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Impact of Wildfires on LPG Tanks

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During wildland fires, wildland-urban interfaces may cause significant problems for emergency managers throughout the world. Several works focused on safety zones aiming to prevent houses to burn, but no work focused on the LPG tanks which can be located in the surroundings of houses. A finite elements modelling was developed to calculate safety distance preventing from BLEVE. The safety distances required by law in several countries (50 m; 30 m; 25 m) are checked. It appears that the required safety distances are correct to prevent the tank from BLEVE.

1. Introduction

Research on wildland fires focused traditionally on two main objectives: the prediction of the velocity at which a fire will spread and the estimation of the released heat from the flame front of the wildland fire. Both topics are key points in order to evaluate the gravity of the fire and to organize firemen intervention to fight the fire (Alexandridis et al., 2011).

The wildland-urban interface (WUI) may be defined as a contact zone between a natural zone such as a forest and a heavy or light urbanized area. At this interface, the threat to homes and their destruction during wildland fires, with associated concerns for life safety, are significant problems for emergency managers throughout the world. Due to the increasing urbanization of the surrounding countryside, the number of these areas is growing rapidly. In the last ten years, wildfires resulting in residential destruction occurred in Australia, Canada, Mediterranean countries and the United States. The WUI areas are complex systems, difficult to manage, especially in the context of wildfire prevention.

(Butler, 1974) contributed the first description of urban wildland interface not in geographic terms but in terms of fire process. He defined that interface as the occurrence of fire spreading from wildland fuel (vegetation) to urban fuel (homes), in terms of the wildland fire becoming close enough for its flames and (or) its firebrands (lofted burning embers) to contact flammable parts of a home or the home's immediate surroundings. The main question of his description is "How close is close enough for home ignition ?".

Well know operational models of fire spreading (for example BEHAVE, FIRE CODE, FORE FIRE models) are no longer valid in the urban interface. Some authors coupled wildfire dynamics with structure ignition models. (Cohen, 2000) proposed the Structure Ignition Model (SIAM). This model is based on strong assumptions, as the flame is assumed to be a uniform parallel-plane black body emitter. The flame-to-structure distance does not allow for flame contact. This model overestimates the heat received by the structure, as reported by (Porterie et al., 2007). These latter authors developed a three-dimensional physics-based model able to describe the near-field dynamics of a wildland fire, as well as its impact on structural elements. This model was validated by a prescribed burning and fire tunnel experiments. (Zarate

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et al., 2008a) proposed a study as a basis for establishing zones in which houses are safe in the event of fire. They considered several building materials such as wood, polyurethane, PVC and deduced safety distances which are useful both in terms of prevention and emergency planning, in the determination of adequate separations between houses and wooded areas. All these authors considered the concern of house ignition, but none considered the presence of a LPG tank in the surrounding of housing.

Liquefied Petroleum Gas (LPG) is a common fuel used for home heating, hot water production or cooking. This fuel is usually stored out of the house in pressurized cylindrical tanks of medium capacity (1 or 2 m^3). These tanks are not protected by passive protection layer against fire but are prevented from excessive pressure by a relief valve. However, when such a tank is exposed to external fire, there is a chance that the tank will fail despite the action of the pressure relief valve. If the failure mode is catastrophic then this could lead to a boiling liquid expanding vapour explosion (BLEVE). The immediate hazards from the BLEVE are blast and projectiles. Since LPG is flammable, a fireball is possible with the associated hazards of fire engulfment and thermal radiation. If the LPG is not ignited immediately, delayed ignition may lead to widespread fires or in some cases explosions. A well know example of LPG tank located close to a fire and entailing a BLEVE is the accident of Ste Elisabeth de Warwick, Canada, in 1993. A LPG tank was located close to a burning house and the tank suddenly circumferentially separated at its central girth weld. There were four fatalities and five injuries into the fireman group fighting the fire (Tan et al., 2003).

Physics of BLEVE is as following. The impacting heat flux leads to an increase of wall temperatures and therefore material weakening. Heat it also transferred to the liquid phase which increases the liquid temperature and the vapour pressure. This internal pressure increase leads to creep and thinning in the hot wall area and this may eventually lead to formation of a tear or fissure in the tank wall. If the tear propagates the entire length of the tank then a BLEVE takes place. If the fissure stops short, then a transient jet release takes place (Birk and Cunningham, 1994).

Determining whether or not a heated LPG tank will entail a BLEVE is a tricky task. The maximum wall temperature occurs when the liquid level is low in the tank, on portions of the vessel that are not internally wetted by the liquid content. The internal pressure results from LPG boiling, fluid temperature increase and stratification. Rupture occurs when internal pressure exceeds heated steel resistance. The pressure relief valve controls pressure but entails liquid mixing and therefore changes thermo-hydraulics of the system (Brambilla et al., 2010).

In order to draw the safety line between BLEVE issue or not, the American Petroleum Institute (API) considered the maximum radiant heat flux that the tank can undergo without bursting, considering that the pressure valve prevents from an excessive internal pressure. Below this level of radiant heat flux, the vessel can still be considered in a safe condition with the relief valve venting, since the shell metal will be below the threshold for stress creep rupture: the bulging, thinning and consequent rupturing of the shell. The API value for that is 7,000 British thermal units per hour per square foot (22 kW/m^2) (API 2510 publication, 1996). This value will be considered in this work to establish safety distances to prevent BLEVE from a tank submitted to a radiant heat flux from a wildfire.

An extended work was undertaken in order to study the safety distances to prevent from BLEVE, including real-scale experiments. This first piece of work focuses on the theoretical modeling of the heat flux transferred to the LPG tank and a discussion about safety zones that should be respected.

2. Theoretical part

2.1 Wildland fire radiation modelling

Modeling the radiative heat flux from a wildland fire to a target requires to know the emitted radiative power of the fire and to calculate the transmission of the radiative energy to the target by view factor considerations (Sacadura, 2005). The first point is a tricky task since the emitted power depends on many variables such as flame combustion kinetics and temperatures, flame thickness, emissivity of gases and soot. A popular approach to the estimation of the radiation flux from wildland fires is the use of the solid flame model (SFM). In this model, the visible flame is idealized as a solid body with a simple geometrical shape and with thermal radiation emitted from its surface. The contribution of non-visible zones of the fire plume to the radiant heat flux is usually not taken into account. Even if several authors (Wang, 2009),(Parent et al., 2010) suggest that this model may be questionable for wildland fires, the SFM model is easy to use and give results in acceptable agreement with experimental data (Butler and Cohen, 2000). In the SFM, the radiant heat flux per unit area reaching a remote target is given by:

$$q = \tau . F . E \qquad (1)$$

Where F is the view factor, E the surface emissive power (SEP) of the visible flame, and τ the transmittivity of the air (of gas) layer between the flame and the target. The atmospheric transmittivity corresponds to the fraction of the thermal radiation that is transmitted from the fire to the target; it is function of the atmospheric humidity, the concentration of carbon dioxide and the distance, and can be calculated using semi-empirical equations. The worst case occurs when the transmittivity equals unity, this will be assumed in order to be in a conservative approach. The surface emissive power of the flame may be calculated as:

$$E = \varepsilon . \sigma . T^4 \qquad (2)$$

Where ε is the effective emissivity of the flame, T is the flame temperature and σ is the Stefan Boltzmann constant. Data about SEP values can be found in the literature, the most valuable of them having been measured during the International Crown Fire Modeling Experiments (ICFME) (Butler and Cohen, 2000). These authors measured SEP on large crown fires of Jack pine trees (average height 12 m) in square forest squares (75-200 m side length). SEP measurements were taken at different heights: 3.1; 6.2; 9.2; 12.3 and 13.8 m. The authors averaged the data measured at theses heights on 6 experiments and concluded that the maximum peak radiant flux was nominally 190 $kW.m^{-2}$ through the entire stand, with a standard deviation of 90 $kW.m^{-2}$. However, these values are only valid during the maximum fire intensity, which lasts a few seconds. When considering the effect of wildland forest fire radiation on a LPG tank, the considered time is much longer since the heat transfers and thermal inertia of fluids and steel are slower and a minimum time of several minutes is required in order to make the internal pressure increase. When averaging Butler data over the time of significant fire (SEP > 20 $kW.m^{-2}$), it appears that the average heat flux is 70 $kW.m^{-2}$. Others SEP values can be found in literature, such as 57 $kW.m^{-2}$ (Billaud et al., 2011), 118 $kW.m^{-2}$ (Zarate et al., 2008b), 90 $kW.m^{-2}$ (Trabaud, 1992), 60 $kW.m^{-2}$ (Leicester, 1988). In this study, we considered that 90 $kW.m^{-2}$ was realistic.

The view factor E is defined as the fraction of the radiation leaving a surface A that is intercepted by a surface B. Oriented elemental areas dA and dB are connected by a line of length R, which forms the polar angles θ_A and θ_B , respectively, with the surface normal vectors $\mathbf{n}_A$ and $\mathbf{n}_A$. The values of R, θ_A and θ_B vary with the position of the elemental areas on A and B. Assuming that both surfaces emits and reflects diffusely, and that the radiosity is uniform, the view factor can be defined as :

$$F = \frac{1}{A} \int_A \int_B \frac{cos\theta_A cos\theta_B}{\pi R^2} dAdB \qquad (3)$$

Three different types of methods can be used in order to calculate or approximate this double integral. The first one is the exact or approximated analytical solution of the equation. This is the easiest way to proceed but analytical solutions were only proposed in simple configurations (Hollands, 1995, Van den Bosch and Weterings, 1997). The second method is a finite element method (FE method) whose accuracy depends mainly on the meshing thinness. This method is computing time consuming since the total calculation steps equals the multiplication of number of cells of A_i by A_j. The last method relies on Monte Carlo method (MC) which reduces the calculation steps by selecting stochastically cells in both areas in order to approximate the double integral. (Billaud et al., 2011) compared this latter method with an analytical equation in a simple case and revealed a good agreement of the two methods. In this work, since the considered geometric configuration is quite simple but that no analytical equation was found in the literature, the FE method was selected in order to approximate the impacting heat flux on the LPG tank. The FE solving of the previous equation is achieved by meshing the A surface into i cells (dA_i) and the B surface into j cells (dB_j). The equation can be written as:

$$F = \frac{1}{A}\sum_i \sum_j \frac{\cos\theta_{Ai}\cos\theta_{Bj}}{\pi R_{ij}^2} dA_i dB_j \qquad (4)$$

The accuracy depends strongly of the size of the cells and therefore, the number of cells which is time consuming.

2.2 Validation of the FE modeling

Before scaling the setup, the first point was to check the validity of authors' FE modeling. A relevant case study was found in (Billaud et al., 2011). This case study is a 20-m-wide vertical planar flame (height = H_f) front and a vertical small surface element located in front of the flame center at a varying distance from the flame. The receiving element was located at a distance x=15m from the flame front.

The view factor F was calculated a different x/H_f ratios with two Macguire analytical equations (MG1 and MG2 (McGuire, 1953)), the analytical equation of Van den Bosch and Weterings (Van den Bosch and Weterings, 1997), the MC calculation of Billaud et al. (2011) and the FE modelling (this work). Results are reported in Figure 1. As concluded by Billaud, the same trend is observed but a strong difference occurs with the MG1 and VW solutions and these solutions should not be used for the scaling. The FE calculation gives an intermediate result between MG2 and MC solutions, and reveals that the authors' model is in good agreement (less than 10%) with these previous works.

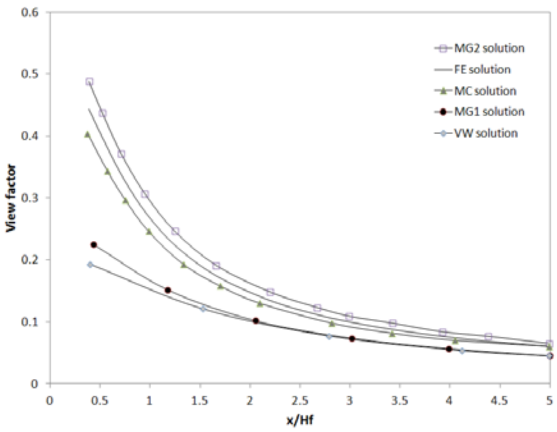

Figure 1: Comparison of differents view factor calculations at different x/Hf ratios

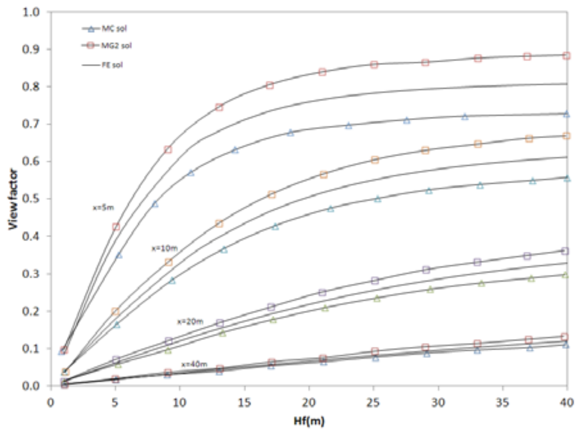

Figure 2: Comparison of McGuire, MC and FEM view factor calculation

The accuracy of the FE model with distance and flames height is reported in Figure 2. View factor calculations are in very good agreement for all fire heights when the fire is very far from the tank (x=40 m). The more the tank is closer to the fire, the higher is the deviation between models. At five meters, the deviation is 10 % between the FE model and both other models. The FE model is therefore relevant to calculate the effect of a distant fire radiation to a LPG tank.

3. Results and discussion

The FE model was used in order to calculate the maximum heat flux impacting a LPG tank. Three parameters where investigated: height H and length L of the firewall, distance D between the tank and the fire (Figure 3). For each calculation, all fluxes impacting the tank were calculated and a 3D matrix was filled with a mapping of local heat fluxes impacting the shell. An example of 3D sketch drawn from flux matrix is given in Figure 4. All values were compared in order to extract the highest value impacting the tank. This value was always located in the upper part of the tank. Iso-flux parametric curves were calculated. For each (distance; fire length) couple, the height of fire was sought in order to get 22 kW/m^2 at the LPG tank (Figure 5).

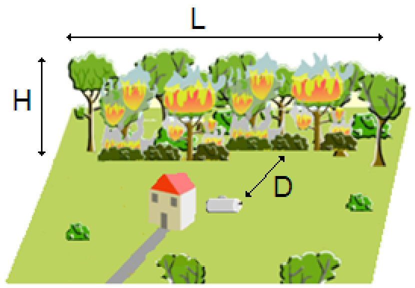

Figure 3: LPG tank located in WUI, submitted to a wildfire heat flux

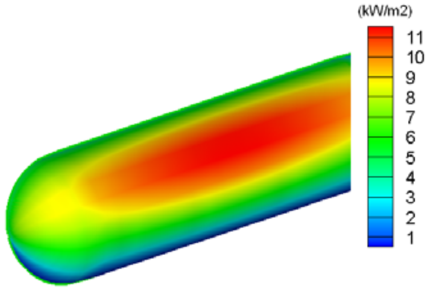

Figure 4: 3D sketch of impacting radiant heat flux

The maximum height that a wildfire may reach is often considered as 20 m. However, this study considered a conservative approach and investigated a height up to 40 m. The length of the fire wall depends on the geometric configuration of the surroundings of a house located close to a forest, and the local law requirements. Indeed, in several countries, the law obliges homeowners to clear the undergrowth within a distance from their house in order to stop the fire and prevent it from burning the house. For example in France this distance equals 50 m, in the US it is 30 m in high risk areas whereas in Spain this distance is reduced to 25 m. A maximum firewall length of 100 m was considered.

Results of the FE model confirm that a safety distance of 50 m prevents from BLEVE with a conservative approach in any fire scenario, even if the crown fire is exceptional (height 40 m, length 100 m). However, several authors consider that the maximum fire height is only 20 m. In that assumption, a safety distance of 30 m is sufficient to prevent any BLEVE risk. Reducing this distance to 25 m could be considered as not safe. But one should not forget many assumptions of this work:

- The entire firewall burns on its entire length and height during the time required to lead to a BLEVE. This time is known as longer than the few minutes of intense combustion of the wildfire.
- The safety zone will probably not be totally free of trees and a screen effect has to be considered.

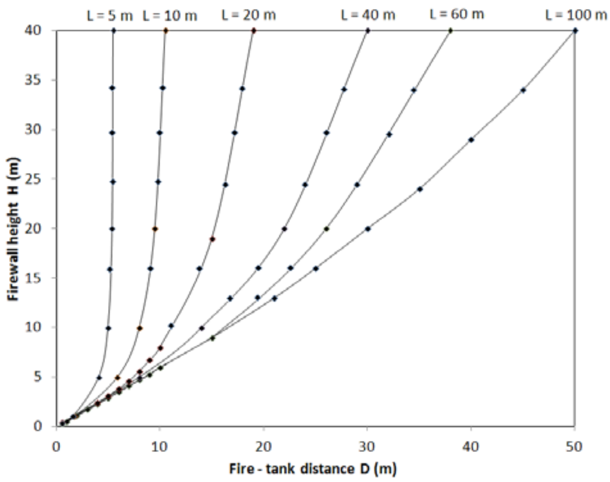

Figure 5: Safety distance as a function of firewall height and length

On an another hand, when the fire is as close as 3 m from the tank (frequent mandatory distance between a tank and its combustible surroundings), results show that a small fire of 2 m high and 5 m long (for example a house or a hedge fire) can entail a heat flux higher than 22 kW/m^2. This is evidence that even if a safety zone is respected between the forest and the tank, the BLEVE could occur if fire brands ignite combustible located close to the tank or the house itself.

4. Conclusion

The impact of a forest crown fire on structures was previously studied but no study focused on LPG tanks. In areas where wildfire risk is high (south of Europe, US, Canada, Australia for example) the possibility of a LPG tank to be located close to the fire is a major risk for fire fighter and population. A finite elements model was developed and tested versus a literature case study. The agreement with several others works was good. This model was then used to calculate the maximum heat flux impacting a LPG tank as a function of distance, height and length of firewall. Results showed that a mandatory safety distance of 50 m is sufficient to prevent from BLEVE in any case of wildfire. Safety distances of 30 and 25 m should prevent from BLEVE in most cases of wildfire. However, even if a safety zone is respected, care has to taken to avoid fuel in a 3 m zone around the tank. Ignition of this fuel could provoke the BLEVE.

References

API Publication 2510A, 1996, Fire-Protection Considerations for the Design and Operation of Liquefied Petroleum Gas (LPG) Storage Facilities, 2nd Edition, American Petroleum Institute, Washington DC, USA.

Alexandridis A., Russo L. & Vakalis D., 2011, Simultation of Wildland Fires in Large-Scale Heterogeneous Environments, Chemical Engineering Transactions, 24, 433-437.

Billaud Y., Kaiss A., Consalvi J. L. & Porterie B., 2011, Monte Carlo estimation of thermal radiation from wildland fires, Int. J. Therm. Sci., 50, 2-11.

Birk A.M. &Cunningham M.H. ,1994, The boiling liquid expanding vapour cloud explosion, J. Loss Prevent. Proc. 7, 474-480.

Brambilla S., Totaro R. & Manca D., 2010, Simulation of the LPG Release, Dispersion, and Explosion in the Viareggio Railway Accident, Chemical Engineering Transactions, 19, 195-200.

Butler B.W. & Cohen J. D., 1998, Firefighter safety zones: a theoretical model based on radiative heating, Int. J. Wildland Fire, 8, 73-77.

Butler B.W. & Cohen J.D., 2000, Field verification of a firefighter safety zone model, Proceedings of the 2000 International Wildfire Safety Summit, 54-61.

Butler C.P., 1974, The urban/wildland interface, Proceedings of the Western States Section Symposium, Combustion Institute papers, 74, 1-17.

Cohen J. D., 2000, Preventing Disaster: Home Ignitability in the Wildland-Urban-Interface, J. Fores, 98, 15-21.

Hollands K.G.T., 1995, On the superposition rule for configuration factors, J. Heat Transf., 117, 241-245

Leicester R., 1988, Building technology to resist fire, flood and drought, Proceedings of the Ninth Invitation Symposium, 16-17 october, Syndney, 221-236.

Mcguire J.H., 1953, Heat Transfer by Radiation, Fire Research Special Report n°2. HM Stationery Office, London.

Parent G., Acem Z., Lechêne S. & Boulet P., 2010, Measurement of infrared radiation emitted by the flame of a vegetation fire, Int. J. Therm. Sci, 49, 555-562.

Porterie B., Consalvi J.-L., Loraud J.-C., Giroud F.& Picard C., 2007, Dynamics of Wildland Fires and their Impact on Structures, Combust. Flame, 149, 314-328.

Sacadura J.F., 2005, Radiative heat transfer in fire safety science, J. Quant. Spectrosc. Ra., 93, 5-24.

Tan D.M., Xu J.& Venart, J.E.S., 2003, Fire Induced Failure of a Propane Tank: some Lessons to be Learnt, Proceedings of the Institution of Mechanical Engineers, part E: J. Process Mech. Eng., 79-91.

Trabaud L., 1992, Wildfires. Mechanisms, behavior and environment, Eds France-Selection, Aubervilliers, France (In French).

Van Den Bosch C.J.H. & Weterings, R. A. P. M., 1997, Methods for the calculation of physical effects due to release of hazardous materials (liquids and gases), Director-General of Labour, The Hague, The Netherlands.

Wang H.H., 2009, Analytical Model for Determining Thermal Radiance of Fire Plumes with Implication to Wildland Fire. Combust. Sci. Technol., 181, 245-263.

Zarate L., Arnaldos J.& Casal J., 2008b, Establishing safety distances for wildland fires, Fire Safety J., 43, 565-575.