_3H_8
Vapor pressure kPa (at 20.0 °C)	853.16
Boiling Temperature (°C)	- 42
Density ($g\ cm^{-3}$)	0.002 (0°C) - 0.493 (25 °C)
Heat of combustion (kJ/kg)	46400
Specific heat capacity C ($J\ K^{-1}\ mol^{-1}$)	73.60
Auto ignition temperature (°C)	470

Table 3 illustrates the conditions of weather during the incident. There are three stability classes evaluated with respect to their wind speeds. Since this incident simulated to occur at the North -South Expressway (NSE), the selected terrain was either urban or forest.

Table 3 Weather profile during the accident

Parameter	Value
Humidity (%)	80
Solar Radiation (kW/h)	1
Stability Class	B-C-F
Wind Speed (m/s)	2-1.5-1
Terrain type	Urban or forest
Atmospheric Temperature (°C)	30
Atmospheric Pressure (bar)	Ambient (1)

2.4 Evaluation of the Outcomes

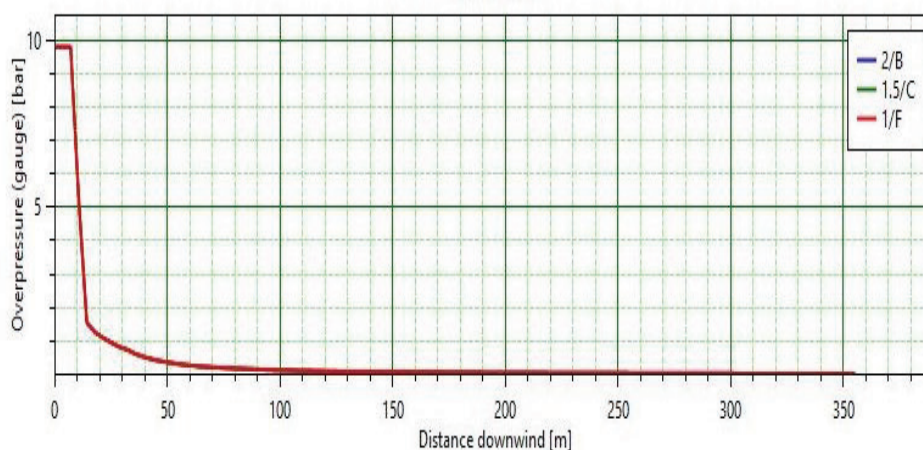
The outcomes of the accidents were illustrated based on their impacts on people and properties. The effects might be due to thermal radiation and overpressure for explosions which were portrayed as causative variables. For the effects on human, the outcomes were demonstrated as fatalities or injuries. The effects of explosions on people were predicted using probability equations that estimate the extent of eardrum rupture, lung damage and head impact (Shariff *et al.*, 2016) and (Assael & Kakosimos, 2010). The thermal radiation dose was estimated based on the heat flux generated from fires (CCPS, 2000). Hence, the probability of death, 1st and 2nd degree burn was evaluated.

The effects of the accidents on the properties, *i.e.* buildings and structures were analysed based on the indirect effect of the thermal radiation level and overpressure. This can be translated into destruction of building, shocking experienced at the building or failures on building materials.

The affected zone was calculated based on radial distance from the source of release. Here, the thermal radiation or overpressure values are greater than the specified set of endpoints (Wang *et al.*, 2017 & CCPS, 1994). The region located outside the specified zone was considered as safe area.

3.0 RESULTS AND DISCUSSION

The overpressure of LPG explosion was evaluated using PHAST software and mathematically calculated using TNT equivalency method. In the latter approach, the fuel was treated to be of equivalent to the mass of TNT. The peak side-on overpressure as proposed by Shariff *et al.* (2016) was used in this case. Fig. 3 and Fig. 4 show the result of the overpressure versus distance of the receptor for both PHAST and TNT equivalency method respectively.

**Figure 3 Overpressure vs. distance - PHAST**

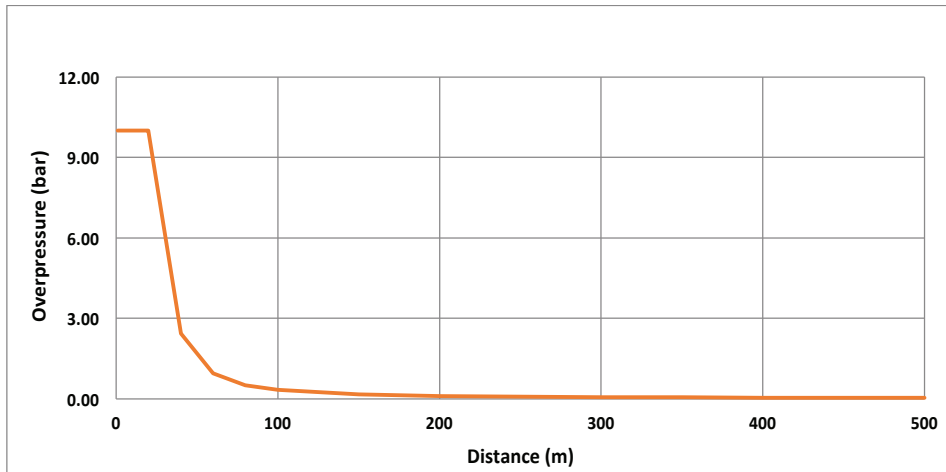


Figure 4 Overpressure vs. distance – calculation

From the figures, both models showed that a point located 10 m in radius from the source point (0 m) experienced a constant overpressure of 9 bars and higher. Here, the receptor will be engulfed by blast and flame. For a distance that is approximately 2 to 40 m away from the source point, the mathematical model shows that all objects around the area experienced more than 2 bar overpressures. Subjects who were 60 m away can be exposed up to 0.96 bar pressure. In contrast, PHAST software showed that the overpressure effect detected at 20 m away was only 1.5 bar. This effect gradually decreased and at about 25 m away from the point source, the overpressure value was estimated at 0.96 bar. In the case of BLEVE, the weather condition has shown no major impact as the explosion occurs practically immediately at the release point and the state of dispersion in atmosphere is insignificant.

It is essential to evaluate the potential consequences and effects of overpressure caused by explosion on people and surrounding. The probit and probability equations were used to estimate eardrum rupture, lung damage and head impact as that described by Shariff et al. (2016). Table 4 shows the probability of eardrum rupture and death due to lung damage and head impact due to overpressure, respectively. The presented probability was based on the direct effect of overpressure only.

Table 4 Probability effects of overpressure on human				
Distance (m)	Pressure	Probabilities %		
		Eardrum Rupture	Lung Damage	Head Impact
20	4.3	100	100	100
40	2.4	90	95	50
60	0.96	50	20	10
150	0.1	1	1	1

The results showed that at 20 m distance, the probability of death is 100% either by head impact or lung damage. Around 40 m, 90% of people at the vicinity could have eardrum rupture and 95% and 50% of them might experience lung damage and head impact, respectively. Beyond 150 m distance, the probability of the impact was only one percent for all the three effects. The results in Table 3 was quite reasonable and can be compared with previous work *e.g.* that published by CCPS (2000).

It should be emphasized that for lung damage and head impact, the assumption made was based on worst case scenario, *i.e.* choosing the position of human body with respect to the potential shock wave (Assael & Kakosimos, 2010). Thus, these results are approximate and not precise and exact. The indirect effect on people due to overpressure can still occur when they are within or inside a building or a structure, *e.g.* injury due to flying debris or fragment or even impacts due to heat radiation.

Thermal radiation associated with BLEVE fireball was illustrated using both PHAST software and mathematical calculation. With the intention of estimating the potential radiation heat flux mathematically, solid flame BLEVE model was applied (Malviya & Rushaid, 2018). Some deviations were noted on the output of the two approaches in which PHAST provided a much larger radius covered in each scenario, except for the worst thermal radiation value, *i.e.* 37.5 kW/m^2 . These differences can be attributed to the algorithm used to calculate surface emissive power, height and time in PHAST software. Bariha *et al.* (2017) discussed some other related models to elucidate thermal radiation effects.

Fig. 5 shows the contour of thermal radiation of the fireball. The red zone (Zone A) has a thermal radiation value of 37.5 kW/m^2 which can cause death to human within few seconds and possible collapse or destruction of buildings and structures. This zone extended from the failure point to approximately 150 m. The orange ellipse (Zone B) represents area with a thermal radiation exposure of 12.5 kW/m^2 which can cause a direct impact of a 2nd degree burn on human and melting of plastic on structures. This ellipse reached the distance of up to 300 m in radius. The yellow zone (Zone C) illustrates areas that are within the 4 kW/m^2 thermal radiation. The radial distance is estimated up to 500 m in radius. People who are within this zone might get 1st degree burn. No fatality is expected even for a long time of exposure. These outcomes show that BLEVE can be catastrophic and generate shocking consequences. More details about thermal radiation harm criterion in respect to distance with type of injury and harmful degree are shown in Table 5.

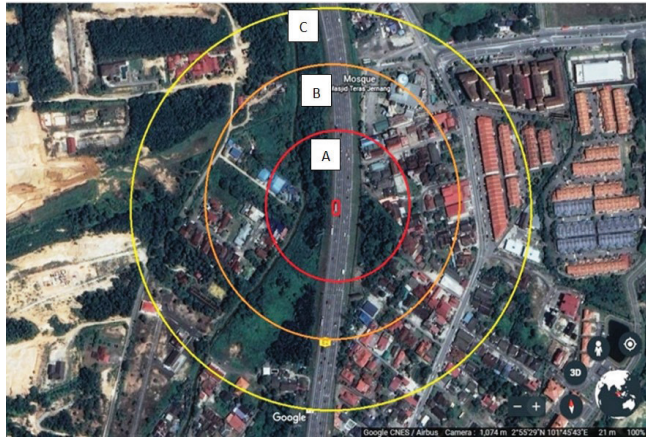


Figure 5 Contour for fireball radiation – BLEVE

Table 5 Thermal radiation harm criterion

Thermal radiation (kW/m^2)	Distance (m)		Type of injury	Possible harm on building and structures	Harmful degree
	PHAST	Calculation			
>37.5	<170	<175	Death	equipment destroyed completely	Fatal
25	208	200	3 rd degree burn	Wood ignited	Severe
12.5	295	273	2 nd degree burn	Plastic melted down	Moderate
4.0	500	418	1 st degree burn	0% fatality	Slight
<1.6	>520	>500	Safe	-	Safe

4.0 CONCLUSIONS

In conclusion, the analysis of BLEVE due to loss of containment of fuel road tankers had been described. The potential consequences resulting from overpressure blast and thermal radiation were evaluated. The outputs obtained from PHAST software with established mathematical model were compared. The overpressure profile was similar for both approaches with some deviations at specific locations. Injuries due to thermal radiation effect affected much larger areas compared to that due to overpressure. The weather condition has shown no major impact in BLEVE scenario as the explosion occurred instantaneously. The trend and estimated degree of consequences obtained from both approaches were also similar. Refinement of mathematical models will be able to emulate that produced by PHAST software.

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