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Experimental Study of Expanded Aluminium Products Efficiency for BLEVE Suppression

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A boiling liquid expanding vapour explosion is an explosion caused by the rupture of a vessel containing a pressure liquefied gas above its boiling point. When the pressurized liquid is suddenly released from its containment, it will change phase from liquid to vapour violently to produce a BLEVE. Possible effects are blast waves, projectiles and a fireball if flammable. Different technological devices aim to reduce the occurrence and gravity of a BLEVE. Among them, pressure relief valve (aiming to control pressure increase) and thermal insulation (aiming to reduce wall temperature) are commonly used. Expanded aluminium packings are sometimes believed to reduce the risk of a BLEVE, by conducting the heat out of the vapour space wall and convecting it into the vapour and thereby reduce the wall temperature in that area. This technology is promoted by manufacturers, but there is today no proof of its effectiveness. This work aimed to provide experimental data to understand the thermal kinetics of this technology.

1. Introduction

Packings made from expanded aluminium (EA) have been successfully used for explosion suppression in fuel tanks (Szego et al., 1980). The expanded aluminium (EA) consists of a thin aluminium foil that is sliced, stretched and stacked or rolled to produce a highly porous matrix of low-density expanded aluminium. This matrix can be inserted into a tank and it only takes up 1–3 % of the tank volume. Some EA manufacturers claim efficiency for Boiling Liquid Expanding Vapour Explosion suppression (BLEVE).
BLEVE happens if a pressure vessel holding a pressure-liquefied gas (PLG) fails catastrophically. A PLG is a substance that is normally a gas at ambient temperature and pressure but is stored and transported as an ambient temperature liquid under pressure. Propane is a very common PLG used in our society. If this pressurized liquid is suddenly released from its containment, it will change phase from liquid to vapor violently to produce a BLEVE. A BLEVE can cause blast waves, and in certain circumstances projectiles and/or a fireball (Heymes et al., 2013).The PLG may also be toxic (examples are chlorine or anhydrous ammonia). The failure of the pressure vessel may be caused by severe vessel weakening by corrosion or by a major flaw or by fire impingement (Heymes et al., 2014).. Or a failure can be caused by a severe external impact of some kind (i.e. collision, external explosion, etc.). It can also be caused by an uncontrolled pressure rise in the vessel. Or it can be caused by a combination of all of the above.
If a PLG tank is impacted by fire impingement, the BLEVE may be caused by weakening of the pressure vessel by high temperatures in the vapour space wall (Birk et al., 2013). Even if the PRV is working properly to control the vessel internal pressure build-up, the pressure vessel can still fail due to reductions in the wall material strength at high temperature. According to the literature, is it possible that the EA could provide the following benefits to systems that can suffer a BLEVE (Birk, 2008):

- Possible cooling effect on vapor space wall by surface area enhancement.
- For near full PLG vessels, the expanded metal matrix may act to promote boiling and two phase swell during pressure relief. During the early minutes of the fire, the swelling liquid could wet the pressure vessel upper wall surface to maintain lower temperatures and this may delay failure of the pressure vessel until the vessel empties.

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- The EA may affect the PRV temperature and this could cause enhanced spring relaxation that could reduce the pressure in the vessel. This too could delay failure because it could result in lower wall stress.
- The EA may mitigate liquid impact forces and crack tip cooling during the failure of the vessel and this may suppress total loss of containment. Total loss of containment is needed for a BLEVE to take place.
- The EA may mitigate the blast overpressure hazards from a BLEVE, if a pressure vessel does fail due to fire engulfment. It is possible that the EA will slow the opening of the vessel and this could suppress the formation of a shock

The first point could delay vessel failure in a fire: it only takes a small decrease in wall temperature to change the failure time by several minutes. In some cases, even a few minutes delay of failure could lead to the vessel emptying safely through the PRV before the vessel ruptures (Birk et al., 2006). The EA engineers thought the aluminium matrix would conduct the heat out of the vapour space wall and convect it into the vapour and thereby reduce the wall temperature in that area. A heated bare wall exchanges heat at internal side by two ways: natural convection and radiation. If the tank is completely or partially filled with expanded aluminium, heat can be moreover transferred by conduction through the net (Figure 1).

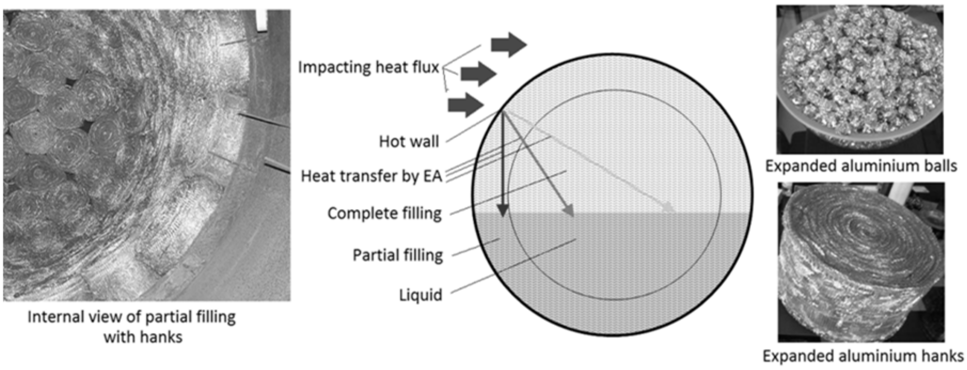

Figure 1: Expanded aluminium configurations and assembly in a reservoir

Aluminium is usually chosen because of its excellent conduction capacity and low density. Natural convection and radiation are modified by the presence of this mesh. If it is clear that natural convection at the wall will decrease because the vapour circulation will be lowered by the porous structure of the mesh, it is not easy to know how the radiation will be affected. Radiation is reflected many times by the reflective surface of the packing and may be reflected back to the tank wall. Another point is that EA has to be put tightly in contact with the tank wall in order to reduce heat transfer contact resistance.

However, quite no scientific work was undertaken in order to study this principle. (Appleyard, 1980) performed several medium scale tests (980 L), but according to (Birk, 2008), no data from these tests showed conclusively that the EA saved the pressure vessels from failure. In the engulfing fire tests, one of the unprotected pressure vessels suffered a BLEVE and the other unprotected pressure vessel suffered a fish mouth rupture. The EA equipped pressure vessels did not fail at all, and safely vented to empty through the pressure relief valve (PRV). The fire test results suggested that EA suppressed BLEVEs. However, further analysis suggests that variable fire conditions could also explain the non-BLEVE outcomes in the tests. (Venart et al., 1985) performed lab scale in order to determine thermal properties of a commercialized EA with different styles, orientations and thicknesses. But he didn't conclude about a theoretical efficiency about EA in real case scenarios. In conclusion, this question remains today and further research is needed before EA can claim to be a BLEVE suppressor. This work aimed to provide data to better understand how EA behaves when a pressure tank is exposed to an external fire. Two sets of experiments were performed. The first set was performed at lab scale in order to measure thermal properties of the EA in various configurations. The second set was performed at large scale in order to avoid scale effects in the EA efficiency investigation.

2. Materials and methods

2.1 Description of the expanded aluminium net

The protection systems constituted by EA are usually available as balls made by thin aluminium (thickness [55-68] μm). In this study, two configurations of expanded aluminium (balls and hanks) were selected and presented in Figure 1. Density of this EA varied in the range [40 - 65] g/L depending on the configuration, the

corresponding porosity varied in the range [1.4 - 2.2] %. The surface exchange was quite high (5,924 cm² per litre that is 164 times greater than the surface of a cube equitable heavy).
A tank can be filled entirely by EA or only on a layer close to the wall. Some manufacturers propose to put in place a covering with a thickness of 200 mm. For particular tanks where it could be difficult to install the hanks, the protection of the tanks is gotten with balls of around 2 cm of diameter using a maintaining mesh.

2.2 Small scale experiments
Conduction can be calculated through the net if heat transfer contact resistances are known. But convection and radiation are very difficult to calculate. Therefore experiments were performed at lab scale in order to determine apparent conductivity. Different configurations were tested: one with balls and two others with different hanks orientations (Figure 2). The main difference in both hanks configurations is the orientation of the major axis. In hanks#1 the heat is transferred in the major axis direction whereas in hanks#2 the heat is transferred perpendicular to the major axis. Two columns (H = 0.2 m, D=0.65 m) were made by EA and insulated on the side of the cylinder with 5 cm glass fibre. An aluminium plate was put on the top of the columns (pressure = 50 kg/m^2). The plate was uniformly heated by an epiradiator at a steady state temperature of 350°C. The bottom of EA column was in contact with water (100 g), contained in an insulated reservoir. Temperature of the water and steady state temperature profile across the EA sample were measured to determine the apparent thermal conductivity excluding the effect of contact conductance.

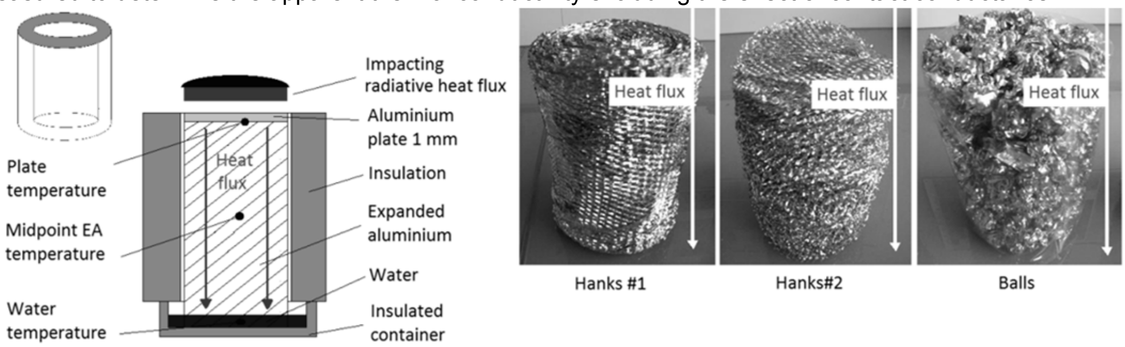

Figure 2: Lab experiments to determine thermal conductivity

2.3 Large scale experiments
Efficiency of EA depends on geometric considerations since the heat transfer depends on the thermal pathway. This point was investigated at real scale. Large scale experiments were performed in order to test the efficiency of EA. A 22 m^3 pressure tank was filled with 7.5 m^3 of water, which corresponds to a 34 % filling (diameter of the tank 2.4 m). The level of water can be observed by IR picture on Figure 3. The mixture was excess air resulting in a complete combustion and a colourless flame. The instrumentation was required to provide several data such as internal wall temperatures, fluids temperature and pressure. A mesh of 24 K type thermocouples was fixed inside at the wall by discharge welding. 2 K type thermocouples were put in water and 2 other ones in vapour.

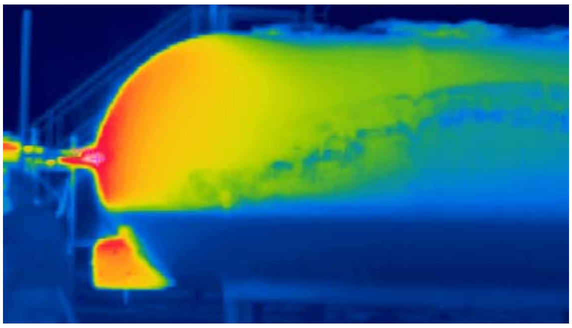

Figure 3: IR picture during test

Three tests were performed in order to compare the behaviour of the tank in case of no EA (test 1); partial filling with hanks #1 configuration (test 2) and complete filling with hanks #1 configuration (test 3). In case of partial filling (200 mm thick layer), the temperature of EA in contact with the vapour space was also recorded.

In addition with the wall temperature, temperature gradient is therefore evaluated. Experiments lasted more than 70 min with a constant gas supply. It has to be noted that test 3 was performed with a higher propane flow rate in order to increase the impacting heat flux.

3. Results

3.1 Heat transfer conductivity measurement at small scale

Water temperature (Figure 4) and steady state temperature profile across the EA (Figure 5) sample were measured in order to calculate the heat flux transferred to the liquid and the apparent thermal conductivity, excluding the effect of contact conductance (Table 1).

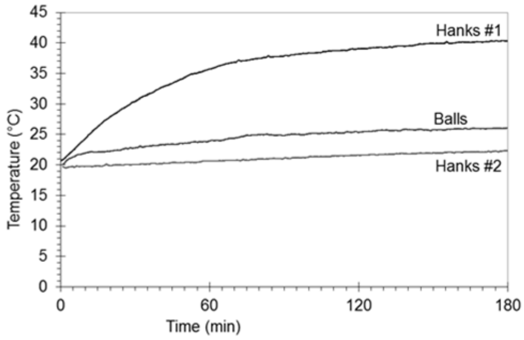

Figure 4: Water temperature

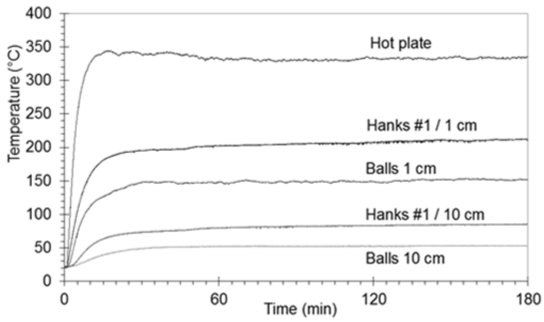

Figure 5: Hot plate and EA temperatures

Table 1: Apparent thermal conductivity of expanded aluminium

Configuration	Heat flux $W.m^{-2}$	Apparent thermal conductivity $W.m^{-1}.K^{-1}$	Venart $W.m^{-1}.K^{-1}$
Hanks #1	210	0.774	0.450
Hanks #2	9	0.074	0.200
Balls	20	0.102	---

Accordingly, the apparent conductivity of the hanks#1 configuration was significantly higher than other cases. This is attributed to the fact that other configurations present multiple thermal contact resistances between balls or sheets and decrease apparent thermal conduction. Data measured by (Venart et al., 1985) on Explosafe EA were also reported for comparison. It appears that in hanks#1 configuration, the apparent thermal conductivity measured by Venart et al. was significantly lower than the data provided by this work. Operating conditions of Venart et al were different; they performed tests at a lower temperature than in this work and thickness of aluminium varied too. In case of hanks #2 configuration, Venart et al measured higher apparent thermal conductivity. The pressure applied to the stack of sheets was different: 0.49 kPa in this work and more than 2 kPa in case of Venart et al work. Pressure applied on the EA against the wall plays a key role, when applied pressure increase contact resistance decreases, with an additional effect on overall EA compactness. These results show that apparent thermal conductivity of EA depends strongly on many parameters: aluminium thickness, configuration, applied pressure and the way of installation in the tank. Considering all data from this work and from Venart, apparent thermal conductivity of tested EA varies in a [0.102 – 2.60] $W.m^{-1}.K^{-1}$ range which is more than one order of magnitude.

Some engineering considerations reveal that on the basis of previous results, efficiency of EA seems not to be very high in transferring heat. If we consider a partial filing, with a thickness of 20 cm of EA, the thermal resistance varies in a range [0.077 – 1.96] $m^2.W^{-1}$. K. This range of thermal resistance can to be compared with natural heat convection resistance on a bare surface in vapour phase. Convection coefficients of gaseous LPG depend on the level of filling and pressure relief valve flow rate (if open). Some authors reported that these coefficients may vary in a range of [1.5 – 35] $W.m^{-2}.K^{-1}$ range (Birk, 2000) and therefore the corresponding thermal resistance varies in a range [0.03 – 0.7] $m^2.W^{-1}$.K, which is half of the range calculated with EA. Large scale experiments were therefore performed in order to investigate EA efficiency in real size.

3.2 Large scale investigation

Figure 3 shows an IR picture of the impinging flame at the end of the tank. A colour distribution of wall temperatures shows the effect of the jet on the tank, with a clear difference between vapour space wall temperature and wetted wall temperature. Note that the colour scale of thermography picture was removed because it was meaningless since the emissivity of the tank surface changed with time and was unknown. The internal temperature at hottest point is reported on Figure 6. Data show that there is quite not difference in wall maximum temperature with a partial filling of EA and without this device. However, a clear time shift (16 min) can be seen between both curves. Some data like wind velocity were missing, so it was not possible to explain that time shift. The fuel flow rate was identical and vapour space wall temperature rose for both experiments to quite 600 °C (Table 2). This temperature is very high, and exceeds the safety value recommender by the American Petroleum Institute (427 °C).

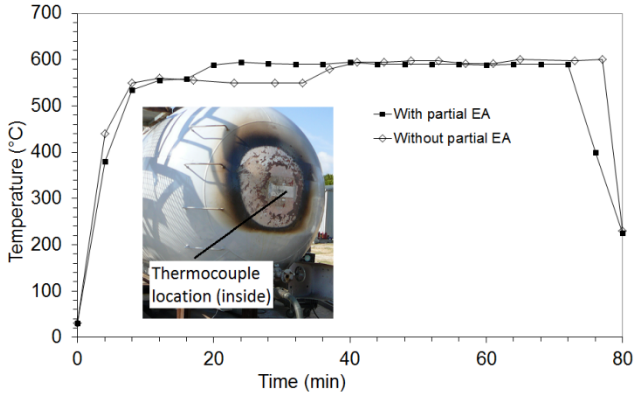

Table 2: Maximum wall temperature

Test	Filling	Fuel flowrate kg/min	Max wall temperature °C
1	Empty	0.64	598
2	Partial	0.69	600
3	Complete	1.68	780

Figure 6: wall max temperature with partial filling or empty tank

Vapour and liquid temperatures are reported on Figure 7. Water temperature remained low, at 30°C. No significant difference between the three cases is observed, showing that no significant energy was transferred to the liquid by the partial or complete filling with EA. Considering vapour space, an identical increase of temperature was observed for all tests, with a maximum at quite 100 °C. This is consistent with tests in laboratory which let thinking that EA thermal conductance is quite similar to natural convection alone.

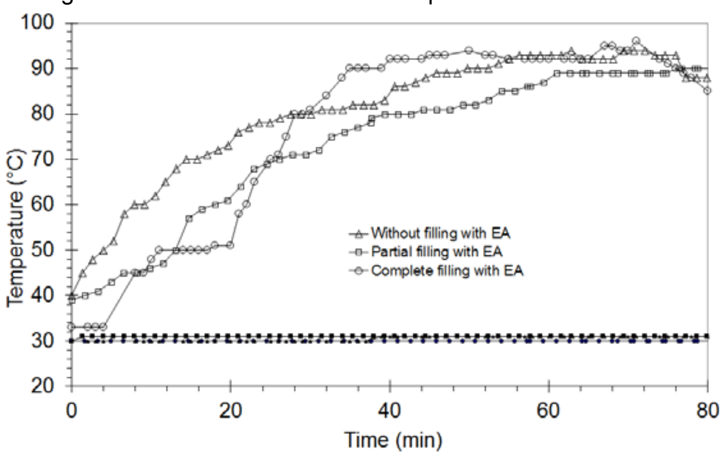

Figure 7: vapour and liquid temperature in the three tests

Figure 8 shows two temperatures: the hottest sport at internal wall surface and the corresponding interface temperature between EA and vapour. Since the thickness of EA was 20 cm, and using the apparent thermal conductivity determined in lab tests, heat transfer can be calculated and is also reported on Figure 8. Data show that a maximum heat flux occurred at the beginning of the test. The burner heated the wall quickly and inside air was very cool. This calculation assumes a perfect heat transfer between EA and vapour. The maximum heat flux was 214 W/m^2, which is consistent with data recorded at laboratory scale. This heat flux is very low compared to the impacting heat flux.

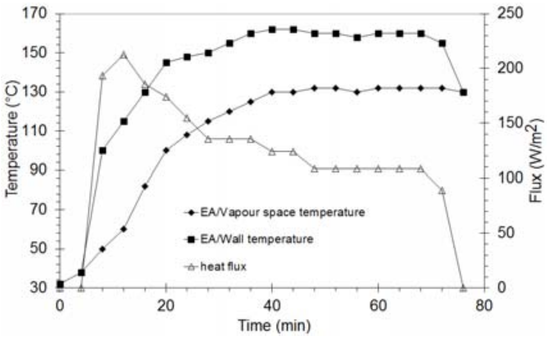

Figure 8: Temperature profile in EA and heat flux

Figure 9: View of altered aluminum

Test 3 was the more severe test; the wall temperature rose to 780°C. Examination of EA after test showed that this high temperature altered aluminium, increasing heat transfer contact resistance.

4. Conclusions

Some manufacturers claim that expanded aluminium packings could reduce the risk of BLEVE by transferring heat from hot wall to the liquid phase. This study provided several data showing that heat transfer from wall to vapour or from wall to liquid is quite low. No significant gain of wall cooling effect was observed. This is due on one hand to the very thin aluminium of EA, which creates weak thermal bridge. On another hand, there are several contact resistances depending on the pressure applied.

Real scale tests were performed without specific attention to have a best thermal contact of EA with the wall. The results could be explained by a bad contact resistance between EA and the wall. But this is a reallistic case and could occur in real EA equipement.

Other points have to be considered. It is also possible that the EA could make things worse at certain scales and conditions. For example, the matrix could provide a huge area for boiling nucleation and this could enhance the pressure transient during failure if the pressure vessel suffers a finite rupture. This could make the difference between a BLEVE and a non-BLEVE finite rupture with jet release. Another consequence of EA could be that at high temperature after vessel failure, the EA could worsen the fire intensity since aluminium is flammable and the combustion is highly exothermic.

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