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Modelling Pressure Tanks under Fire Exposure: Past Experience, Current Challenges and Future Perspectives

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CFD and lumped parameter models are available in the literature for the analysis of pressure tanks under fire exposure. The first type of models allows for a detailed representation of the phenomena occurring in the tank, providing accurate results in terms of pressurization rate and temperature distribution. However, they are computationally expensive and are currently unable to simulate PRV opening. Lumped parameter models run in very short time, but may lead to not conservative results. The present contribution provides an overview of the strengths and limitations of both approaches, highlighting the new challenges posed by the development of models for the analysis of cryogenic tanks exposed to fire.

1. Introduction

The availability of accurate and robust models for the prediction of the behavior of pressurized tanks under fire exposure is a key requirement to improve design of fire protection and emergency depressurization systems. As reported in the literature reviews by Moodie (1988) and (Birk, 2006), several experimental campaigns were carried out over the last 50 years, especially on LPG tanks. These produced valuable knowledge in the field, allowing for the identification and characterization of the physical phenomena occurring in pressure vessels during fire exposure. The role of thermal stratification in the liquid phase due to the establishment of free convective flow field was recognized as the most important driver for tank pressurization (Aydemir et al., 1988). On the other hand, the presence of hot spots in the steel wall in contact with the vapor space was found to be responsible for severe mechanical wakening of the tank structure, finally leading to tank failure (Birk et al., 2006a).

This knowledge supported the development of numerous models, aiming at predicting tank heating and pressurization, ultimately providing an estimation for the expected time to failure. Most of the models present in the literature and available to industry fall under the category of lumped models: they are based on the solution of integral mass and heat balance equations. Lumped models are easy to use and provide results at a very low computational cost. However, they rely to different extents on adjustable parameters and simplifying assumptions, often disregarding key phenomena such as thermal stratification. Thus, their applicability is limited to the range of experimental conditions adopted for their development and validation.

Recently, several authors succeeded in overcoming these limitations proposing CFD-based models, although the high computational cost represents a severe obstacle to their adoption by industry (Scarponi et al., 2021). In practice, their use is restrained to academic research. Moreover, to the best of the authors' knowledge, no currently available CFD model is able to reliably simulate tank behavior under the action of pressure relief devices (such as PRVs). This eliminates the possibility of using such models for the sizing of depressurization systems. Further research efforts are thus required in this direction. All this adds up to the new challenges that are emerging for fired tank modelists. Many researchers and authorities agree on considering hydrogen as one of the best candidates to achieve a sustainable economy and on recognizing that natural gas will play a key role

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in the energy transition (Ball and Weeda, 2015). The capacity of production, storage and transportation of such compounds is already increasing and will foreseeably keep growing in the near future. This comes along with the need for reliable tools to ensure a safe design and management of the equipment involved in their supply chain. Available models will have to be extended to cover fire scenarios involving hydrogen and natural gas, which can be stored either as compressed gas or as cryogenic liquids. This is not an easy task, also considering that very few fire tests are available for this kind of tanks, especially for cryogenic ones.
The present contribution provides an overview of the models available in the literature for the analysis of the thermo-hydraulic response of pressure vessels under fire exposure, comparing lumped and CFD-based approaches and highlighting their strengths and limitations. A specific section is devoted to discussion of codes for the modelling of cryogenic tanks, which are receiving increasing attention due to the fast spread of liquid hydrogen (LH_2) and liquid natural gas (LNG) storage and transportation facilities.

2. Zone models

Models based on the partition of a problem domain into control volumes (or zones) and the solution of integral mass and heat balance equations for each of them are called zone models. It is possible to categorize the models available in the literature according to the number of zones in which the than lading is partitioned. As schematized in Figure 1, there can be a unique zone encompassing both phases (Figure 1a), two distinct zones for the liquid and the vapor (Figure 1b), several zones in one or both phases (Figure 1c).

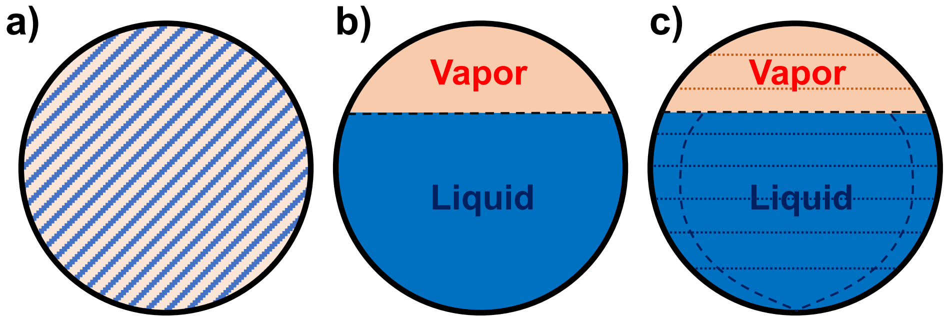

Figure 1: Simplified schematization of single (a), two (b) and multiple (c) zone models for fired tank simulation.

To the best of the authors' knowledge, the first zone model developed to predict the response of a vessel exposed to fire is CALSPAN (Graves, 1973), presented in 1973. CALSPAN calculates tank pressure as the saturation pressure at the temperature of the lading. Two separate zones are considered for the liquid and the vapor space. However, they share the same temperature. Thus, thermal stratification of the liquid, which is widely recognized to be the driver for tank pressurization (Aydemir et al., 1988), is disregarded. This represents a strong limitation, making pressurization prediction unreliable. Over the years, more and more complex models were proposed by several authors, a (non-exhaustive) list of which is reported in Table 1.

Table 1: List of the main zone models for fired tanks available in the literature.

Model name	Number of fluid zones	Thermal stratification is accounted for (yes/no)	Reference
CALSPAN	1 temperature zone 2 mass zones	NO	(Graves, 1973)
AFFTAC	2	NO	(Johnson, 1998)
TCTCM	1 vapor zone 2 liquid zones	YES	(Birk, 1988)
ENGULF	2	NO	(Hunt and Ramskill, 1985)
ENGULF II	2	NO	(Ramskill, 1988)
HEATUP	2	NO	(Beynon et al., 1988)
PLGS1	1 vapor zone 4 liquid zones	YES	(Aydemir et al., 1988)
TAC7	20 vapor zones 20 liquid zones	YES	(Germany et al., 1990)
VessFire	2	NO	(Berge, 2009)
RADMOD	2	NO	(Cozzani et al., 2006)

Some of them, such as AFFTAC and VessFire (currently adopted by the North American Standard for modelling hazardous materials tanks exposed to fire), suffer the same limitation as CALSPAN. Improvements in this sense are found in TCTCM, in which the liquid phase is divided into two thermal nodes (see the blue dashed line in Figure 1c): the liquid boundary, that absorbs all the heat entering the tank wall below the liquid-vapor interface and drives tank pressurization, and the liquid core, that remains cold.
Similarly to TCTCM, PLGS1 and TAC4 consider multiple liquid zones, exchanging mass and energy among them. For both, the tank pressure corresponds to the saturation pressure calculated at the liquid zone temperature. The more physically sound representation of the thermohydraulic in the tank provided by this kind of models comes at the expenses of introducing additional parameters governing the extension of the vessel zones and the heat and mass transfer among them. Such parameters are tuned on specific experimental data sets, thus limiting the application of the models to the range of the fire test conditions considered for their validation.

3. CFD based models

With the aim of overcoming the inherent limitations of zone models, several authors proposed a distributed parameter approach, namely CFD. The computational domain is discretized in small volumes, in which transport equations for mass, momentum and energy are solved in their local form. The first model of this kind was PLGS-2, proposed by Hadjisophocleous et al. (1990). PLGS-2 was based on a 2D approach and several simplifying assumptions (no phase change, Boussinesq approximation for free convective flow, constant effective viscosity, etc.). Several other authors developed 2D CFD models, gradually removing such assumptions. Scarponi et al (2018a) proposed an improved version of the 2D CFD model developed by D'Aulisa et al. (2014) and validated it against pool fire and remote burner array fire tests (Scarponi et al., 2018b). The good agreement with experimental results proved the potentiality of CFD models in predicting tank behaviour under fire exposure. However, the 2D approach excluded the possibility to simulate complex fire scenarios, such as partial engulfment by pool fires or local jet fire impingement. In 2019, the same authors extended the model from 2D to 3D (Scarponi et al., 2019) and validated it successfully against partial engulfment fire tests (Scarponi et al., 2021). The adoption of a CFD approach allowed for a physically sound simulation of the relevant phenomena such as thermal stratification, liquid expansion, turbulent free convective flow, phase change, which ultimately determine tank pressurization rate. Figure 2 shows two examples of how CFD results can be used to obtain a detailed insight about tank lading behaviour.

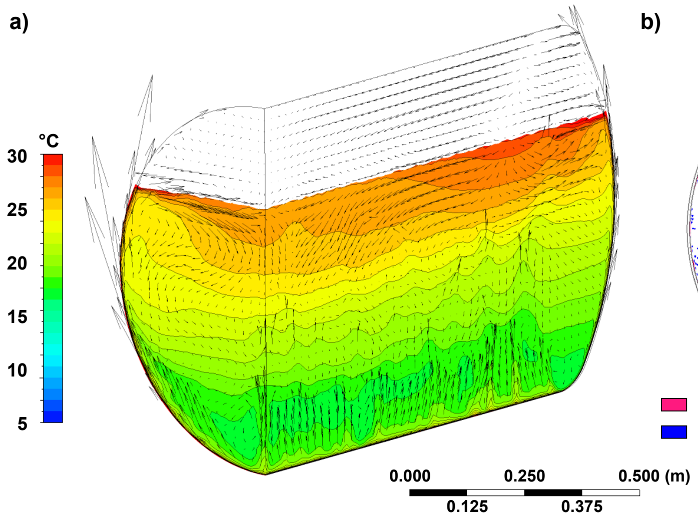

Figure 2: simulation results (simulation time = 180s) of a 1.7 m diameter LPG tank under pool fire exposure (initial liquid fraction 72%): (a) Temperature contour plots and velocity vector field in the liquid phase; (b) evaporation and condensation zones (adapted from Scarponi et al 2018a).

In Figure 2a it is evident how the free convective flow produces strong thermal stratification in the liquid phase, while Figure2b shows the effect of temperature inhomogeneity on the extension of the domain zones where evaporation and condensation occur. The rate at which the tank pressurizes is a direct consequence of the phase change taking places in these zones. Clearly enough, such a detailed representation of the thermo-fluid dynamics cannot be achieved by lumped models.

4. Comparison between zone and CFD based models

From the process safety standpoint, the final purpose of models for the simulation of fired tanks is to provide an acceptable representation of the pressurization curve and (more importantly) a conservative estimation of the time to failure, at a computational time as low as possible. CFD models ensure a physically sound description of the phenomena characterizing the thermohydraulic inside a tank exposed to fire, but are very computationally expensive. Thus, their use is often limited to academic research, with practitioners preferring lumped parameter ones. Nevertheless, many authors of experimental and numerical studies have pointed out that disregarding local phenomena may lead to not conservative results when a PRV is not present or until it is closed. This is particularly true for tanks featuring large diameters and high filling degree, as well as for non-uniform fire scenarios. A clear example of how neglecting local phenomena may lead to a large underestimation tank pressurization is illustrated in Figure 3. This was adapted from the work by Scarponi et al., (2021) and compares the pressure curve from a partial engulfment fire test on a LPG tank featuring no PRV (Birk et al., 2006b) with the results obtained from CFD calculation and the RADMOD two zones model (Cozzani et al., 2006).

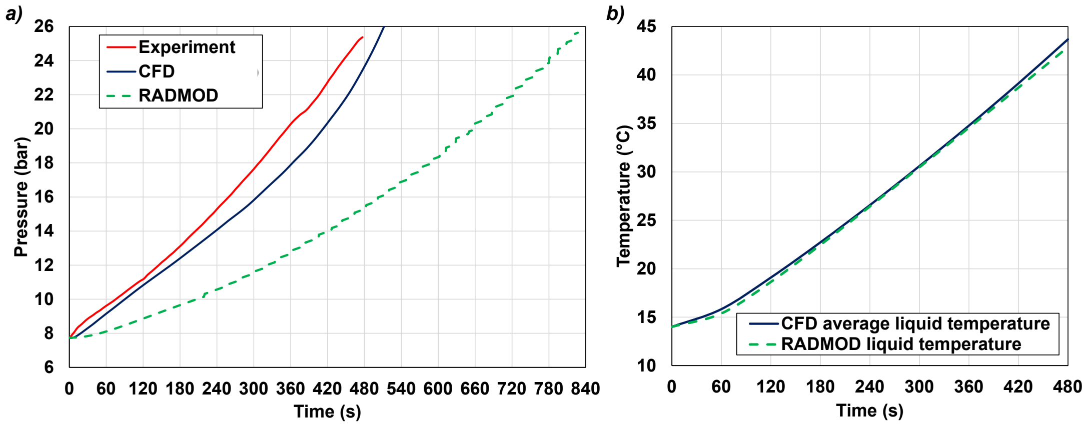

Figure 3: Comparison of experimental, CFD and RADMOD zone models pressure curve (adapted from Scarponi et al., 2021)

Although the experimental and CFD results curves in Figure 3a are not coincident, their slope (pressurization rate) and final value are quite similar, while the curve obtained from RADMOD shows a considerable deviation (and not in the conservative direction) with respect to these two. On the other hand, the CFD and RADMOD results in terms of average liquid phase temperature (Figure 3b) almost overlapped. This demonstrates the importance of accurately reproduce local inhomogeneities and thermal stratification. Clearly enough, the use of a more complex lumped model, with a higher number of zones, could potentially provide a more accurate result. However, as discussed in Section 2, this would require a fire scenario specific tuning of additional model parameters. Thus, the application of the model to a different fire scenario would lead to arguable results.

It should be remarked that the degree of pressure underestimantion decreases when the PRV (if present) opens. This event causes a sudden drop in pressure, inducing strong and generalized boiling, and promoting mixing of the liquid phase. Thermal stratification gradually vanishes (a phenomenon often referred to as de-stratification), the liquid temperature becomes more uniform and approaches the saturation temperature corresponding to the tank pressure. This condition is more in line with the assumptions at the base of lumped parameter approaches. Thus, the use of zone models for vessels equipped with one or more PRVs is considered acceptable, although experimental results (e.g. Anderson et al., 1974) show that de-stratification can take several minutes to effectively homogenize liquid phase temperatures.

Despite the evidence of the superior predictive capabilities of CFD based models, the huge computational cost makes their use still unfeasible for industrial applications and a lumped parameter approach remains the largely preferred option. The constant increase in computational power will possibly solve this issue in the future. In the meanwhile, transient solutions could be adopted, as developing surrogate models trained on CFD results.

Besides the high computational cost, the most important limitation of currently available CFD models remains their inability to simulate the tank lading behaviour after PRV opening. The sudden and generalized boiling in the bulk of the liquid phase and the high velocities experienced in the gas phase in the proximity of the valve (at pressure levels usually present in tanks exposed to fire the flow becomes chocked at the valve throat) make CFD simulation quite challenging from the numerical point of view. This aspect requires further research.

5. Zone and CFD based models for cryogenic storage tanks

The LNG supply chain experienced a fast and constant growth in the last decade. Liquid Hydrogen (LH_2) is foreseen to follow a similar trend. Parallel to the economic interest, safety concern is rising towards the technologies involved in storage and transportation of these cryogenic flammable liquids. Past accident analysis evidences that external fires can affect cryogenic tanks leading to their catastrophic failure (Planas et al. 2012). LNG and LH_2 are usually stored in super insulated tanks. Compared with pressure tanks for liquefied gases at ambient temperature, cryogenic ones present a peculiarity: the constant production of boil-off gas (BOG) due to the heat leakage through the insulation leading to tank self-pressurization. CFD (Kassemi and Kartuzova, 2016) and lumped parameter (Gursu et al., 1993) approaches were proposed for the analysis of this phenomenon. In principle, such models could be extended to the simulation of cryogenic tank response to fire exposure. However, many authors pointed out how insulation systems may undergo severe performance loss when exposed to the high temperatures and heat fluxes typical of hydrocarbon fires (Hulsbosch-Dam et al., 2017). Depending on the type of system, this can be caused by direct thermal degradation of the insulation material (e.g. in the case of polyurethane or multi-layer insulation) or/and by loss of vacuum. An example of the latter case was observed during the tests carried out by TNO in 2015 (Kamperveen et al., 2016) on a double walled cryogenic tank featuring perlite insulation, in which the outer tank failed, with subsequent loss of vacuum and release of perlite powder. This kind of phenomena introduces a high degree of uncertainty on the actual value of insulation system thermal conductivity to be used in models for the prediction of tank response. Figure 4 reports the results obtained by Iannaccone et al. (2021), who developed a CFD model to reproduce the experimental measurements from one of the TNO 2015 tests.

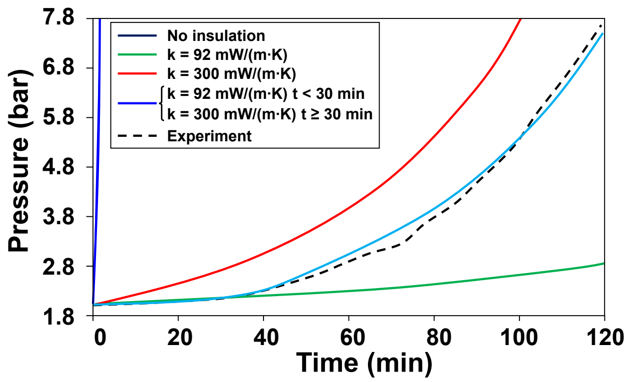

Figure 4: Effect of insulation thermal conductivity (k) on the pressurization curve predicted by the CFD model developed by Iannaccone et al. (2021).

The figure illustrates the effect of insulation thermal conductivity on the pressurization curve. The experimental curve falls between those obtained considering values of 92 mW/(m·K) (intact insulation) and 300 mW/(m·K) (damaged insulation) and is very well matched if a switch between these two values (this was done to mimic a sudden loss of vacuum in the insulation) is made after 30 min of fire exposure. The blue curve refers to the extreme case of absent insulation. These results suggest that models for the response of cryogenic vessels must face the additional challenge of reproducing thermal degradation of the insulation system. Unfortunately, very few data about the performance of cryogenic insulation systems under fire exposure can be found in the literature. Extensive experimental work is needed to fill this knowledge gap and to support the development of both CFD and lumped parameter models. Finally, focusing on LH_2, it is worth to point out that storage conditions commonly adopted for this fuel (pressure around 1 atm, temperature of about 20 K) are quite close to the critical temperature (33.20 K). As a result of fire exposure, part of the fluid in the tank might easily become supercritical, a condition that CFD models developed for two phase flows cannot handle without specific modifications.

6. Conclusions

CFD-based models are a reliable tool for the simulation of pressure tanks under fire exposure, especially if complex fire conditions are considered, when lumped models may produce non-conservative results in terms of pressurization rate. Nevertheless, the high computational cost hinders the use of CFD simulations for industrial applications. In perspective, a solution to combine the accuracy of CFD based models with the low computational time typical of lumped parameter ones is represented by the development of surrogate models trained on CFD simulation results. Besides the high computational time, the main limitation of currently available CFD approaches remains their inability to adequately simulate the behaviour of tanks when the PRV is activated.

Further research is needed to address this important issue. Additional challenges arise when models for the analysis of cryogenic tanks are considered. The correct simulation of thermal insulation degradation, for which limited data to assist model development is available, is the most critical issue that will need to be addressed.

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