

An experimental study of water BLEVE

Frederic Heymes, Roland Eyssette, Pierre Lauret, Pol Hoorelbeke

▶ **To cite this version:**

Frederic Heymes, Roland Eyssette, Pierre Lauret, Pol Hoorelbeke. An experimental study of water BLEVE. Process Safety and Environmental Protection, 2020, 141, pp.49-60. 10.1016/j.psep.2020.04.029 . hal-02775607

HAL Id: hal-02775607

https://imt-mines-ales.hal.science/hal-02775607

Submitted on 4 Jun 2020

HAL is a multi-disciplinary open access archive for the deposit and dissemination of scientific research documents, whether they are published or not. The documents may come from teaching and research institutions in France or abroad, or from public or private research centers.

L'archive ouverte pluridisciplinaire **HAL**, est destinée au dépôt et à la diffusion de documents scientifiques de niveau recherche, publiés ou non, émanant des établissements d'enseignement et de recherche français ou étrangers, des laboratoires publics ou privés.

An experimental study of water BLEVE

Frederic Heymes [a,*], Roland Eyssette [a], Pierre Lauret [a], Pol Hoorelbeke [b]

[a] IMT Mines Ales, 6 Avenue De Clavières, 30319 Ales, France
[b] Total SA, 24 Cours Michelet, 92069, Paris La Défense, Cedex, France

A B S T R A C T

A boiling liquid expanding vapour explosion (BLEVE) is a physical explosion caused by a sudden rupture of a vessel containing superheated liquid. A BLEVE can occur with many types of fluids and is not an exclusive phenomenon for flammable liquefied gases such as propane or butane. Other superheated liquids suffering a fast depressurization at high temperature may entail a BLEVE, such as water in steam generation systems. Several pieces in literature suggest that superheated water may produce a BLEVE, but little experimental data can be found on that topic.

The aim of this work was to perform water BLEVE tests with a 14 L pressure vessel designed on purpose to produce high superheated liquid water (290 °C; 75 bar) and to trigger a BLEVE through calibrated rupture disks. Pressure sensors were set in the vessel to measure the internal phase change pressure dynamics and other aerial overpressure sensors were put around the relief rupture disk to capture the blast wave. Temperature of water was also recorded, and a fast camera (Phantom V2512) was used to see the phenomenon.

Data show clearly the pressure recovery due to rapid boiling in the vessel. Explosive boiling did not add additional internal pressure force on the containment. Two main blast waves were observed, they were strongly related with outlet orifice area but little dependant on filling ratio. The two phase jet reached a 20 m range.

Keywords:
BLEVE
Superheat limit temperature
Explosion
Superheated water
Explosive phase change
Blast
Boiler explosion

1. Introduction

High temperature steam is frequently used in industry to carry heat. Indeed, steam delivers a huge heat during condensation because of its high phase change energy. After that, hot water flows usually back to a furnace (boiler) to be reheated and vaporized in order to start a new cycle. According to the process temperature requirements, steam is produced at various temperatures and pressure values. Typically, steam below 3.5 barg is termed as low pressure steam. Steam above 3.5 barg but below 17.5 barg is termed as medium pressure steam and steam above 17.5 barg is termed as high pressure steam. Some users define their steam above 40 barg as ultra-high pressure steam. A complete heat transfer circuit involving high pressure steam involves automatically high temperature pressurized water leaving the condensation equipment, flowing into pipes and a pump to the boiler.

The hydraulic circuit may open up to the atmosphere accidentally as a result of a rupture or other loss of containment. Since the pressurized water is at a higher temperature than boiling water would have been at ambient atmospheric conditions, some of the water will flash into steam as soon as the containment fails. Steam and boiling-hot water are released, entailing a burning danger for humans. The loss of containment of pressurized steam or water can also generate a blast wave that can cause great damage to humans and property. This will happen when water temperature overcomes 100 °C, the more the water will be superheated the more steam will be produced.

But a worse outcome may occur in case of very high temperature water, close to the superheat limit temperature. When containment fails, pressure drops suddenly in the circuit and water reaches a high superheated state. This state is metastable, water vaporizes in the vessel from liquid to vapour with extreme speed (homogenous nucleation), increasing dramatically in volume. This entails an increase of pressure in the vessel that may destroy the vessel and produce a blast (Abbasi and Abbasi, 2007a). Thus, some steam explosions appear to be boiling liquid expanding vapour explosion (BLEVE), and rely on the release of stored superheat. The degree of superheat (i.e. the difference between the temperature of the hot water actual temperature and the atmospheric boiling temperature of the water) determines the violence of the explosion (Heymes et al., 2019).

* Corresponding author.
E-mail address: frederic.heymes@mines-ales.fr (F. Heymes).

Some cases of water BLEVE are documented. For example, the explosion in the Mihama Nuclear Power Reactor accident in Japan, in August 2004 was considered as a water BLEVE (Abbasi and Abbasi, 2007a). According to the authors, the initiating event was a leak in large pipe carrying superheated water. The leak instantaneously reduced the pressure inside the pipe to atmospheric and the resulting violent nucleate boiling of the superheated water gave rise to a major explosion. The two-phase release of superheated water and steam scorched 11 workers. Some of these lost their lives, the others were severely injured. Abbasi and Abbasi (2007a) cite also the case of Spencer, USA (1982), where seven people died when a tank containing overheated water entailed a BLEVE. They cite also the accident of Louisville, USA (2003) where a mixture of maltodextrine and overheated water was considered as a BLEVE. The boiler explosion in Medin, USA (2001) and the explosion on the ship S.S. Norway at Miami, USA, occurred both when vessels containing superheated water developed cracks are both likely to be BLEVE (Abbasi and Abbasi, 2007a).

Boilers explosions are particularly difficult to interpret since three causes of explosion coexist: flammable gas; hot surfaces and superheated water. Thus, in some cases it may be difficult to understand if boiler explosions were due to fuel-air explosion (in the flame part), steam explosion (due to water projection on a hot surface) or true BLEVE. According to Abbasi and Abbasi (2008) and Hemmatian et al. (2019), most steam boiler explosions were not considered as BLEVE by lack of understanding of this phenomena. This is undoubtedly the reason why the number of water BLEVEs in most surveys is quite low and it is difficult to have a precise view on the occurrence and consequences of water BLEVE. According to Hemmatian et al. (2019), water represents 11% of all registered BLEVE accidents. Another question is related to the failure scenario and the destruction extension. Which scenario can entail water BLEVE in a water-steam circuit? Fire engulfment, pressure overshot, mechanical failure or other event (Heymes et al., 2014)? According to Abbasi and Abbasi (2007a), fire is the main cause of BLEVE. This is probably why most water BLEVE was reported for boilers. Fire, mechanical impact or corrosion decrease resistance of containment which is, according to Birk and Vandersteen (2006) a criteria for BLEVE.

This work aimed to study fundamentals aspect of water BLEVE (phase change dynamics), supplementary pressure stress applied to the containment (tangential or perpendicular), blast effects (near and far fields) and vapour release dynamics. The scenario considered is a sudden depressurisation of superheated water contained in a tubular vessel, with different release diameters. The next part of this work will look into details current knowledge about water BLEVE.

2. Theoretical considerations

2.1. Phase diagram (P–T)

Water properties are well known. Because of its polarity, a water molecule in the liquid state can form up to four hydrogen bonds with neighbouring molecules. These bonds are the cause of water's high surface tension and also the reason why the melting and boiling points of water are much higher than those of other compounds of same molecular weight. These intermolecular bonds also explain its exceptionally high specific heat capacity, heat of fusion, heat of vaporization and thermal conductivity. These properties are key parameters for phase change conditions and boiling kinetics. Facts and theories that are quite well known for propane or refrigerants (which were most studied in literature) could be very different for water.

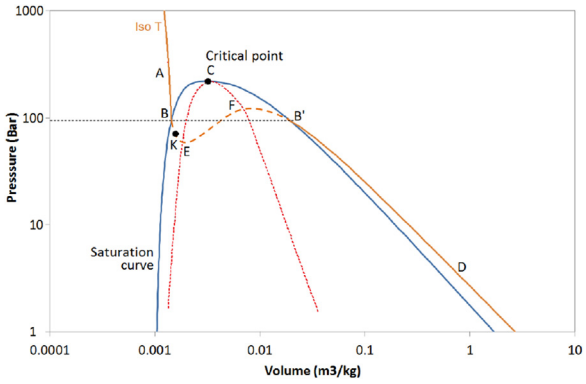


Fig. 1. Coexistence line (BCB'), isotherm at equilibrium (ABB'D), liquid spinodal (CE) and vapour spinodal (CF) in (P, v) coordinates (Mengmeng, 2013).

Phase change lines and critical point (T = 373.946 °C; P = 220.6 bar) are given in Fig. 1. When water is in saturated state, pressure is defined by liquid temperature and conversely, water must be kept at a minimum pressure to exist in liquid state. If order to avoid cavitation, pressure can be set above the saturation pressure; water is therefore subcooled.

2.2. Superheated state

Water can be in superheated state when its temperature exceeds the saturation temperature of a given pressure or when its pressure decreases below the saturation pressure of a given temperature while the liquid is still not boiling: $T_L > T_{sat}(P_L)$ or $P_L < P_{sat}(T_L)$. Superheating may happen at any pressure below the critical point and is usually reached by two ways: 1/ at constant pressure superheat occurs when the temperature increases quickly (for example by contact with a molten metal); 2/ at constant temperature superheat occurs if there is a sudden depressurization of a vessel containing pressurized water at a temperature significantly superior to 100 °C. Superheat domain is delimited by the superheat limit temperature (SLT). Two different superheat limit temperatures are considered in literature.

2.2.1. Thermodynamic superheat limit (TSL)

The superheat limit temperature can be defined theoretically. On the usual (P,v) diagram as follow (Fig. 1), C is the critical point. [BCB′] is the saturation curve or the binodal. One isotherm is [ABEFB′D]. B and B′ are equilibrium states on the binodal. When the liquid state is between A and B, it is called the subcooled liquid. The liquid at point B is called the saturated liquid. When the liquid state is between B and E, it is superheated liquid. In this state the liquid becomes metastable which means its stability can be easily broken by external perturbations. If so, it can no longer maintain its liquid state and phase transition must occur. When the meta-stability of the liquid becomes larger (the liquid is approaching point E), the minimum perturbation required to break the stability of the liquid becomes smaller and finally homogenous nucleation occurs. Point E in Fig. 2 is called the thermodynamic superheat limit (TSL) of the liquid and [CE] is called the superheated liquid spinodal. The phase separation occurring at the TSL is called spinodal decomposition.

The thermodynamic superheat limit (TSL) curve is defined by the spinodal curve, given by the equation:

$$\left(\frac{\partial P}{\partial V}\right)_T = 0$$

This equation is a condition of thermodynamic stability. It separates two regions on the P–V diagram (Fig. 1) separated by the superheat limit curve, defined by the value of the pressure gradient:

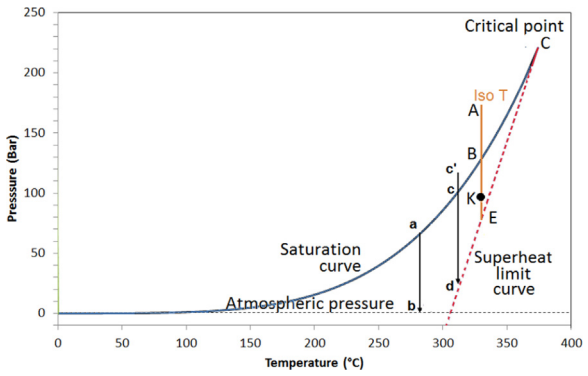


Fig. 2. Phase change diagram of water in (T,P) coordinates (Abbasi and Abbasi, 2007b).

If $\left(\frac{\partial P}{\partial V}\right)_T < 0$ the system is stable

if $\left(\frac{\partial P}{\partial V}\right)_T > 0$ the system is unstable

TSL can be predicted by deriving equations of state (EOS). Many equations of state can be used. Abbasi and Abbasi (2007b) used 7 models to calculated TSL in case of water (Table 1): Redlich Kwong (RK), van der Waals (VDW), Soave Redlich Kwong (SRK), Peng Robinson (PR), Robinson–Mathias–Copeman (PRMC), Twu–Redlich–Kwong (TRK) or Peng-Berthelot (B).

According to the authors calculations, the TSL vary in the range (546.6–604.5) K, that is a range of ΔT = 58 K depending on the considered EOS.

2.2.2. Kinetic superheat limit (KSL)

Some authors tried to measure the superheat limit temperature experimentally. The thermodynamic stability limit where phase transition will spontaneously occur without any external perturbations or without any suitable nucleation site is however delicate to reach. In experiments on superheating measurements of a liquid, bubble nucleation (generation of small bubbles) will start when point K on the isotherm in Fig. 1 is reached. Point K is called the kinetic superheat limit (KSL). The KSL can be measured experimentally provided early bubble generation by impurities or wall effects is prevented (no heterogeneous nucleation). Large discrepancy may be observed in experimental data. Three values at atmospheric pressure were found in the literature: (Avedisian, 1985) proposed a KSL of 575.1 K (301.95 °C), Abbasi and Abbasi (2007b) proposed a value of 553.2 K (280.05 °C) and Reinke (1997) reports a value of 575.25 K (302.1 °C).

2.3. The boiling liquid expanding vapour explosion (BLEVE)

The standard theory of BLEVE was originally proposed by Reid (1979). The essential idea is illustrated in Fig. 1. Coexistence line (BCB'), isotherm at equilibrium (ABB'D), liquid spinodal (CE) and vapour spinodal (CF) in (P, v) coordinates (Mengmeng, 2013). Under normal conditions the content of the vessel containing a liquid and its vapour is in thermodynamic equilibrium and the pressure and temperature combination lies at the saturation curve (points a or c). In the case of vessel rupture the pressure suddenly decreases resulting in superheated liquid. According to Reid's theory, when the pressure of the liquid decreases from point c to d, the liquid reaches the superheat limit curve and a BLEVE will occur while in the process of a to b, the liquid does not reach the superheat limit curve, no BLEVE will occur. If the liquid is subcooled, that is if pressure exceeds saturation pressure (c′), saturation conditions are crossed and liquid enters superheated state directly.

However, the situation in a real incident will be much more complicated than the simple explanation of Reid (1979). Direct correspondence between a BLEVE and the spinodal decomposition has never been proven by experimental data. In a practical BLEVE, the way the tank opens will influence strongly the rate of depressurisation. Abbasi and Abbasi (2007a) report that some authors think that "the severity of the final failure may not necessarily be a function of the extent to which the contents get superheated but may have more to do with the initiating mode of the vessel failure and the thermo-hydraulic contents of the final failure". The decrease in pressure is not felt all over the liquid instantaneously but spreads as a wave. Furthermore the liquid temperature at different locations may be different (for example if thermal stratification occurs), depending on the accident scenario causing the vessel rupture. In some cases, the tank rupture will not result in a BLEVE but in a two phase flow release, the tank remaining in one piece. Some authors, as for example Birk et al. (2007) performed BLEVE experiments and concluded that BLEVE explosions occurred at temperatures lower than SLT. Reid himself has observed (MCdevitt et al., 1990) that BLEVE may still occur but with less than 100% certainty if the initial temperature of the liquid is below the SLT.

Thus, Reid's theory is not applied nowadays to define a BLEVE. The definition of this type of explosion commonly accepted nowadays is "a BLEVE is an explosion resulting from the failure of a vessel containing a liquid at a temperature significantly above its boiling point at atmospheric pressure". Considering LPG, (Birk et al., 2007) state that "a BLEVE is the explosive release of expanding vapour and boiling liquid when a container holding a pressure liquefied gas fails catastrophically".

2.4. BLEVE hazards

Since water is not flammable, consequences that have to be feared from water BLEVE are mainly blast effects, fragments and a powerful dynamic force on the ground. To our knowledge, this latter point was never considered previously. This work will focus only on the blast effects.

When the vessel fails, there is a violent phenomenon consisting in the expansion of the pre-existing vapour and the partial flash vaporization of the liquid; the practically instantaneous increase in volume originates the explosion with an overpressure wave and, often, ejection of vessel fragments. The overpressure wave can be very high in the near field (Laboureur et al., 2015a). The way both phases contribute to the overpressure is still a subject of discussion. Among the existing models for predicting the peak overpressure of

Table 2
Experimental setup.

Vessel volume	14.17 L
Depressurization hole size	10 to 140 mm
Design pressure	120 bar
Design temperature	300 °C
Internal diameter	139.76 mm
Wall thickness	14.27 mm

Table 1
TSL of water calculated by different equations of state (Abbasi & Abbasi, 2007).

Equation of state	RK	VDW	SRK	PR	PRMC	TRK	B
TSL (K)	579.6	546.6	604.5	596.9	597.8	585.8	594.8
TSL (°C)	306.45	273.45	331.35	323.75	324.65	312.65	321.65

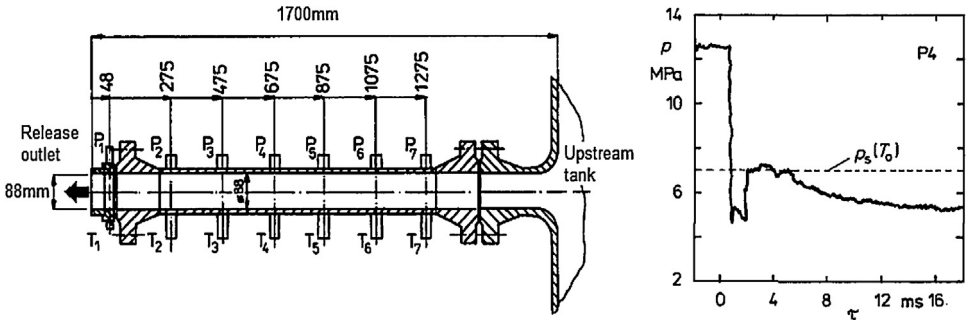


Fig. 3. Experimental prototype and experimental result (Bartak, 1990).

the explosion, some authors Prugh (1991) and Planas-Cuchi et al. (2004) have considered both contributions,; others Casal and Salla (2006) have considered only the contribution of the superheated liquid phase change; and finally, some others like Birk et al. (2020) have come to the conclusion that in the case of rupture of high pressure vessels only partially filled with pressure liquefied gas, the shock waves observed in the far field seem rather produced by expansion of the vapour and not by the vaporization of the liquid, which is said to be a too slow process for generating a strong blast.

Another question is the number of pressure peaks caused by a BLEVE. Laboureur et al. (2015) discussed BLEVE overpressures by comparing the data with data from literature. They highlighted that the first overpressure peak is followed by an underpressure of similar magnitude to the overpressure, caused by an overexpansion of the vapour flow. Then underpressure is followed by a second overpressure from the recovery of the vapour flow. A third overpressure is also observed afterwards, and believed to be caused by the flashing liquid.

Hemmatian et al. (2019) performed a thermodynamic estimation of the contribution of the liquid and the pre-existing vapour to the blast creation. They compared different ratios of vapour expansion and liquid flashing to data obtained with propane, the propane BLEVE being the most widespread type of BLEVE. Their calculations highlighted a larger energy release in case of water than propane (for same vessel and rupture pressure conditions). But these data are thermodynamics balance equations, not phase change dynamics ones. The way thermodynamic energy may be converted into blast is still a difficult question, depending on the vessel rupture pattern and the flashing wave dynamics.

2.5. Previous experimental work on water BLEVE

Scientific literature includes several papers about pressurized water releases (Alamgir and Lienhard, 1981; Barbone et al., 1995; Bartak, 1990; Chen et al., 2008, 2007; Eckhoff, 2016; Ivashnyov et al., 2000; Kendoush, 1989; Lenclud and Venart, 1996; Lin et al., 2010; Ogiso et al., 1972; Shmulovich et al., 2009). Most studies were performed at low superheated state, excepted (Bartak, 1990). Bartak (1990) cite other previous works, but since in all of them the experimental prototype was used with closed end they were not considered.

(Bartak, 1990) studied the loss of containment of superheated water that can occur during nuclear power plants accidents. Such situations are typical for pipe rupture accidents, which can occur in processing equipment and have to be taken into account, for example, in the design of nuclear power plants with water-cooled reactors. This kind of accidents is called a loss-of-coolant accident (LOCA). In that case, pressure falls from the initial pressure (~160 bar) to a value well below the saturation pressure corresponding to the initial temperature (~ 300 °C). The authors were mainly interested by the two-phase flow study and not the BLEVE event possibility.

Results are based on a series of 13 tests in a scale model of a pressurized water reactor and its internal structures. A 88 mm internal diameter pipe of 1700 mm long was connected to a tank on one side and to a system of double rupture disks on the other one. Data show that the rapid depressurization of hot water was stopped by explosion-like vapour generation in the superheated liquid, leading to a steep short-term increase in pressure followed by a relatively long period (from 10 to 100 ms) of quasi-static pressure (Fig. 3). The pressure overshoot was significant when initial temperature exceeded 240 °C. They observed multiple reflected pressure waves that perturb nucleation and pressure behaviour. The nucleation of vapour bubbles during the depressurization process was described successfully within the framework of homogeneous nucleation. The repressurization process was very limited and didn't lead to overcome initial or saturation pressure. No data was provided on the blast that could be created at the outlet of the setup.

2.6. Objectives of this work

Little data from historical surveys or from scientific literature allows understanding water BLEVE and which consequences have to be feared. Most previous works were performed on LPG, propane or refrigerants which behave differently than water (in terms of intermolecular bonds). Experiments performed with water were slightly superheated or data was missing.

This work aimed therefore to perform a perfectly controlled experiment of superheated water depressurization to collect data on phase change dynamics and blast formation. Both fundamental and practical data was expected:

- What is the depressurization rate in the vessel?
- Is there a repressurization, to which extend?
- If there is repressurization, what are the supplementary tangential and perpendicular forces applied to the wall?
- How many blast waves, which intensity, which decay (near and far field), what is the influence of the direction on the blast intensity?
- What is the speed and range of the two phase steam jet?
- What is the influence of filling level on previous points?
- What is the influence of discharge orifice area on previous points?

These questions as a whole aim to better understand water BLEVE.

3. Materials and methods

A heavy duty steel apparatus (700 kg) has been designed to heat water at high temperature and pressure, according to technical constraints aimed at enduring high pressure and enabling heating or

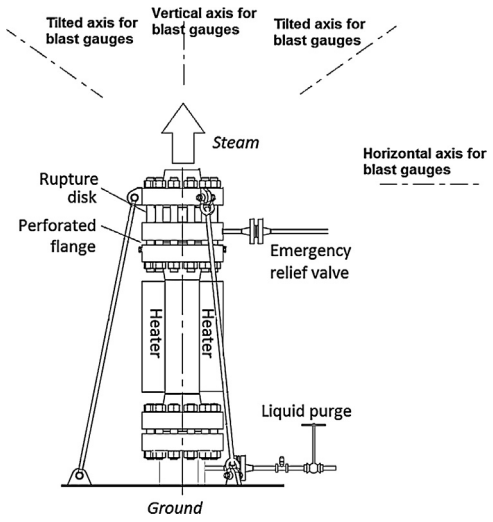


Fig. 4. Detailed sketch of the experimental vessel.

sensors fittings (Fig. 7). A tubular shape was chosen to offer large heating surface and good resistance to pressure. The bottom of the vertical tube was closed with a thick steel plate. When the pressure target was reached, pressure was relieved thanks to a perforated flange and a rupture disk located at the top of the vessel. Rupture disks nominal pressure was chosen to burst at 85 bar (T =300 °C) in order to reach Reid's superheat limit temperature criteria at the moment of rupture. Regrettably, the disks failed before the target pressure and burst at 76 bar (T = 290 °C), which is however in the range of KSL.

A set of perforated flanges was machined and could be replaced on the setup to vary the discharge orifice. Perforated flanges were set between the main body of the vessel (containing water) and the upper disk rupture (Fig. 5). This paper presents results obtained with flanges of different internal diameter, varying from 10 mm to 140 mm (tube internal diameter =140 mm). The specifications of the vessel are given in Table 2, a sketch of the apparatus is given in Figs 4 and 5.

Three water cooled dynamic pressure sensors (Kistler 601C) were set inside the vessel to measure the internal transient pressure in the vessel. Data acquisition rate was set at 250 kHz. Two static pressure sensors (TCSA 250 bar, 20 Hz) were put on pipes at a distance from the vessel and remained cold during the tests. A mesh of 24 thermocouples was put in the vessel to measure liquid, vapour and wall temperatures. A set of blast pressure sensors (PCB 137A23) was put around the vessel to measure the blast from BLEVE (Fig. 4):

- Four sensors were put above the discharge orifice at 103; 108; 118 and 128 cm from the rupture disk;
- Four other sensors were tilted 45° at a distance of 70 and 115 cm from the rupture disk;
- The four last sensors were located horizontally at 71; 215; 415 and 615 cm from the rupture disk.

The power of the heater was 20 kW, so almost one hour was necessary to reach the target water temperature (290 °C). The apparatus was completely insulated to minimize heat losses. Experiments were performed on a military facility and the technical team was protected in a concrete shelter. A Phantom V2512 high speed camera was used to record the vapour release and to capture the blast wave.

The experimental vessel was filled with an accurate quantity of water. The vapour space was initially filled with air at atmospheric

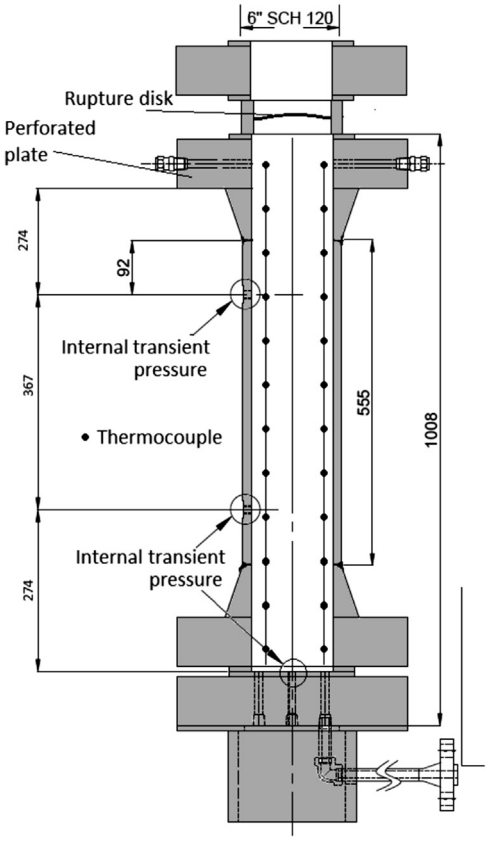


Fig. 5. Detailed sketch of the internal configuration and sensors location.



Fig. 6. Vapour jet released during the experiment.

pressure. When the vessel was filled and sealed, the heater was switched on. In order to purge the air, the relief valve remained open until water vapour was observed at the exit of the valve, approximately for 10 min. Then the valve was closed. A very small amount of water was lost during the air purge. During this operation most of dissolved gases were also removed. After about 50 min the rupture disk burst and a powerful blast was created. A two phase vapour jet was released at a height of ten to twenty meters (Fig. 6) with a loud noise. The blast pressure sensors located just above the release orifice were engulfed in the steam and were rapidly displaced by a mechanical system after explosion to avoid damaging of the sensor.

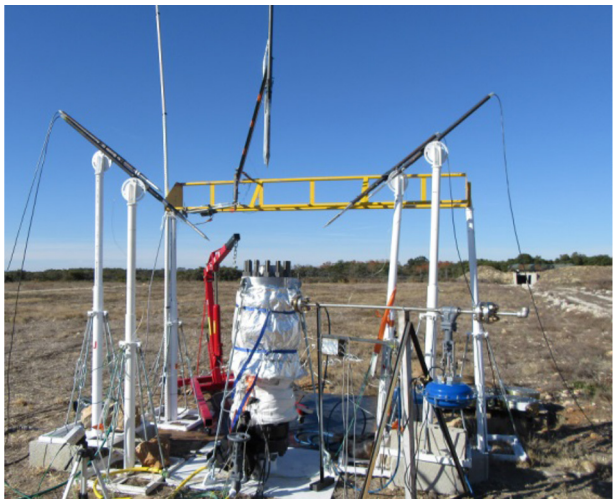


Fig. 7. Picture of the insulated vessel and blast sensors.

Background Oriented Schlieren (BOS) was used to visualize shock waves expanding out of the vessel. It consists in observing the deviation of the light (natural sunlight in this case) on a contrasted background. The light deviates from its straight path because of a variation of refractive index in the medium which through which it goes. In the case of explosion, the variation of refractive index is due to sudden density change from the shocks and pressure waves.

A proper visualization through BOS requires a background with strong contrasts. These backgrounds can be printed grid patterns. The scale of the experiment would have required a very large print, which was hard to set up because of outdoor windy conditions. Thus the natural background of the experimental site was used for the purpose. The deviation from the reference image requires a small numerical computation between the target image (on which the shock needs to be observed) and a reference image to be emphasized correctly:

$$BOSimage\,(i,j) = \frac{(target\,(i,j) - ref\,(i,j))^2}{\frac{(target(i,j)+ref(i,j))}{2} + 1} \quad (1)$$

where (i,j) are the x and y-coordinates of the pixels of the image. In the scope of this work, the reference image was the image right before the target image in the high speed imaging sequence. More details on principles and applications of BOS can be found in literature (Hargather and Settles, 2010).

4. Results and discussion

Many data were collected during the experimental campaign. Around 27 tests were performed in order to study the influence of filling ratio and rupture disk diameter. The following first part presents results aiming to describe and discuss what happened during a test. One specific test (liquid filling = 79%, outlet diameter =140 mm) was selected for that purpose. Then, the influence of filling ratio and outlet hole diameter on aerial overpressure are discussed.

4.1. Description of the phenomena

When the heating process was engaged, thermal stratification started in the liquid. After a while, boiling at the heating surface started and mixing due to free convection cancelled thermal stratification. Thus, most of the content of the vessel was homogeneous in temperature, to the exception of the bottom layer of 18 cm of the vessel, which could not be reached by the heating devices neither mixed through convection because colder than the top volume of the vessel. It was heated solely by diffusion through the metallic structure and from upper layers of fluid.

The homogeneous heated part of the fluid showed a perfect fit with the saturation curve of water (P–T diagram, Fig. 8). In the selected test, the rupture disk failed when internal pressure reached 76 bar at t = 38 min. Water temperature was 291 °C at this moment, which is above the KSL reported by (Abbasi and Abbasi, 2007b) but below all other kinetic or thermodynamic superheat limit data.

When the rupture disk failed, a powerful and noisy jet was created and reached 20 m high (Fig. 6). Pressure dropped swiftly in the vessel. It has to be not noted that pressure and temperature drop could not be recorded accurately by the low speed pressure and temperature acquisition system since the pressure drop and flash dynamics were too fast for these low acquisition rate data (20 Hz). Moreover, sheathed thermocouple thermal inertia (diameter =1 mm) does not allow measuring such fast phenomena. Last data before disk rupture and first data after disk rupture are given on Fig. 8. However the two points show that atmospheric pressure was reached within 50 ms, and the flash phase change cooled water below 140 °C. It can be estimated that the actual water temperature was 100 °C, in accordance with the flash theory. Accurate internal pressure data was recorded thanks to high speed pressure transducers and will be discussed later in this work.

A collection of frames from high speed camera is first presented. In the first frames, a white dome left the prototype at high speed with a large expansion cone shape (expansion angle close to 45°) (Fig. 9a). The cloud edges slowed quickly with ambient air friction and recirculation zones of the vapour cloud were observed. This allows thinking that the jet had low inertia and therefore contained little amount of small droplets.

This expansion slowed down progressively as internal pressure decreased (Fig. 9b). At time t =5 ms, boiling restarted to increase in the vessel and a second expanding diphasic bulge leaving the prototype was observed (Fig. 9c). The diphasic jet expansion was observed at maximum angle (expansion angle close to 180°) during 20 ms (Fig. 9d). Then the expansion ratio started to decrease again (Fig. 9e). At t = 52 ms, the global momentum of the jet was sufficiently low to let the local winds shift the plume (Fig. 9f). The experiment ended with slow rate boiling and buoyant steam plume during several minutes until most water was completely vaporized in the vessel.

It has to be noted that the time indications given on Fig. 9 are approximately zeroed, since rupture disk burst time is not exactly known. t = 0 was defined as the time of last picture before the jet was visible by leaving the vessel. A shift of several milliseconds may be expected between true zero (burst time) and estimated one. This arbitrary zero time was also used for high speed pressure data, synchronized with high speed camera.

The next data to be presented are aerial overpressures. Three sets of data are reported on Fig. 10: blast data measured on a vertical axis above the vessel, on a 45° tilted axis and on a horizontal axis at near and far distance (aiming to measure damage to humans).

Overpressure measurements along the different axes of measurements lead to almost similar profiles of pressure waves (Fig. 10):

- Vertical overpressures: these are the strongest overpressure measured (up to 1 bar at 1 m from the exit of the tube). Excepted the maximum overpressure of the first shock, there is little information to extract from these signals because the sensors were quickly engulfed in the hot diphasic jet, leading to unpredictable thermal shifts.
- 45° angle overpressures: They exhibit smaller overpressures, the pressure curve looks like a classic blast wave signal, because the

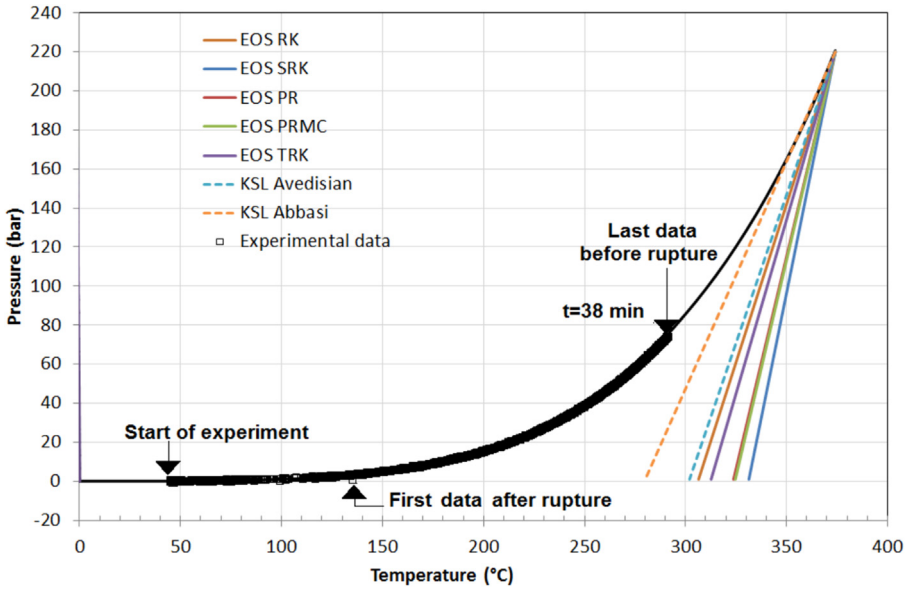


Fig. 8. Thermodynamic transformation on phase diagram (P,T) (fill = 79%, outlet diameter =140 mm).

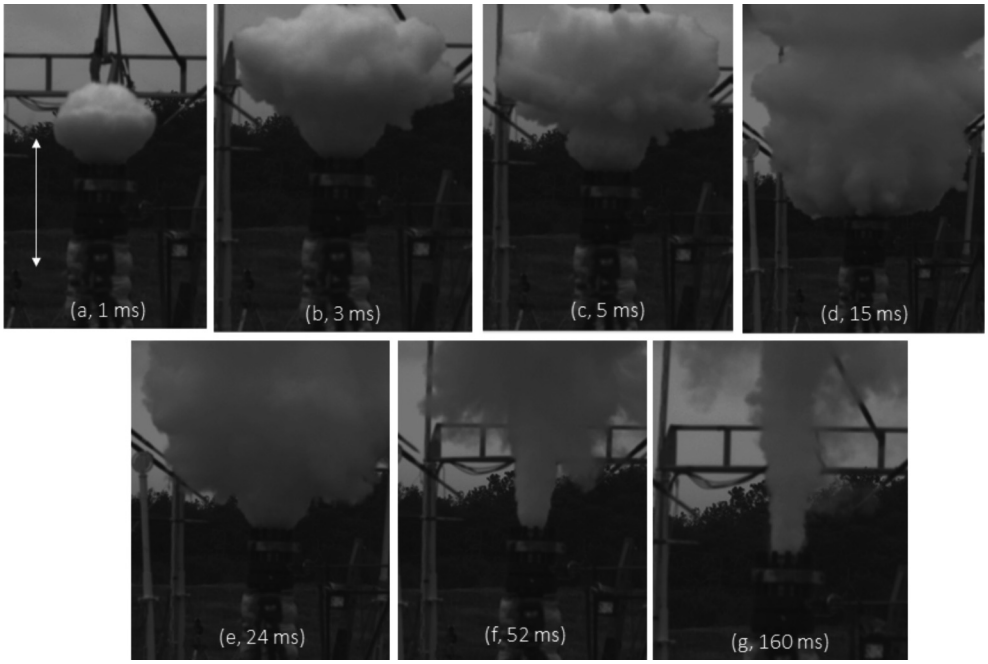


Fig. 9. High speed imaging of a water BLEVE (fill = 79%, outlet diameter =140 mm).

blast gauges remained out of the hot jet for the whole test. The first steep peak is followed by a negative pressure phase, and a second peak is observed 4 ms later. It has to be noted that two sensor axis were set, only one is given in Fig. 10.

- Horizontal overpressures: They show the smallest overpressures because they are measured perpendicular to the axis of the tube. They exhibit classical blast behaviour with a second shock as well. They allow also measuring the decay of the shock. The shock velocity averaged between the sensors decays from 370 m s^{-1} between first and second sensor, 364 m s^{-1} between second and third sensor, 357 m s^{-1} between third and fourth sensor and 345 m s^{-1} between the two furthest sensors.

When comparing pressure data between the different axes, it can be seen that the second pressure peak observed at tilted axis and horizontal axis cannot be seen on the vertical axis. We believe that the two phase jet and cloud mitigate the second shock before arriving to the sensors. Indeed, properties of water mists to mitigate blasts are well known (Jourdan et al., 2010).

Peak pressure numerical values are reported in the table embedded in Fig. 11. Data show powerful pressure peaks on the vertical and tilted axes. The pressure wave was very anisotropic since a factor of two can be observed between vertical and tilted axes at 1 m from the exit. A factor of almost 3 is observed between tilted and horizontal peak pressure at 0.7 m from the exit. The decay of blast intensity follow is very sharp (−2.388 power function) in near field on the vertical axis above the vessel, and a perfectly fitted (−1.035 power function) in near and far field on the horizontal axis (Fig. 11). Safety distance for people (50 mbar threshold) was about 4 m from the setup. It has to be noticed that the shock continued to built-up

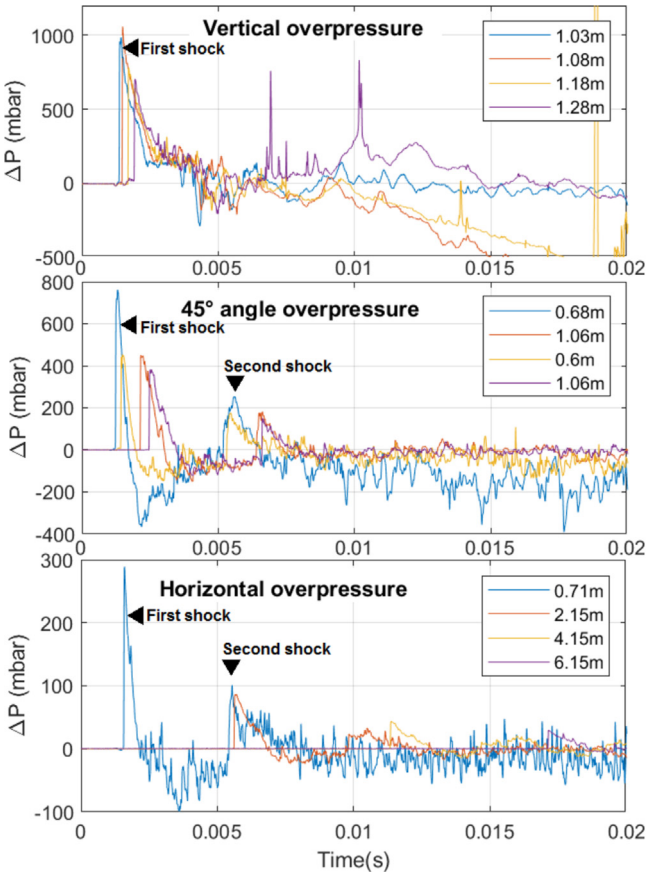


Fig. 10. Overpressure measured at different locations around the vessel opening.

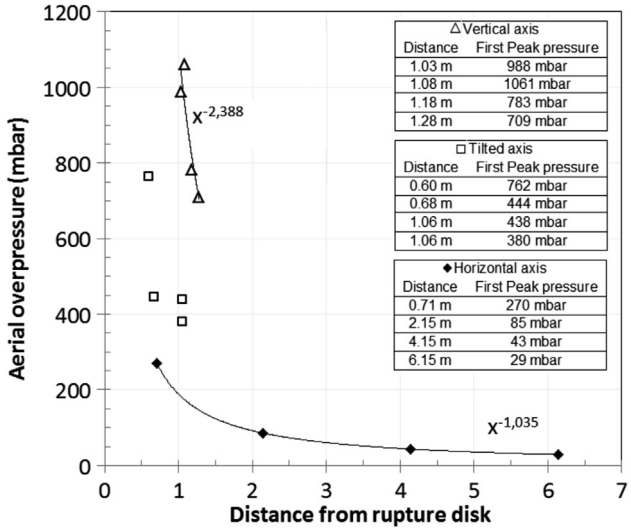


Fig. 11. Aerial overpressure peak values decay.

between the two nearest pressure gauges (d = 1.03 and d = 1.08 m) on the vertical axis between the two nearest data.

Shock waves corresponding to these measured pressure peak where observed by high speed imaging thanks to the BOS technique (Fig. 12). Blasts are clearly visible on the high speed camera movies due to light deviation (due to refractive index change of the compressed air in the blast wave), but cannot be seen on a still image. Thus they are emphasized with white lines on Fig. 12. Numerical treatment allowed creating a streak image of the shock propagation. To do so, a horizontal band of pixels where the contrast of

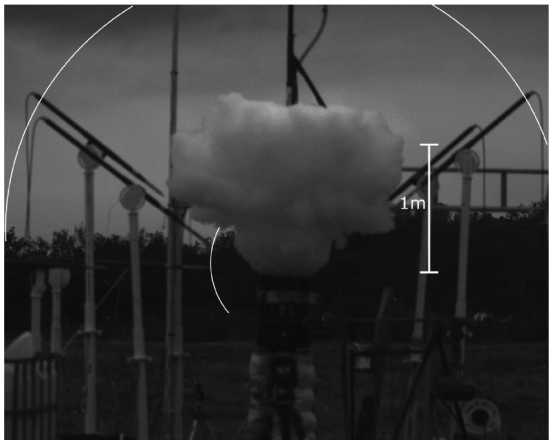


Fig. 12. High speed imaging of the cloud expansion and shock propagation (fill = 79%, opened diameter =140 mm, t =5 ms).



Fig. 13. Zone of interest for BOS calculation.

the background is maximal was chosen (Fig. 13). The method to determine streak miages is given in (Lauret et al., 2017). The BOS numerical treatment through Eq. (1) was performed on this band of pixels for 100 images after the steam cloud starts expanding out of the vessel. The result was averaged over the vertical width of the band of pixel, and a threshold was set to filter out the strong variations due to the presence of the cloud expanding from the prototype, and focus on the variations from shock propagation. The result in Fig. 14 exhibits clearly the two shocks appearing with a delay of 4 ms. The velocity of both shocks can be estimated through this streak image, with an average of 408 m s^{-1} for the first shock and 387 m s^{-1} for the second shock. These data are consistent with blast gauges measurements.

To understand what happened during and after the fast depressurization, synchronized data of pressure signals inside the vessel (internal) are compared to aerial overpressure measured outside (external) (Fig. 15). The external pressure signal was chosen on the tilted axis since no interference with the diphasic jet was expected. The distance between rupture disk and pressure gage was 68 cm. Three internal pressure gauges are reported: bottom position (z = 0 cm); mid position (z = 27 cm) and top position (z = 64 cm). Time axis of aerial overpressure was shifted to take into account wave propagation time. The comments are following:

- The fast initial internal pressure drop after failure presents a slight delay between the sensor at 64 cm of height and the sensor at the bottom of the vessel (Fig. 5). This corresponds approximately to the propagation time of the pressure drop wave between top and

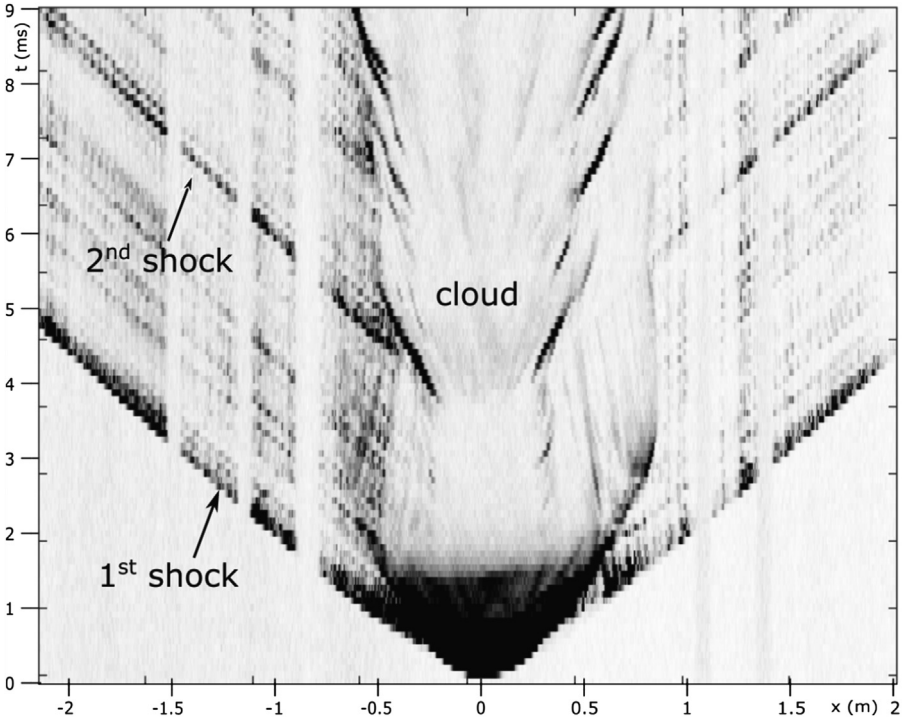


Fig. 14. Streak image of the BOS calculated on the horizontal row of interest for 100 successive images (fill = 79%, opened diameter =140 mm).

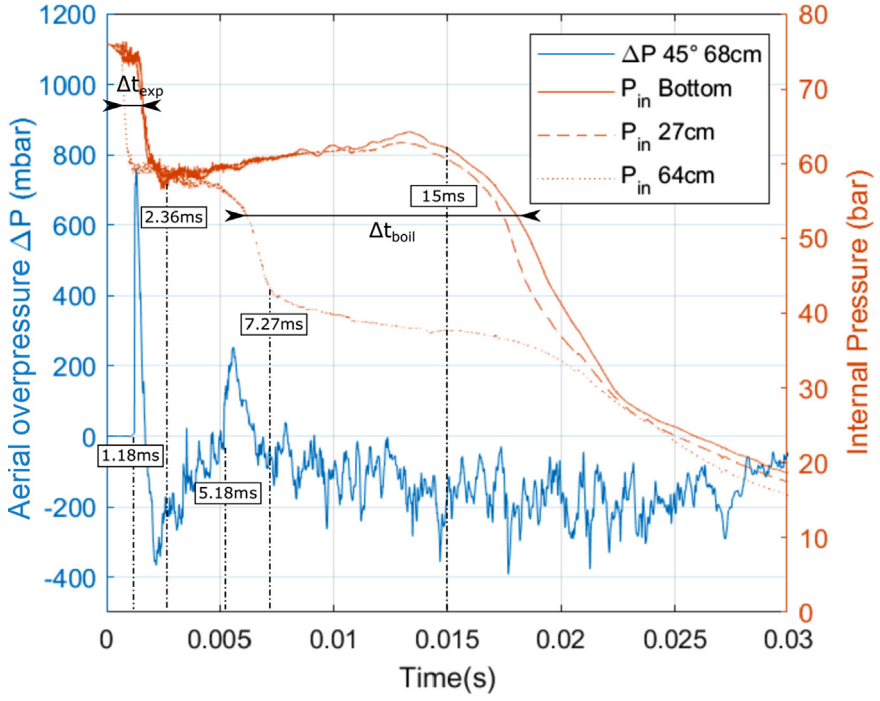


Fig. 15. External aerial overpressure (left) and internal transient pressure of a water BLEVE (fill = 79%, opened diameter =140 mm).

bottom sensors. The pressure drop lasted 1.45 ms, with a rate of 17 300 bar s^{-1}.

- t =1.18 ms: The first pressure peak measured on the tilted axis blast gage corresponds to a visible aerial overpressure (Fig. 9) just ahead of the initial cloud expanding out of the vessel. This shock was produced by the vapour release.
- t = 2.36 ms: Internal pressure stops decreasing at about 60 bar and starts slowly increasing again during 10 ms at the bottom of the vessel. The pressure build up mechanism due to violent boiling has started.
- t = 5.18 ms: A second aerial overpressure wave is measured on the blast gage 4 ms after the first one. The jet exiting the vessel starts widening significantly at this time, correlating the appearance of the shock with the mass flow increase out of the vessel.
- t = 7.27 ms: Boiling seems to stop after 2 ms at the top sensor. This apparent shorter boiling time is due to the fact that the liquid

level lowered because of water release: after 2 ms the sensor came probably out of the boiling zone.
- During the following phase, bottom pressure remains stable (with a slight pressure increase) at 60 bar, it can be assumed that boiling compensates pressure release. Top sensor pressure decreases slowly probably at choked flow conditions.
- t = 15 ms: The pressure at the bottom of the vessel restarts dropping. The diphasic jet is at its thickest outside of the vessel. The boiling wave reached the bottom of the vessel. This assumption allows estimating a boiling wave velocity between the two pressure sensors of 54 m s^{-1}. This is close to the ranges of 30–50 m s^{-1} observed in the literature (Birk et al., 2019).
- t =52 ms: The jet shrinks in size. The mass flow decreases at the exit of the vessel. At t = 160 ms, the jet escaping the vessel has almost no velocity.

Several conclusions can be drawn from these results:

- As claimed by Abbasi and Abbasi (2007a), the overall phenomena is very short in time and lasts less than 20 ms, the pressure drop lasts almost 1 ms.
- Pressure drop doesn't reach atmospheric pressure but stops at an intermediate pressure which results from rapid boiling and fluid discharge balance. This was also observed by Bartak (1990).
- Two aerial pressure peaks were observed; the first one fits perfectly with the vapour expansion timing; it ends before liquid boiling starts counterbalancing the internal pressure drop. The second pressure peak seems to match with the liquid boiling, but according to Laboureur et al. (2014), the second peak may also be an over-expansion followed by a recompression of the vapour space release. Two observations have to be highlighted on that uncertainty. The first is that liquid boiling keeps pressure in the vessel at intermediate level for a longer period of time than if not boiling had occurred (single pressure drop of pressurized vapour). This entails that boiling contributes to blast formation by sustaining a constant pressure in the vessel and therefore certainly to blast built-up. However, the second pressure peak ends before boiling has stopped. This could be due to the two-phase jet leaving the vessel. Indeed, large pressure fluctuations were measured after the first peak and reveal the disturbing effect of the two-phase jet leaving the prototype. This could have stopped the pressure build-up of the second pressure peak.
- Boiling during repressurization phase didn't lead to supplementary tangential and perpendicular pressure forces at the wall; pressure remained under the burst pressure.
- Data of internal pressure drop and blast data are consistent with the work of Birk et al. (2019) measured during a complete flattening of a small tank containing propane.
- Data are also consistent with Bartak (1990) and show a similar trend.

4.2. Influence of liquid fill level and available cross section area at exit

It can be expected that the liquid filling level and the available release cross section area are key parameters during the production of the blast wave. According to Birk et al. (2018), the first and main blast produced by a BLEVE is due to vapour expansion only. Liquid phase change contributes to secondary aerial overpressures but in a limited way. Other authors consider that liquid is the main energy source producing the blasts. Since the experimental setup of this work was able to repeat exactly the same burst and release orifice conditions, it was interesting to investigate the influence of liquid fill level on the blast intensity.

Another point of interest is the influence of the failure opening size during a BLEVE. The way energy is converted into blast

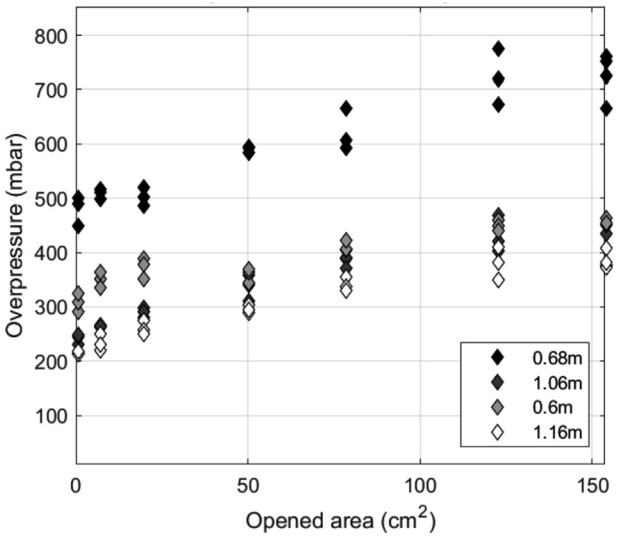


Fig. 16. Maximum overpressure from 45° angle probes as function of release area.

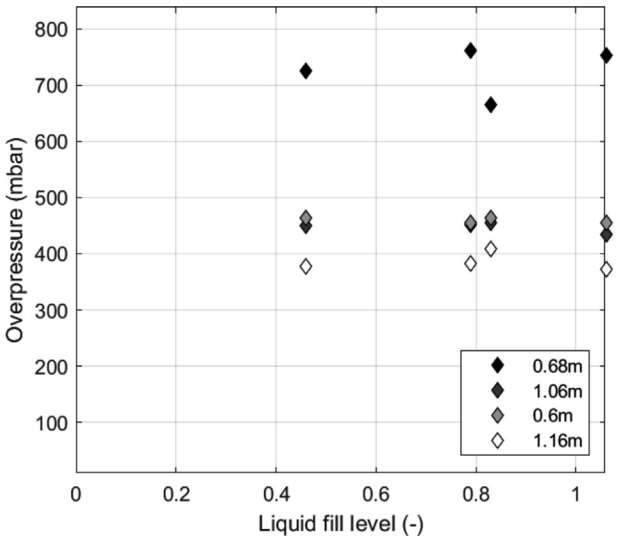


Fig. 17. Maximum overpressure from 45° angle probes as function liquid fill level for fully opened cross section (140 mm).

is certainly linked with the size of the outlet enabling the blast to be produced. This point is intricately linked with the considered scenario that triggered BLEVE. In other words, for two vessels containing the same amount of liquid and failing at the same temperature and burst pressure, will the blast be different according to the way both vessels failed? The experimental setup was able to investigate this point.

Figs 16 and 17 show the results of the comparison between maximum aerial overpressure of blast sensors located on the tilted axis and the failure parameters (liquid fill level and available cross section area at exit).

Firstly, considering the influence of outlet orifice area (Fig. 16), the trend is very clear: the larger the release area the stronger the blast. This shows clearly that geometric parameters influence blast production by vapour expansion. The way the tank opens will influence the blast intensity. To understand this effect, we have to go back to the way a shock is produced in a shock tube configuration. The shock is generated through piston effect; the flow chokes at the diameter restriction and contributes to the shock according to the available area to escape the pressure vessel. This is consistent with the shock start theory proposed by Birk et al. (2018).

In these experiments, none of known energy based models (Laboureur et al., 2014) would be able to reproduce the influence of opening size on aerial pressure peak. This doesn't mean that energy based model are wrong to calculate blast effects, but in case of partial failure of the tank the blast will be less than the calculated one by energy based models.

In fill level experiments, the release area was maximum (diameter 140 mm, which corresponds to an outlet hole area of 154 cm^2). The prototype was filled with three different amounts of water: around 5.5 kg; 9 kg and 11.5 kg. Thanks to the water temperature profile at burst time, liquid volume was recalculated taking into account thermal volume expansion of liquid. In some cases, the filling level at the time of rupture exceeded 100%: the main body of the vessel was completely fully filled with water, the excess liquid having flown in the space between perforated flange and rupture disk. Results show that blast intensity does not change with filling ratio (Fig. 17). This confirms that in these experiments, blast cannot be calculated from single energy calculations. If the blast intensity is supposed to be linked with the energy in the vapour phase, it should depend on the filling level. If the blast is supposed to be linked with the energy in the liquid phase, it should depend on the filling level. In our results, filling ratio doesn't influence the blast intensity which indicates that the blast is not only related on how much energy is contained in both liquid and vapour phases.

As explained in the previous paragraph, our experimental setup presents a shock tube configuration. Smaller exit cross section area leads to choking of the vapour content under the diameter change, making it ineffective in term of shock generation. Thus it decreases the strength of the lead shock. At constant opening, change in liquid fill fraction does not impact the shock strength. It is interpreted as follow: the flow is choked at the exit itself when the contraction gets close to maximum opened area. Thus larger vapour content below the contraction does not change the decay of the shock outside of the tube. The same behaviours were observed with blast gauges above the vessel as well as horizontally in the far field.

5. Conclusion

Several authors analysed past accidents involving superheated water explosions and concluded that water BLEVE occurred several times in history. Moreover, misunderstanding of BLEVE implied that many water BLEVE were not recognised as true BLEVE since no fireball appeared. This study aimed to perform experimental tests to improve knowledge of water BLEVE and to measure intensity of blast consequences. The following conclusions have been made based on the data presented. A first set of practical conclusions are:

i) Depressurisation of superheated water (290 °C, 75 bar) in the considered prototype produced a main aerial overpressure peak of severe intensity in front of the opening (1 bar at 1 m), with high anisotropy (400 mbar at 45° and 118 mbar perpendicular to the main direction). The pressure decayed sharply in the main direction and less in the perpendicular direction. The safety distance for people on the side of the vessel is 4 m (threshold of 50 mbar).
ii) The boiling two phase jet released by the vessel reached 20 m.
iii) The so-called explosive boiling in the vessel that followed depressurization did not create supplementary tangential and perpendicular pressure forces at the wall; pressure remained under the pressure at rupture time. As a consequence the vessel didn't explode.
iv) A guillotine rupture of a pipe without total destruction will reproduce a shock tube configuration. It can be expected that the blast effect will not be linked with the energy contained in the pipe but on the rupture orifice size and the internal pressure and temperature.

Other scientific conclusions may contribute to a better understanding of water BLEVE:

v) The first pressure peak was doubtless created by the pre-existing vapour expansion.
vi) A second peak was observed, it happened during intense boiling phase. This peak was lower in intensity but lasted longer that the first peak. Data doesn't demonstrate that this peak was due to liquid boiling or overexpansion of the vapour followed by a recompression of the released gas.
vii) Pressure drop following disk rupture didn't reach atmospheric pressure but stopped at an intermediate pressure level resulting from a balance between discharge and boiling; this intermediate pressure lasted 15 ms. After that, pressure dropped to atmospheric pressure at saturated temperature.
viii) Overpressure of the lead shock was positively correlated with the opening size, confirming its generation through piston effect of the vapour space. On the other hand, more vapour or liquid quantity did not affect blast intensity. Models based on single energy assumption are not suitable to this configuration.

One objective of this work was to determine whether or not water can undergo a BLEVE. To say it in other words, the question was not to know if a tank containing superheated water may explode (which could occurs without BLEVE), but to know if superheated water may boil explosively and contribute to tank destruction or consequences gravity (such as propane for instance). Experimental data show that water boiling had a clear effect on pressure drop in the vessel, keeping pressure at an intermediate level during 15 milliseconds. Time analysis shows that the second pressure peak occurred during liquid boiling, it can therefore be expected that liquid boiling contributed to blast build-up. This is however not a demonstration and supplementary work aiming to analyse all data collected in this experimental campaign will be required.

As said previously, BLEVE has no precise and unanimous definition. The most widely accepted definition is related to what happens and says that BLEVE is "an explosion resulting from the failure of a vessel containing a liquid at a temperature significantly above its boiling point at atmospheric pressure". Some authors require that the vessel has to be completely destroyed by the explosive boiling. In our tests, the vessel was designed to resist to a nominal pressure, and remained safe after intense depressurisation and repressurization. This could happen in industry when piping systems for instance are designed for a certain pressure. If such pipes would suffer accidentally rupture guillotine, can we expect a total failure of the pipe? To observe catastrophic vessel failure, an intense pressure overshoot seems to be necessary, but this was not observed in our results. The study demonstrated that the rapid phase change involved during our tests was not sufficiently intense to produce a strong internal pressure overshoot or to destroy the vessel.

Next work will try to use experimental data to better understand how fast boiling could produce a blast, and will try to model the blast using models from literature.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgments

The authors are grateful to Total SA for supporting this research work, to the Institute for Risk Science team (namely Zacaria Essaidi, Christian Lopez, Laurent Aprin, Florian Dizier and Clément Chanut) for their help during the testing campaign, and the Camp des Garrigues military camp for access to the facility.

References

Abbasi, T., Abbasi, S.A., 2007a. The boiling liquid expanding vapour explosion (BLEVE): mechanism, consequence assessment, management. J. Hazard. Mater. 141, 489–519.

Abbasi, T., Abbasi, S.A., 2007b. Accidental risk of superheated liquids and a framework for predicting the superheat limit. J. Loss Prev. Process Ind. 20, 165–181.

Abbasi, T., Abbasi, S.A., 2008. The boiling liquid expanding vapour explosion (BLEVE) is fifty . . . and lives on! J. Loss Prev. Process Ind. 21, 485–487.

Alamgir, M., Lienhard, J.H., 1981. Correlation of pressure undershoot during hot water depressurization. Trans. ASME.

Avedisian, C.T., 1985. The homogeneous nucleation limits of liquids. J. Phys. Chem. Ref. Data.

Barbone, R., Frost, D.L., Makris, A., Nerenberg, J., 1995. Explosive boiling of a depressurized volatile liquid. In: IUTAM Symposium on Waves in Liquid/Gas and Liquid/Vapour Two-Phase Systems., pp. 315–324.

Bartak, J., 1990. A study of the rapid depressurization of hot water and the dynamics of vapour bubble generation in superheated water. Int. J. Multiph. Flow 16 (5), 789–798.

Birk, A.M., Vandersteen, J.D.J., 2006. On the transition from non bleve to bleve. Trans. ASME 128, 648–655.

Birk, A.M., Davison, C., Cunningham, M., 2007. Blast overpressures from medium scale BLEVE tests. J. Loss Prev. Process Ind. 20, 194–206.

Birk, A.M., Heymes, F., Eyssette, R., Lauret, P., Aprin, L., Slangen, P., 2018. Near-field BLEVE overpressure effects: the shock start model. Process Saf. Environ. Prot., 116.

Birk, A.M., Eyssette, R., Heymes, F., 2019. Early moments of BLEVE: from vessel opening to liquid flashing release. Process Saf. Environ. Prot. 132, 35–46.

Birk, A.M., Eyssette, R., Heymes, F., 2020. Analysis of BLEVE overpressure using spherical shock theory. Process Saf. Environ. Prot. 134, 108–120.

Casal, J., Salla, J.M., 2006. Using liquid superheating energy for a quick estimation of overpressure in BLEVEs and similar explosions. J. Hazard. Mater. 137, 1321–1327.

Chen, S.N., Sun, J.H., Chu, G.Q., 2007. Small scale experiments on boiling liquid expanding vapor explosions: vessel over-pressure. J. Loss Prev. Process Ind. 20, 45–51.

Chen, S., Sun, J., Wan, W., 2008. Boiling liquid expanding vapor explosion: experimental research in the evolution of the two-phase flow and over-pressure. J. Hazard. Mater. 156, 530–537.

Eckhoff, R.K., 2016. Water vapour explosions - A brief review. J. Loss Prev. Process Ind. 40, 188–198.

Hargather, M.J., Settles, G.S., 2010. Natural-background-oriented schlieren imaging. Exp. Fluids 48, 59–68.

Hemmatian, B., Casal, J., Planas, E., Rashtchian, D., 2019. BLEVE: the case of water and a historical survey. J. Loss Prev. Process Ind. 57, 231–238.

Heymes, F., Aprin, L., Slangen, P., Lapébie, E., Osmont, A., Dusserre, G., 2014. On the effects of a triple aggression (fragment, blast, fireball) on an LPG storage. Chem. Eng. Trans., 36.

Heymes, F., Lauret, P., Hoorelbeke, P., 2019. An experimental study of water BLEV e. Chem. Eng. Trans. 77, 205–210.

Ivashnyov, O.E., Ivashneva, M.N., Smirnov, N.N., 2000. Slow waves of boiling under hot water depressurization. J. Fluid Mech. 413, 149–180.

Jourdan, G., Biamino, L., Mariani, C., Blanchot, C., Daniel, E., Massoni, J., Houas, L., Tosello, R., Praguine, D., 2010. Attenuation of a shock wave passing through a cloud of water droplets. Shock. Waves 20, 285–296.

Kendoush, A.A., 1989. The delay time during depressurization of saturated water. Int. J. Heat Mass Transf. 32, 2149–2154.

Laboureur, D., Heymes, F., Lapebie, E., Buchlin, J.M., Rambaud, P., 2014. BLEVE overpressure: multiscale comparison of blast wave modeling. Process Saf. Prog., 33.

Laboureur, D., Birk, A.M., Buchlin, J.M., Rambaud, P., Aprin, L., Heymes, F., Osmont, A., 2015a. A closer look at BLEVE overpressure. Process Saf. Environ. Prot., 95.

Laboureur, D., Birk, A.M., Buchlin, J.M., Rambaud, P., Aprin, L., Heymes, F., Osmont, A., 2015b. A closer look at BLEVE overpressure. Process Saf. Environ. Prot. 95, 159–171.

Lauret, P., Slangen, P., Heymes, F., Aprin, L., Lecysyn, N., Osmont, A., 2017. Natural background oriented Schlieren and multiscale visualizations of overpressure wave resulting from vapor cloud explosion. In: The 11th Pacific Symposium on Flow Visualization and Image Processing., pp. 2–7.

Lenclud, J., Venart, J.E.S., 1996. Single and two-phase discharge from a pressurized vessel. Rev. Générale Therm.

Lin, W., Gao, T., Gu, A., Lu, X., 2010. An energy fluctuation approach to calculate homogeneous nucleation rate in superheated liquids and its verification by performing an LPG rapid discharge experiment. J. Chem. Eng. Japan.

MCdevitt, C.A., Chan, C.K., Steward, F.R., Tennankore, K.N., 1990. initiation step of boiling expanding vapour explosions. J. Hazar. Mater. 25, 169–180.

Mengmeng, X., 2013. Thermodynamic and Gasdynamic Aspects of a Boiling Liquid Expanding Vapour Explosion. TU Delft.

Ogiso, C., Takagi, N., Kitagawa, T., 1972. On the mechanism of vapor explosion. Proc. Loss Prev. Saf. Symp., 233–240.

Planas-Cuchi, E., Salla, J.M., Casal, J., 2004. Calculating overpressure from BLEVE explosions. J. Loss Prev. Process Ind. 17, 431–436.

Prugh, 1991. Quantitative evaluation of BLEVE hazards.pDf. J. Fire Prot. Eng. 3, 9–24.

Reid, R.C., 1979. Possible mechanism for pressurized-liquid tank explosions or BLEVE's. Science 203, 1263–1265.

Reinke, P., 1997. Surface Boiling of Superheated Liquid. Rapport de l'Institut Paul Scherrer, Villigen, Suisse.

Shmulovich, K.I., Mercury, L., Thiéry, R., Ramboz, C., El Mekki, M., 2009. Experimental superheating of water and aqueous solutions. Geochim. Cosmochim. Acta 73, 2457–2470.