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A Discussion on the Risks Associated with Water Filling of Propane Tanks

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The events in March of 2011 in Japan have provided us with an example of what can happen when a LPG sphere filled with water is exposed to an earthquake (Birk et al., 2013). A sphere was filled with water to prepare an inspection. The main earthquake shock caused several of the diagonal braces that were supporting the tank legs to fracture. During the after-shock, some legs holding up the tank bent and the tank collapsed, severing LPG pipes and resulting in leakage. The leak ignited and spread to the adjacent spherical tanks stocking liquefied butane and butylene. The rapid development of the fire caused the fall of most tanks (broken foot support) and a cascade of BLEVE (boiling liquid expanding vapor explosion).
There is another issue. What could have occurred if another propane tank filled with water had been exposed to fire? Is there a risk that the tank suffered a BLEVE? This paper deals with the risks associated with earthquake and fire which may be a secondary effect of the earthquake.

1. Safety during water filling of propane tanks for inspection

Propane tanks are pressure vessels that require periodical inspection and certification according to standards such as API 510 or EN 12819. A series of tests must comply with standards, such as ultrasonic/radiographic tests, magnetic particle or penetrant tests, hydraulic tests, paint thickness tests, leak detection. In case of internal inspections, it is necessary to drain the propane and remove vapor before entering the vessel. This can be achieved by filling the vessel with water, ensuring that no propane remains in the vessel before inspection.
Another reason to fill a tank with water is pressure resistance testing. The preferred method in the standards is the hydraulic method rather than the pneumatic method. In the latter, the energy available is large and any failure during the test is likely to be highly explosive. For a hydraulic test, the fluid is usually water, but other liquids may be utilized instead if necessary. The reasons are generally that the vessel and the structure cannot withstand the weight of water, that the water may be difficult to remove completely or that it may freeze.
Filling a vessel with water requires various precautions. Checks should be made on the effects of static head, on the ability of the vessel and the structure to withstand the weight of water. In case of pressure testing, the hazard of brittle fracture should be considered. In order to avoid the risk of freezing, the temperature of the water should be not less than 7°C. If water is used with austenitic stainless steel, it is essential to control the chloride and alkali content. These points are related to normal procedures. The following parts will consider the risks associated with accidental conditions such as earthquake or fire. Others risks such as flooding, aggression by fragments or a blast are not discussed in this paper but are discussed in (Heymes et al., 2014) and (Landucci et al., 2014).

2. Safety of a tank filled with water during an earthquake

The API 2510 standard for propane pressure vessels states that the supporting structure of the vessel should consider the static load during operation (including the load of fireproofing), plus applicable combinations of wind, ice, snow and earthquake loads. The structure shall also bear the static load during water testing + 25% of the wind, ice and snow loads. However, the case of the Tohoku earthquake in Japan highlighted the fact

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that during an earthquake, the complex interactions between the earthquake and the structure led to a catastrophic collapse of the vessel.
The effects of an earthquake may be classified as direct or indirect. The direct effects include ground shaking; ground lateral displacement; ground lift up and subsidence. An indirect effect that may impact a vessel is soil liquefaction (Cubrinovski et al., 2001). This part considers only the effects of shaking.
Static behavior
An empty or a completely full storage sphere behaves like a solid structure without any fluid motion (static behavior). The response of the tank and lading to the vibrations induced by the earthquake depends on the design of the structure (mass distribution, steel properties). Numerical simulation of structural dynamics allows calculating the loads and spectra of resonance frequencies.
A sphere is a supported structure which differs from ground based tanks due to the flexibility of legs and braces. Only few works focused on the behavior of elevated spherical tanks (Curadelli et al., 2010). This requires performing non-linear modeling of the structural components. According to Den Hartog (Den Hartog, 1956), the natural frequencies of the vessel may be approximated by the equation:

$$f = \frac{1}{2\pi}\sqrt{\frac{2k_e}{m_e + 0.23km_l}}\sqrt{1 - \frac{P_0}{P_{cr}}} \quad (1)$$

Where f is the natural frequency of the vessel, k_e is the shear stiffness of one leg, m_e is the vessel and lading mass, m_l is the mass of the legs. This approximated equation shows that the natural resonance frequency of the filled vessel will decrease when filled with water instead of propane.

2.1 Dynamic behaviour

This part considers partially filled vessels. During an earthquake, the free-liquid surface dynamics interacts with the supported elastic-structure dynamics. Indeed, if the base of the supporting structure moves, the fluid container experiences motion in a certain trajectory governed by the excitation and the liquid response. The free-liquid surface motion exerts hydrodynamics forces that are fed back to the supporting structure. This sloshing effect is represented on Figure 1, extracted from (Curadelli et al., 2010). The interaction is critical when the liquid sloshing modes are coupled with the support structure dynamics though inertia non linearity.

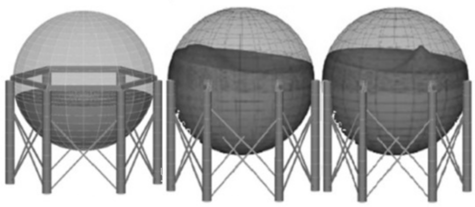

Figure 1: Still and sloshing behavior of the lading during earthquake

Table 1: Physical properties or water and propane (20°C)

Commodity	Liquid Density $Kg.m^{-3}$	Saturated vapour density $Kg.m^{-3}$	Liquid Viscosity mPa.s	Density ratio DR
Water	1000	0.005	1.08	$1.74x10^{-5}$
propane	529	10 kg.	0.12	$3.6x10^{-2}$

The sloshing results in two types of dynamic pressure: the impulsive and convective pressures:

- Impulsive pressures are rapid pressure pulses due to the impact between the liquid and the solid surface. Such impulsive pressures are much localized and extremely high pressures. They are usually associated with hydraulic jumps and traveling waves.
- Convective pressures are the ordinary dynamic pressures in an oscillating fluid. They are slowly varying pressures that result from standing waves. The most severe impact pressures occur near the still water level or at the abrupt intersections of the tank walls.

For a given liquid depth/tank width ratio and frequency of oscillation, sloshing pressure is in general proportional to the specific weight of the liquid, linear dimension of the tank and amplitude of excitation of the tank. Some authors propose to use the density ratio DR, defined as the ratio between the gas density and the liquid density. This ratio has a significant role as described by (Rafiee et al., 2010). (Zou et al., 2015) highlighted that viscosity plays a role on the sloshing phenomena.
The design codes such ASCE Code and Eurocode do not provide methods for the calculations and consideration of sloshing effects on spherical tanks (Wieschollek et al., 2011). Since the physical properties of water and propane are very different (Table 1), the response of the structure to the earthquake will be different in terms of loads, pressures and resonance frequencies. Thus a cautious design of the supported vessel resisting to earthquake with two liquids as different from each other such as propane and water is required to avoid any collapse.

3. Safety of tank filled with water and engulfed in fire

When a pressurized tank containing a liquid lading is exposed to external fire, there is a chance to have a boiling liquid expanding vapor explosion (BLEVE). The BLEVE is defined as the explosive release of expanding vapor and boiling liquid when a container holding a liquid gas fails catastrophically. For the BLEVE to occur, this vessel must be heated for example because of the heat radiation emanating from a nearby fire (Heymes et al., 2013). Once the vessel is being heated, the pressure within the vessel will rise, until the pressure relief valve operates and begins to release the liquid vapor. Then the vessel may fail. This is because vessels are designed to withstand the relief valve set pressure, but at the design temperature. If the metal is heated in excess of the design temperature, the metal will lose strength and eventually rupture. When a vessel fails, there is instantaneous depressurization. The liquid inside the vessel, which hitherto was at a temperature corresponding to a high pressure, is suddenly at atmospheric pressure but at a temperature well above the liquid's atmospheric pressure boiling point. The liquid is thus superheated. But there is a limit to what liquids can withstand superheating. If the temperature of the liquid is above this “superheat limit temperature” (SLT), there will be instantaneous and homogeneous nucleation. It would cause a sudden and violent flashing of a large portion of the liquid, resulting in a BLEVE. Data about SLT for propane and water are given in Table 2
This could happen with a sphere filled with water. According to Abbasi (Abbasi and Abbasi, 2007), some water BLEVE occurred previously. The authors give the example of the nuclear power plant of Mihama (Japan, 2004) or a boiler in Medina chemical plant (USA, 2001). In both accidents, the explosion occurred in cases where water was used as heating fluid and was at high temperature at the moment of loss containment. In the case of a tank filled with water and exposed to fire, the dynamics is different: water is initially cold and heats up with time.If the tank filled with water remains at atmospheric or low pressure thanks to an open vent, no BLEVE will happen. The main risk is a collapse of the structure due to the increased weight of the vessel and a loss of resistance of the structure with fire. But if all vents and valves are closed, the pressure will increase. Is there a risk of BLEVE? How do a vessel and pressure valves designed for propane will behave with water filling and during fire? A discussion based on theoretical considerations and experimental results propose elements to assess this risk.

3.1 Experimental setup

The experimental setup was described in (Heymes et al., 2013). Two tanks ($2m^3$) were filled with water or propane. The fire was generated using a wall fire simulator. The results include fire characterization, radiative heat flux at the tank surface, tank wall temperatures, liquid temperature, tank pressure and vapor space temperature distribution.

Figure 2: Experimental setup

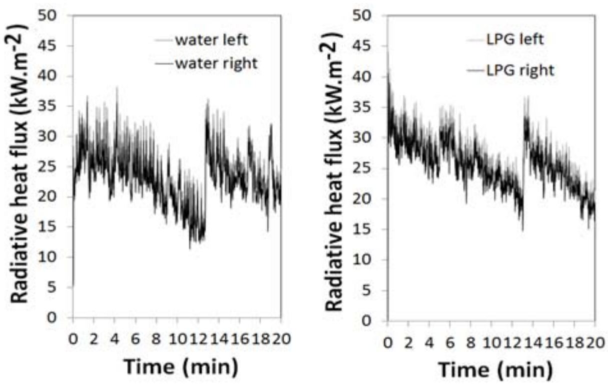

Figure 3: Heat flux impacting the tank with water (left) or propane (right)

For this work, two experiments were performed during 20 minutes. Both tanks were located at the same distance from the fire. The burners were fueled with the same flowrate of natural gas (Figure 2). As a consequence, the averaged heat flux on the external surface of the tank was similar (Figure 3). The step in heat fluxes visible on both graphics is due to a valve handling in order to increase the natural gas flowrate during the experiment.

3.2 Thermal behaviour of the tank

The two points to consider are how quickly the vapour space wall will heat up and how quickly the tank internal pressure will rise thanks to liquid vaporization. The thermal behaviour of the tank and the fluids can be described by a set of heat and mass transfer equations, thermodynamic and phase change equations and the Navier-Stokes equations. Several authors described and solved these equations (Allahdadi et al., 1988). The key issues in modelling are the prediction of inner fluid stratification during the heat up process (D’Aulisa et al., 2014), boiling and the boundary layer flow at wall; the thermo-hydraulic behaviour of the liquid when the pressure valve opens.

In this work aiming to discuss the risks associated with a propane tank filled with water for inspection, the system was simplified. This work assumes the following assumptions: (i) the liquid is perfectly mixed and no stratification occurs and (ii) the liquid phase and the part of the tank adjacent to the liquid are at a same temperature. The first assumption is crude and underestimates the pressure increase. The latter one is considered as realistic by several authors such as (Li et al., 2015). For an accurate prediction of pressure and temperatures increase and rupture time a more detailed computation will be required. The case study performed by (Li et al., 2015) was selected for discussion. A 2000 m^3 sphere is engulfed at 50% in surface by fire. Two fire conditions were investigated (87 $kW.m^{-2}$ and 180 $kW.m^{-2}$), corresponding to pool fire and jet fire scenarios. The sphere was supposed to be filled at 50% in volume (propane or water). All data about the modelling case are given in Table 2.

Table 2: Data for modelling

Commodity	propane	Water	Case study	
Superheat limit temperature (°C)	274 - 334	40 - 59	Sphere volume (m^3)	2000
Heat of vaporisation ($kJ.kg^{-1}$)	2453	344	Sphere diameter (m)	15.6
Liquid thermal conductivity ($W.m^{-1}.K^{-1}$)	0.598	0.096	Surface exposed to fire (m^2)	1000
Gas thermal conductivity ($W.m^{-1}.K^{-1}$)	0.0186	0.0193	Vessel wall thickness (mm)	50
Liquid dynamic viscosity (mPa.s)	0.119	1.080	Vessel surface emissivity (-)	0.9
Gas dynamic viscosity (mPa.s)	8.10	0.0087	Pressure relief valve pressure (bar)	19.6
Liquid thermal capacity ($kJ.kg^{-1}.K^{-1}$)	2.66	4.18	Rated flow capacity ($Nm^3.s^{-1}$)	12.17
Gas thermal capacity ($kJ.kg^{-1}.K^{-1}$)	1.94	1.90	Discharge coefficient (-)	0.8

Results about modelling are given on Figure 4. Since water has a higher density and thermal capacity, the temperature increase is slower than with propane. In case of propane, the lading temperature reaches 68°C after 50 minutes of heating. Moreover, the internal evaporation of water during heating requires more heat for phase change and accentuates the gap. This was confirmed with the experimental data (Figure 5).

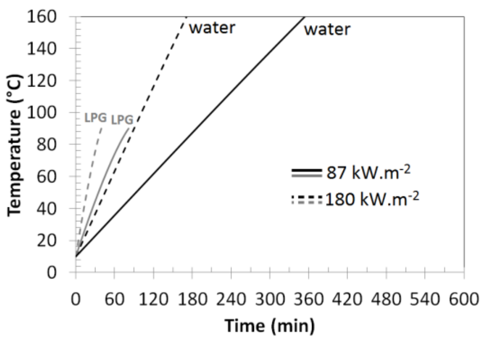

Figure 4: Liquid temperature with water and propane

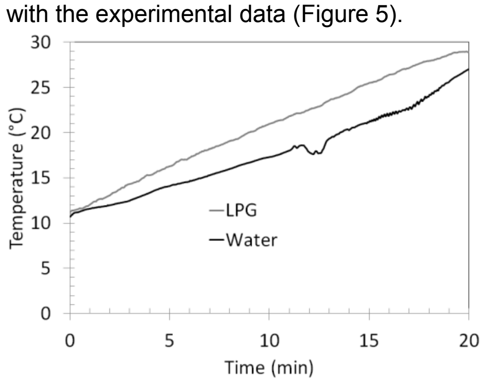

Figure 5: Radiative heat flux impacting the tank containing water (left) or propane(right)

The wall temperature of the ullage volume results from the following heat balance equation:

$$\rho_W C_W \delta_W \frac{\partial T_{WG}}{\partial t} = \underbrace{Q_{FIRE}}_{a} - \underbrace{\sigma\varepsilon(T_W^4 - T_{IN}^4)}_{b} - \underbrace{\sigma\varepsilon(T_W^4 - T_{OUT}^4)}_{c} - \underbrace{h_{IN}(T_W - T_{IN})}_{d} - \underbrace{h_{OUT}(T_W - T_{OUT})}_{e} \quad (2)$$

Where (a) is the impacting heat flux (radiative); (b) is the balance between emitted and received radiative heat flux at internal surface; (c) is the balance between emitted and received radiative heat flux at external surface; (d) is the balance between emitted and received convective heat flux at internal surface; (e) is the balance between emitted and received convective heat flux at external surface.

A parametric study was performed in order to estimate a range of likely values for each term in the heat balance equation. The data show that the convective heat transfer with the vapour in the ullage space is very small and may be neglected. This was also assumed by (Ojha et al., 2012). As a consequence, the maximum wall temperature with propane or water should be quite independent of the nature of the fluid. The experimental results about maximum wall temperature in contact with vapour confirm that point (Figure 6 and Figure 7). This was also predicted by (Allahdadi et al., 1988).

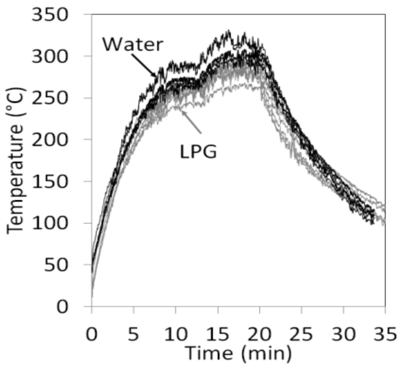

Figure 6: Wall maximum temperature with propane vapour and steam

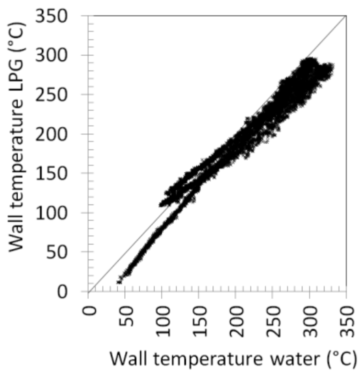

Figure 7: Parity graph of wall temperature with propane vapour and steam

3.3 Pressure increase and pressure relief valve

The saturated vapour pressure of propane is very high in comparison with water (Figure 8). As a consequence the pressure rises very quickly in the tank filled with propane. The internal pressure reaches 22 bar in 50 minutes, which is consistent with the modelling results of (Li et al., 2015). If the tank is filled with water, the pressure reaches 22 bar after 8 hours of heating (490 minutes). This very important time in the heating greatly changes the response scenario of emergency stakeholders.

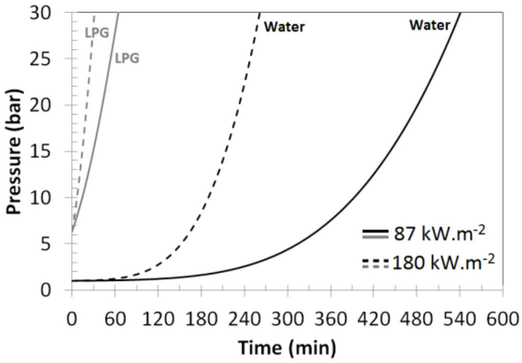

Figure 8: Pressure increase with temperature

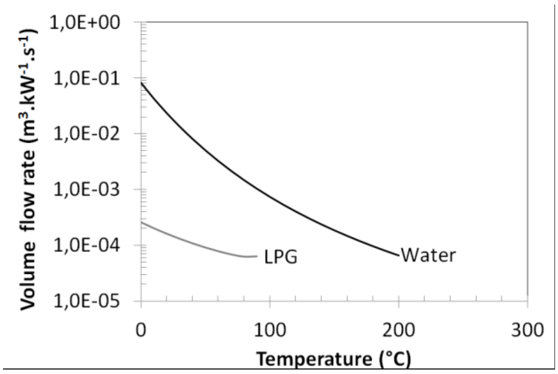

Figure 9: Flowrate per kW of transferred heat flux

Another point of interest is the capacity of the pressure relief valve to vent the vapour created by the heat flux transferred to the liquid. A comparison of both species was performed thanks to the following equation:

$$\dot{V} = \frac{1}{\Delta H_{vap}(T).\rho_{vap}(T)} \quad (3)$$

This equation allows calculating the volume flowrate of vapour produced per kilowatt of heat transferred to the liquid. The pressure remains stable if the pressure relief valve is able to vent the volume flowrate corresponding to the net heat flux transferred to the liquid. Figure 9 compares the data computed in case of water and propane. The volume flowrate produced by water is higher than with propane, but this is a consequence of the low molecular weight of water and the lower saturation pressure of water. If the volume flowrates are converted to normal conditions $Nm^3.h^{-1}$ (0°C, 1 bar). The flowrate is then 1.2 $Nm^3.s^{-1}.kW^{-1}$ in case of propane and 0.5 $Nm^3.s^{-1}.kW^{-1}$ in case of water. Thus, a sphere protected with pressure relief valves designed for propane content will be sufficient if the tank is filled with water.

3.4 Consequences in case of steel rupture

Two temperatures have to be considered: the pressure relief valve pressure set (19.6 bar) and the superheat limit temperature SLT for water [274-334°C] and propane [40-59°C] (Eckhoff, 2014) (Table 2). If the pressure reaches the pressure set of the relief valve, the pressure should remain close to the pressure set. The corresponding saturation temperature of vapor at 19.6 bar is 56°C in case of propane and 205°C in case of water. The tank may fail despite the relief valve since the wall temperature continues to increase. If a sudden steel rupture leads to depressurization as described by (Birk and Cunningham, 1996), propane will end up strongly superheated (above the SLT) but water not. The risk of BLEVE is therefore lower with water according to the theory of BLEVE.

4. Conclusions

Several points were investigated to assess the risk during water filling of a propane tank. On mechanical considerations, the properties of water are very different compared to propane, entailing risks of collapse during an earthquake. The load on the legs and braces is increased. The natural frequencies of the structure are modified, and supplementary low frequency oscillations due to sloshing operate. More work should be undertaken to study the sloshing issues, in particular when a vessel designed to resist to an earthquake when filled with propane is at the time of earthquake filled with water.

On thermal considerations, water has a considerable heat of vaporization and heat capacity. This causes water heating up much slower than propane, and the pressure rises much more slowly consequently. The time before pressure valve opening will change from minutes (in case of propane) to hours (in case of water). On another point, the pressure relief valves designed for propane should be sufficient to prevent an excess of pressure in case of fire attack of the vessel when filled with water. The BLEVE risk seems to be negligible since the SLT of water is very high. An experimental work should be undertaken to confirm these conclusions.

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