CHEMICAL ENGINEERING TRANSACTIONS

VOL. 36, 2014

A publication of AIDIC
The Italian Association of Chemical Engineering
www.aidic.it/cet

Guest Editors: Valerio Cozzani, Eddy de Rademaeker

ISBN 978-88-95608-27-3; **ISSN** 2283-9216

DOI: 10.3303/CET1436091

Analysis of Methodologies and Uncertainties in the Prediction of BLEVE Blast

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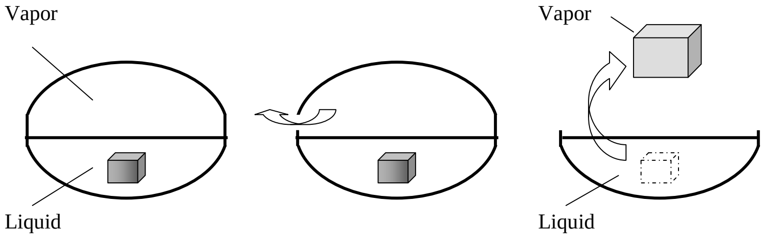
Even though BLEVEs have been studied by a number of authors, there are still significant gaps in their knowledge and in the prediction of their physical effects. Diverse methodologies have been proposed to calculate the peak overpressure of the explosion, but their results show an important scattering. Most of them assume a reversible, isentropic phenomenon, not at all logical for an explosion. Instead, some recent papers have assumed an irreversible process, much closer to the real phenomenon. This communication analyses these aspects, comparing the results obtained by applying the diverse methodologies to data obtained from a real case. The uncertainties found (vessel failure mode, directional effects) are also commented. Finally, some conclusions are derived on the best way to estimate the overpressure.

1. Introduction

A BLEVE was defined for first time by Marsh, Smith and Walls (Walls, 1978) as "a failure of a major container into two or more pieces occurring at a moment when the container liquid is at a temperature above its boiling point at normal atmospheric pressure". When this happens, due to the sudden depressurization to atmospheric pressure there is a flash vaporization of the superheated liquid and a quick expansion of the previously existing vapour (Fig. 1); due to the expansion of the system, the explosion releases a large amount of energy that is partly converted into a strong blast wave.



P	$P_o = 101.3\,kN\,m^{-2}$	$P_o = 101.3\,kN\,m^{-2}$
$T = T_s(P)$	T	$T_o = T_s(P_o)$
$h_l = h_l(T)$	$h_l(T, P_o) \approx h_l(T)$	$h_{lo} = h_{lo}(T_o)$
$h_g = h_g(T)$		$h_{go} = h_{go}(T_o)$

Fig. 1. Vapor expansion and liquid flash vaporization in a BLEVE (Salla et al., 2006).

Later on, Reid (1979) suggested a restrictive condition; according to him, for the explosion to be a BLEVE it was required that the liquid temperature reached a certain value called superheat limit temperature (T_{sl}). According to this author, when this condition was fulfilled the explosion would be much more severe. In another communication (Salla et al., 2006), the authors showed that the superheat limit temperature would correspond to the situation in which the energy transferred adiabatically between the cooling liquid and the vaporizing liquid fraction is at its maximum. However, although the theory proposed by Reid has been

Please cite this article as: Hemmatian B., Planas-Cuchi E., Casal J., 2014, Analysis of methodologies and uncertainties in the prediction of bleve blast, Chemical Engineering Transactions, 36, 541-546 DOI: 10.3303/CET1436091

widely commented in the literature and accepted by many authors, it is a fact that none of the methods proposed for the calculation of the energy released from a BLEVE takes it into account; all methods predict a higher severity as the temperature and pressure in the container increases, but none of them introduces any discontinuity in the calculation of the released energy at $T = T_{sl}$.
An important aspect that introduces uncertainty in the assessment of blast is the respective contribution to overpressure of the previously existent vapour and the one associated to the flash vaporization of the liquid; traditionally it was assumed that blast was caused essentially by flash vaporization, but recently it has been suggested that the expansion of the vapour existing in the vessel just before the explosion is more important (Birk et al., 2007).
The released energy associated to a BLEVE explosion originates a blast and often the ejection of vessel fragments. These mechanical effects can be followed by thermal effects if the released material is flammable; in this case a fireball occurs just after the explosion. Most people associate a BLEVE to a fireball because in many cases both phenomena are coupled. When this happens the thermal effects can be more severe than the mechanical ones; in fact, in risk analysis often only the thermal radiation from the fireball is considered. However, blast can be very strong, especially at short distances.

2. Vessel energy content

The energy released in a BLEVE depends directly on the amount of material contained in the vessel, and on the temperature inside the vessel just before the explosion (and, therefore, on the pressure).
As for the amount of material, the worst case would be the maximum amount legally possible. However, the tank can be, for example, half-full; if the explosion occurs a long time after the start of the emergency and the PRD has been discharging material, the mass contained in the tank will have decreased. Diverse amounts can be assumed to give high and low predictions, or just the worst case can be taken (the maximum capacity, often 85 % of the vessel volume).
It is quite difficult in predictive calculations to establish which will be the pressure inside the vessel in the event of a BLEVE. This is one of the aspects which can introduce a high incertitude in the calculation of blast. The energy contained in the vessel will depend on the pressure concerning the vapor, and on the temperature concerning the liquid. Diverse values can be assumed for pressure:

- The operating pressure (the storage pressure in a pressurized storage tank, or the operating pressure in a boiler). This would be the case if the failure was due to a mechanical impact (because of a road accident or of the impact of a fragment from another explosion).
- The pressure relief device (PRD) set value; if, after a certain time of tank heating –for ex., by a fire– a relief valve actuates and keeps the pressure at an approximately constant value.
- An intermediate pressure if, due to flame impingement, the steel fails in a relatively short time (Casal et al., 2012, Birk et al., 2013). Tests with tanks undergoing jet fires impingement (Birk et al.,1997) have shown how different is the tank wall temperature evolution under and above the liquid surface.
- A pressure higher than the PRD set value if this device is blocked or if the heat flux exceeds the code design conditions.

Thus, a value for the vessel pressure will have to be chosen to perform predictive calculations; the PRD set pressure seems to be a good general hypothesis.

3. Time to failure

This two variables, pressure and content in the vessel just before the explosion, can be affected by the time to failure when –as often happens– the vessel is heated by a fire.
If there is flame impingement, the situation will be quite different whether flames impinge below the tank liquid level (tank wall being therefore refrigerated by the liquid) or if the impingement is on the wall above the liquid level. In this case, wall temperature will increase significantly; its tensile strength will accordingly decrease, eventually leading to the vessel burst. Jet fires can imply very large heat fluxes. It is not possible to predict accurately the heat transfer rate, which depends on the fuel, the size and turbulence of the jet fire, the region of the jet (middle, tip) which impinges, etc. Diverse values have been proposed for propane and natural gas (Casal et al. 2012; Birk et al, 2013)); they can be summarized as follows:

- Natural gas, sonic jet: 50 – 300 kW/m^2; average: 200 kW/m^2.
- Propane (gas) typical value: 300 kW/m^2; propane two-phase flow: 150 – 220 kW/m^2.
- Propane, two-phase flow, low velocity: 50 – 250 kW/m^2; average: 150 kW/m^2.

The time to failure is therefore rather difficult to predict as it depends on the circumstances: sometimes it has been one minute, but it can also be half an hour or more or even failure can not occur.

4. Liquid flash and vapour expansion

When a vessel undergoes a BLEVE, the energy released is originated from the instantaneous vaporization of the superheated liquid and also to the expansion of the pre-existing vapour. It had been usually assumed that the liquid flash contribution was the most important one. Nevertheless, new experimental data would indicate that the overpressure is essentially due to the expansion of the previously existing vapour; the flash vaporization would be too slow to produce a shock wave, although it would contribute with a less important overpressure peak with effects limited to the near field; in enclosed or congested spaces these effects could be important (Birk et al., 2007). While waiting for more data, the assumption that both blast waves are combined could be a good option in the calculation procedures. Different theoretical approaches have been proposed to calculate the energy released in the explosion.

4.1 Isentropic expansion

This is the approach –first proposed by Prugh (1991)– most commonly found in the literature; it assumes that the vapour expands isentropically as an ideal gas. The work associated to the expansion of the previously existing vapour plus the vapour originated by the flash vaporization of the superheated liquid is:

$$W = 10^2 \cdot \left(\frac{P \cdot V^*}{\gamma - 1}\right) \cdot \left(1 - \left(\frac{P_0}{P}\right)^{\frac{\gamma-1}{\gamma}}\right) \quad (1)$$

where V^* is the initial volume of the vapor in the vessel plus the volume (at the pressure and temperature inside the vessel) of the vapor generated in the flash vaporization:

$$V^* = V + V_L \cdot f \cdot \left(\frac{\rho_l}{\rho_g}\right) \quad (2)$$

here V is the initial volume of vapor, V_L is the initial volume of liquid and f is the vaporization fraction:

$$f = 1 - e^{\left[-2.63 \cdot \frac{c_{plT_0}}{H_{vT_0}} \cdot (T_c - T_0) \cdot \left(1 - \left(\frac{T_c - T}{T_c - T_0}\right)^{0.38}\right)\right]} \quad (3)$$

4.2 Adiabatic irreversible expansion

The sudden expansion in a BLEVE is clearly a highly irreversible process. So, as the work associated with an isentropic process is the largest that could be obtained from an adiabatic process, this approach implies a significant overestimation.

Planas-Cuchi et al. (2004) assumed that the expansion (ideal gas) is adiabatic but irreversible. The hypothesis that immediately after the explosion there is liquid-vapour equilibrium at atmospheric pressure and at the corresponding saturation temperature is also assumed. The assumption of irreversible process is much closer to the real situation and allows less conservative and more realistic estimation of overpressure. The real expansion work is $-P_0 \cdot \Delta V$, ΔV being the variation in volume of the whole content of the vessel when it changes from the explosion state to the final state. On the other hand, for an adiabatic process this work must be equal to the variation in internal energy of the vessel content, ΔU:

$$-P_0 \cdot \Delta V = \Delta U \quad (4)$$

This equation can be solved graphically on a $P_0 \cdot \Delta V$ and $-\Delta U$ vs. vapour fraction plot, or can also be solved analytically; taking into account the mass and energy balances:

$$-\Delta U = \left(U_l - U_g\right) \cdot M \cdot x - M \cdot U_l + U_i \quad (5)$$

$$P_0 \cdot \Delta V = P_0 \cdot \left[\left(V_g - V_l\right) \cdot M \cdot x + M \cdot V_l - V_t\right] \quad (6)$$

And, from these two expressions, the vapour fraction at the final state of the process can be obtained:

$$x = \frac{M \cdot P_0 \cdot V_l - V_t \cdot P_0 + M \cdot U_l - U_i}{\left[\left(U_i - U_g\right) - \left(V_g - V_l\right) \cdot P_0\right] \cdot M} \quad (7)$$

Finally, by substituting the value of x in Eq. (5) or (6), ΔU is found.

4.3 Superheating energy of the liquid

Casal and Salla (2006) proposed a different approach, allowing a quick estimation of the energy released, based on the liquid "superheating energy". In an adiabatic vaporization process, the fraction of liquid that is vaporized can only obtain the required energy from the remaining liquid mass that is cooled. If q_v is the required vaporization energy per unit mass of liquid (kJ/kg), it can be expressed as a function of the enthalpy according to the following expression:

$$|q_v| = h_{g0} - h_l \quad (8)$$

If q_l is the heat (kJ/kg) that can be released by the remaining liquid fraction when it is cooled from the initial temperature to the boiling temperature at atmospheric pressure (T_0), then:

$$|q_l| = h_l - h_{l0} \tag{9}$$

The superheating energy (SE) contained in the liquid just before the explosion, with respect to its final state immediately after the explosion, is the energy that will be partly converted to work to originate the overpressure. Then, this superheating energy must be directly related to the severity of the explosion.
The authors did not take into account the contribution of the expansion of the vapour existing inside the vessel just before the explosion, which was considered to be negligible as compared to the contribution of the liquid vaporization. The error thus introduced is relatively low and depends on the relative volumes of liquid and vapour in the vessel. As an example, for a tank with a volume V_t containing propane at 55 ºC and 19 bar, the error is 4% if $V_L = 0.8 \cdot V_t$, 19% if $V_L = 0.4 \cdot V_t$, and 40% if $V_L = 0.2 \cdot V_t$.
As the variation of enthalpy between two liquid states is very similar to the variation of energy, the difference of enthalpy values on the right-hand side of Eq. (9) can be assumed to be the superheating energy of a liquid superheated at a temperature T compared to the energy that it would have if it was in equilibrium at the temperature T_0 (the boiling temperature at atmospheric pressure):

$$SE = h_l - h_{l0} \tag{10}$$

The ratio between the energy converted into ΔP and SE was calculated (Casal and Salla, 2006) for both the isentropic and the irreversible process, for a set of substances. To do this, the "useful" energy of the explosion was multiplied by $\beta = 0.5$ (see next section), divided by the SE and finally expressed as a percentage. From these data, it was observed that for an isentropic process, the energy devoted to ΔP ranges between 7 and 14 % of SE, while for an irreversible process –much closer to the real situation– it ranges between 3.6 and 5 %. Thus, the energy converted into overpressure is (Figure 2):

isentropic process ($k = 0.14$): $Overpressure\ energy = 0.14 \cdot SE \cdot M_L$ (11-a)

irreversible process ($k = 0.05$): $Overpressure\ energy = 0.05 \cdot SE \cdot M_L$ (11-b)

This method allows a quick estimation of the ΔP for a given vessel to be made, if its content and its temperature just before the explosion are known.

4.4 Overpressure

The estimation of the overpressure originated by a BLEVE is subjected to an important uncertainty. Not all the energy released in the explosion will be available for generating the overpressure. A significant amount will be devoted to breaking the vessel and to eject the vessel fragments (kinetic energy of the projectiles). It has been suggested that in a ductile failure (the most common case), the energy in the pressure wave will range between 40 % and 50 %; 50 % ($\beta = 0.5$) could be assumed in a conservative approach.
The estimation of the overpressure as a function of distance can be done by calculating the equivalent mass of TNT, applying the corresponding equivalence, 4,680 kJ/kg TNT. The equivalent TNT mass can be obtained from the energy released, as calculated in the previous section:

a) From Eq. (1): $$M_{TNT} = \frac{10^2}{4680} \cdot \left(\frac{P \cdot V}{\gamma - 1}\right) \cdot \left(1 - \left(\frac{P_0}{P}\right)^{\frac{\gamma-1}{\gamma}}\right) \tag{12}$$

b) From Eq. (4): $$M_{TNT} = \frac{\Delta U}{4680} \tag{13}$$

c) From Eq. (11): $$M_{TNT} = \frac{k \cdot SE \cdot M_L}{4680} \tag{14}$$

The scaled distance can be calculated as a function of the real distance between the tank and the target,

for Eqs. (12) and (13): $$d_n = \frac{d}{\sqrt[3]{\beta \cdot M_{TNT}}} \tag{15-a}$$

and for Eq. (14): $$d_n = \frac{d}{\sqrt[3]{M_{TNT}}} \tag{15-b}$$

Finally, from the plot of overpressure vs. scaled distance for TNT the approximate value of the peak overpressure can be obtained. To take into account the ground effect (in a practical case, the explosion will take place at the surface of the earth or slightly above it) the overpressure should be multiplied by 2 to account for the fact that the expansion volume is hemispherical and there is a reflection of the overpressure wave on ground. However, if this effect has already been corrected in the TNT curve used to determine ΔP (as is usual in the "surface blast curves") these correction is not required.

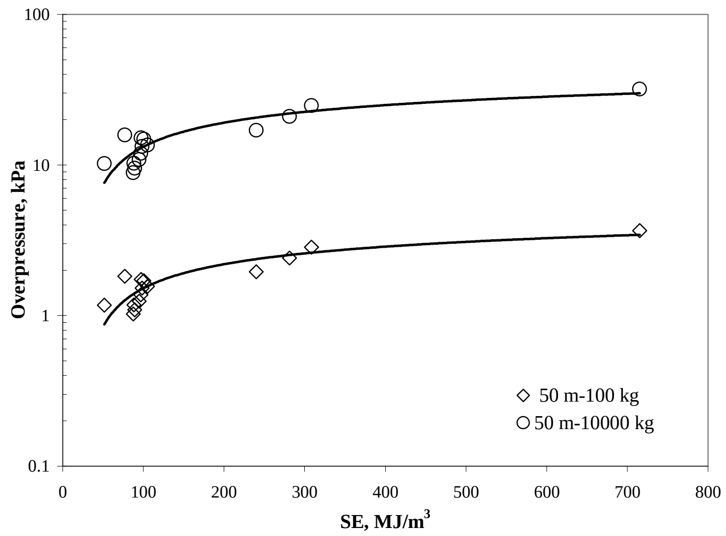


Fig. 1. Variation of peak overpressure as a function of SE (at T_{sl}) for different substances; the highest value corresponds to water (Casal and Salla, 2006).

An analysis of different methods for evaluating ΔP has been published by Bubbico and Marchini (2008), who compared the results to the real value obtained from one accidental scenario (the explosion of an LPG tank of 13 m^3, containing approximately 525 kg of liquid). Their results can be seen in Table 1; the values obtained from the SE method have been added. In this case, both non-isotropic approaches (including the method based on the use of SE) proved to be less conservative but probably more realistic.

Table 1: ΔP (kPa) calculated by different models (LPG tank) (modified from Bubbico and Marchini,(2008))

Distance (m)	Prugh (vapor)	Baker (vapor)	Crowl/Prugh (vapor)	Baker (liquid)	Planas et al.	SE method (irreversible)	Actual (estimated, scenario)
20	18.3	28	11	16.9	8.9	6	5-6
30	11.1	15.5	6.9	9.8	5.4	3.4	3

Laboureur at al. (2013) have compared the predictions from diverse models with data corresponding to approximately ninety experiments at laboratory scale, small scale, mid-scale and large scale. The predictions from the Casal-Salla model for irreversible process and from the Prugh model gave the best estimations of the overpressure; these authors considered Prugh predictions better suited for a conservative approach, as its values where higher than those of the set of analyzed data.

Finally, it should be mentioned that often there is a directional effect. Although the pressure wave should theoretically move uniformly in all directions if there are no obstacles, if it is partly hindered by tanks, pipes or buildings the overpressure map becomes much more complicated and local higher and lower overpressures are generated. There is also an influence of the tank geometry. In the BLEVE of a spherical tank, the blast wave should be expected to expand uniformly in all directions (with the mentioned local disturbances). However, in the explosion of a cylindrical vessel there will be directional effects which will depend on how the tank opens up. The overpressure is often higher in the direction perpendicular to the to the vessel main axis (Birk et al., 2007) (up to double the axial overpressures).

5. Conclusions

Amongst the methods proposed to estimate the blast from a BLEVE, those assuming an irreversible process seem to be the best ones. However, the estimation of the peak overpressure is subjected to diverse uncertainties, the main ones being associated to the amount of energy released, the fraction of this energy devoted to blast, the relative contribution of pre-existing vapour and flash vaporization, and the influence of directional effects. More research would be required to clarify these aspects, an essential point being the detailed analysis of large scale accidents.

6. Notation

c_{plT_0}: specific heat of liquid at T_0(kJ kg^{-1} K^{-1})
d: distance between the vessel and the target (m)
H_{vT_0}: enthalpy of vaporization at T_0 (kJ kg^{-1})
h_{g0}: enthalpy of saturated vapour at T_0 (kJ kg^{-1})
h_l, h_{l0}: enthalpy of liquid at T or T_0 (kJ kg^{-1})
f: vaporization fraction (-)
k: constant accounting for the percentage of energy released converted into ΔP (-)
M: mass of substance inside the vessel (kg)
M_L: mass of liquid inside the vessel (kg)
M_{TNT}: equivalent mass of TNT (kg)
P: pressure in the vessel (bar)
P_0: atmospheric pressure (bar)
ΔP: peak overpressure (kPa)
T: vessel temperature just before the explosion (K)
T_c: critical temperature (K)
T_0: boiling temperature at atmospheric pressure (K)
U: internal energy (kJ kg^{-1})
U_i overall internal energy of the system just before the explosion (kJ)
V: initial volume of vapour (m^3)
V^*: initial volume of vapour plus volume of vapour from the flash vaporization (m^3)
V_L: volume of liquid in the vessel (m^3)
V_g, V_l: specific volume of vapor and liquid (m^3)
V_t: volume of the vessel (m^3)
W: work (J)
β: fraction of released energy converted into overpressure (-)
γ: ratio of specific heats (-)
ρ_g, ρ_l: density of vapour and liquid (kg m^{-3})

Acknowledgements

The authors thank the Spanish Ministry of Science and Innovation (project n. CTQ2011-27285) and the Autonomous Government of Catalonia (project n. 2009 SGR 1118) for sponsoring this research.

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