Boiling Thermohydraulics within Pressurized Vessels

Frank Otremba, Ian Bradley, José A. Romero Navarrete

***Abstract*—Transport safety depends in great extent of what happens to the cargo once the carrying vehicle derails or rollovers. The exposure of tanks to direct fire is a condition that potentially involves catastrophic consequences. Studying the behavior of the contained fluid under these drastic circumstances, is critical to develop methods and techniques to mitigate the serious consequences of many mishaps. In this paper, the experimental potentials of a Particle Image Velocimetry data acquisition system are described, for providing experimental data that could be used to calibrate mathematical models. As an example of the situations that need to be modelled, an experiment is described concerning the effect of the boundary conditions and protecting devices, on the rate of variation of pressure and temperature of the fluid in a tank exposed to a direct fire. In this regard, the results emphasize the importance of equipping the vessels with both thermal insulation and safety valves.**

***Index Terms*—thermohydraulics, particle image velocimetry, fire exposure, transport safety, experimental methods, thermal insulation**

I. Introduction

THERMOHYDRAULICS concerns with the different phenomena that take place when a liquid substance is contained while subjected to a heat source, including the rate of phase change and the pressure build-up within the container. While the liquid substance can be a hazardous material, the source of heat can derive from an accidental fire. In the case of the transportation of hazardous materials, the dynamics of the involved thermohydraulics is critical for defining the elapsed time between the beginning of the exposition of a container to fire, and the moment of the eventual catastrophic failure of the transport tanks.

Two of such catastrophic events, characterized by explosions and multi casualties, are listed in Table 1 [1,2], where the general characteristics of the events are described. While one of these mishaps involves a railway tanker and the other one a road tanker, in both cases the containers were subjected to direct fire, and exploded.

Studying the phenomena involved in such circumstances is, consequently, of crucial interest to many institutions, ranging from academic bodies to state organisms in charge of delivering criteria and rules to design and operate the equipment that is involved in the handling of confined liquid hazardous materials tanks that can be potentially exposed to an open fire.

TABLE I

TWO MAJOR ACCIDENTS INVOLVING SPILL AND EXPLOSION OF CARGO

Country/ Year	Fatalities / injured / evacuated people	Description
Italy / 2009	22/27/1000	Derailment of a liquified Propane tank wagon
Spain/ 1978	200 / 400	Rupture of an overfilled road tanker loaded with propylene.

In the case of Germany, there is the Federal Institute for Materials Research and Testing (BAM: Bundesanstalt für Materialforschung und – prüfung). This institute, with backgrounds dated on 1871 as the Royal Prussian Mechanical Testing Institute, allocates human resources in different areas, that include Materials, Energy, Environment, Infrastructure and Analytical Sciences [3].

In this context, BAM has created a novel testing facility that complements existing testing infrastructure, which involves both destructive and non-destructive testing. For example, Figure 1 illustrates a non-destructive testing facility, where objects with masses of up to 200 tons can be subjected to liquid propane burners, according to the standard UN 1965 [4].

Fig. 1. BAM test rig for non-destructive testing. Own material, published in [4].

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For destructive testing, BAM´s facility can provide a heat load of up to 110 kW/m^2, in a surface of 12 m x 8 m, with capabilities of testing 20 tons of non-vehicular objects, and 40 tons of vehicle objects (Figure 2).

Fig. 2. BAM test rig for destructive testing. Own material, published in [4].

These two facilities represent fire pool and non-engulfing situations, respectively. The other potential fire situation involves a jet fire, which is available as well in BAM. Such different types of firing situations involve different levels of severity and heat flux. Figure 3 illustrates the different types of fires and the associated total incident heat flux [5]. According to this figure, the most severe fire situation involves a confined jet fire, while the less severe situation involves an open pool fire.

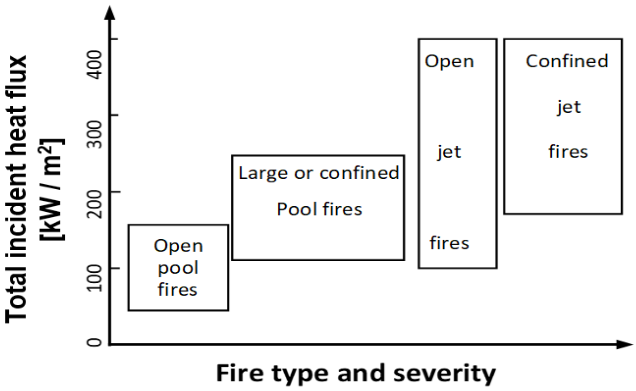


Fig. 3. Comparison of fire types. Redrawn based on [5].

In this paper, a description is presented of experimental and theoretical tools that have been made available to researches in the area of thermohydraulics, including a novel experimental testing facility in BAM as well as theoretical Computer Fluid Dynamics models (CFD). To illustrate the types of practical situations needed to be analyzed and modelled, some experimental results are presented, concerning the effect of safety devices and insulation coatings on the dynamics of a confined fluid`s pressure and temperature variations, when the respective tank is exposed to fire. Some recommendations are further made about potential future research.

II. Thermohydraulics with PIV

The novel testing equipment in BAM was conceptualized to study the boiling process within a container subjected to fire, and was installed at the testing area described in Figure 2. This facility, called Thermohydraulic Monitoring Testing Rig (TMTR) is illustrated in Figure 4, where the testing characteristics are as follows:

- Test vessel: 1-meter diameter
- Variable size fire, fueled by a propane burning system
- A flame shield to protect instrumentation.
- A full-bore glass window that allows a direct view inside the vessel during the fire exposition of the tank.

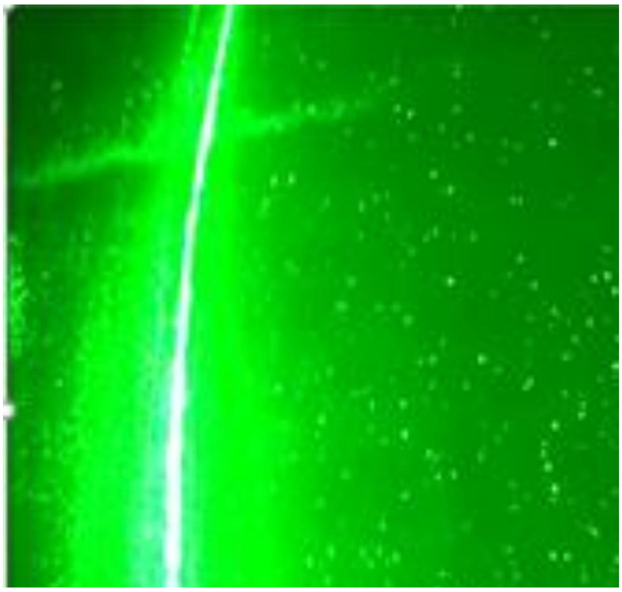
(a) Lateral view of the TMTR testing facility

(b) Front view of the TMTR testing facility

Fig. 4. Novel BAM testing rig for studying boiling thermohydraulics (TMTR). Own material, published in [6,7].

One of the interesting features of this equipment is that it has implemented a Particle Image Velocimetry system (PIV), which is an experimental technique that allows to measure the velocity of particles. PIV systems are based on the interference of a coherent light [8]. Figure 5 illustrates a sample of PIV pictures of the phase change process of water within a vessel that is subjected to a heat source. According to this picture sequence, the size and space density of the vapor bubbles can be monitored through this experimental system, as well as the particle speed concerning both magnitude and direction. In the sequence of images of this figure, the most relevant output corresponds to the size of the boundary area on the left, as the temperature of the fluid raises due to heating, and the water becomes saturated vapor.

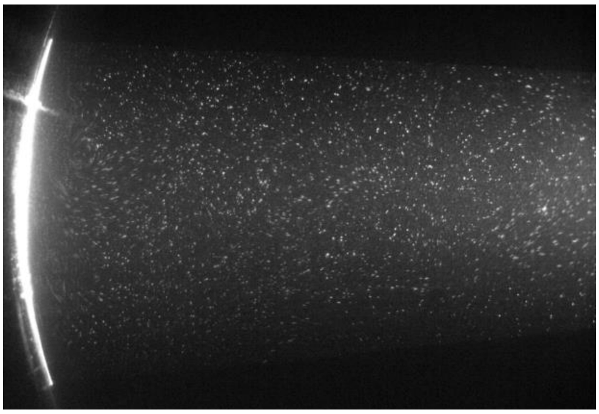
Time 0 s: Fire engulfment initiated.



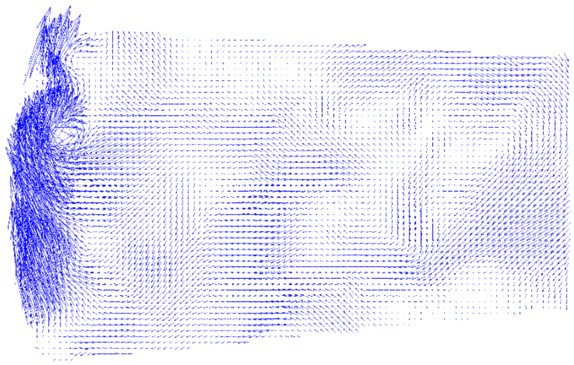
Time 180 s: Bubbles evident on wall and in boundary layer.

Fig. 5. Sample PIV for water phase change dynamics for a vessel at 62% fill level.

The output from the PIV techniques integrates a vector plot that can have a code selection. Figure 6 illustrates a PIV image and the corresponding vector plot.



(a) PIV Image.



(b) Vector plot.

Fig. 6. PIV image and vector plot for phase change experiments presented in Figure 5.

III. Modelling of Vessels

Several approaches in the realm of Computer Fluid Dynamics (CFD) have been introduced in recent years to simulate the dynamics of the heat transfer and phase change of fluids within pressurized vessels, specially concerning the temperature and pressure variation. In this respect, industry and academia use different approaches to simulate thermohydraulics dynamics. For example, Figure 7 illustrates the zone concept used by industry, with one zone (isothermal), and two zones (boundary and subcooled core).

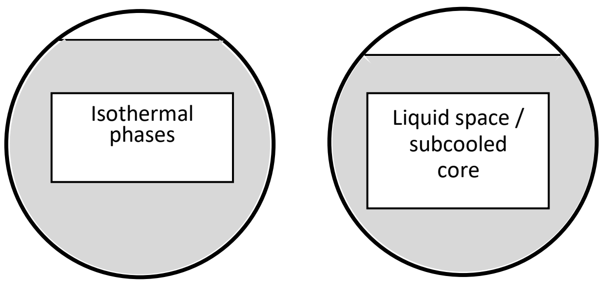


Fig. 7. Types of approaches for modeling the thermohydraulics within the vessel.

In this respect, it can be stated that one-zone models are

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unable to predict accurately the rate of pressurization, while the two-zone model involves the calculation of a saturation vapor pressure at the bulk temperature, where the thermal stratification induces a faster pressure rising, as the liquid surface raises its temperature at a faster rate.

Limitations of the different models to simulate the phase change of the fluid, include that too much empirical data must be used to calibrate the models, as well as several other assumptions, as follows: i) a consistent and uniform heating; and ii) non-three-dimensional effects.

Accordingly, the following challenges remain in the case of CFD simulation of the phase change phenomenon in heated vessels:

- Implementation of boiling process (both saturated and subcooled)
- Stable inclusion of pressure-relief valves
- Validation of the models

The core of these limitations for modeling the dynamics of the phase change within pressurized containers, is the formulation for the phase change phenomenon. A common method of modelling phase change due to wall boiling is based on the heat flux partitioning method first reported in [9]. This mode requires determination of the following:

- Bubble diameter
- Nucleation and density
- Departure frequency.

IV. Gross Experimental Results

As an example of the real testing situations that need to be modelled and analyzed, the results of a destructive testing are described, involving different boundary conditions and the use of safety devices when a vessel is exposed to direct fire.

Three testing situations were considered during the heating process: i) use of a pressure-relief valve only; ii) use of a thermal coating and safety valve; and iii) use of a thermal coating only.

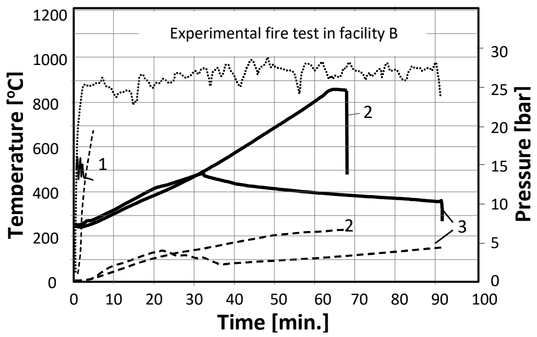
Figure 8 illustrates the outputs from this experiment, for the three conditions described above. The outputs include the time variation of the temperature and pressure of the fluid within the tank, for a flame temperature that remains within a narrow variation band. At the bottom of this figure, the image of the failed vessel is included.

These outputs thus reveal the effects of both the thermal insulation and the pressure-relief valve, on the time variation of the temperature and the pressure. It can be observed that the temperature increases monotonically in the case of the situations involving the thermal insulation protection, where the pressure reaches a maximum value at around 70 minutes after the test initiation. As expected, the pressure decreases in the case of the test with the safety valve, and increases when such pressure-relief device is not present.

The situation in which no thermal coating is provided can be described as a fast heating of the fluid, implying that temperatures that are reached after many minutes in the case of the isolated vessel, are reached in only few minutes in this case. The rate for the temperature increase is comparable for both situations involving the thermal coating.

One important fact in these results, is that the failure of the tank was not avoided through the use of a pressure relief valve. A theoretical failure criterion was used to conclude the test (pressure of 25 bars, and temperature of 350 ^{0}C).

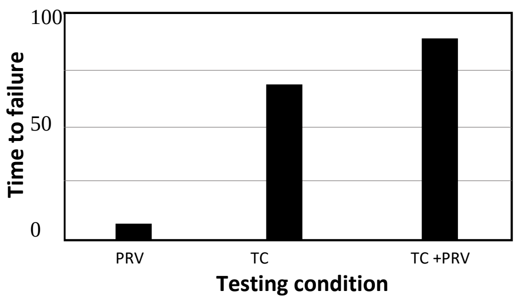
The time-to-failure for the three testing conditions are described in Figure 9, where it can be observed that the use of both the thermal coating and the safety valve, drastically increased the elapsed time for the failure of the tank.



1: Tank with safety valve.
2: Tank with fire protection coating.
3: Tank with fire protection coating and safety valve.

——— Pressure
.... Flame temperature
– – – – – Temperature

Fig. 8. Thermohydraulics outputs of the testing carried at BAM. Effect of the different levels of protection (fire coating and safety valve), on temperature and pressure variation.



1:	PRV :	Pressure relief valve only
2:	TC:	Thermal coating only
3:	PRV + TC :	Pressure relief valve plus thermal coating

Fig. 9. Effect of thermal coating and safety valve on the time for failure.

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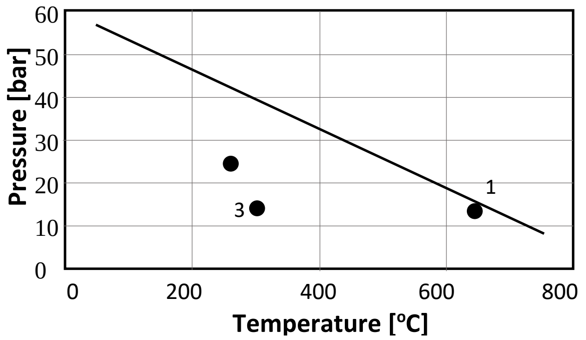
Use of thermal insulation thus generates a remarkable delay for the failure condition, which is critical in case of emergencies involving tanks exposed to fire as a result of mishaps.

The experimental results just described can be put into a practical context involving burst pressure calculations and existing codes. Figure 10 illustrates the graph of pressure versus temperature for the bursting situation, according to a calculation performed with a computer program (ANSYS). On the other hand, this figure also illustrates such relationship in the case of the allowable stress condition, according to the American Society of Engineers Code (ASME), which involves another constant slope line. In this plane, the three experimental outputs are marked, where now the first situation describes the use of the pressure-relief valve (PRV); the second one describes the use of a thermal coating (TC); and the third condition describes the use of both the thermal coating and the pressure-relief valve (PRV + TC). According to these results, there was still a safety margin to reach the theoretical bursting condition, while there is a good agreement with the failure condition.



1: PRV (Failure)
2: TC (No failure)
3: PRV + TC (No failure)
——— Burst temperature (ANSYS).

Fig. 10. Testing results in the context of regulation and theoretical data.

V. Conclusion

As a consequence of transport mishaps, the direct exposure of tanks to fire has had catastrophic consequences, causing fatalities and injured people. In some cases, such mishaps have caused massive evacuations. While the reason for such mishaps cannot be directly attributed to the substances that are being transported, the events that follow the derailment of a rail tanker or the rollover of a road tanker, depend in a great measure of how hazardous the carried substance is. That is, any spill of hazardous material derived from a tank derailment or tanker rollover, represents the critical event for mishaps that have severe consequences. The associated sequence of events includes the exposure of a hazardous material container to a direct fire and its potential explosion. The behavior of the fluid inside the tank is thus critical to somehow asses the severity of the consequences of any accident involving vessels exposed to a direct fire.

Thermohydraulics represents a basic science for providing practical data about the behavior of the fluid within pressurized containers. Critical information in this regard, includes the time variation of both the temperature and the pressure within a tank when it is exposed to direct fire, as a function of different boundary conditions. Such boundary conditions include protection equipment, particularly, an insulation coating and a pressure relief valve. In this respect, the complexities of the thermal and hydraulics phenomena involved in this process, has led to many experimental approaches, including both destructive and non-destructive approaches.

An optical experimental technique is described in this paper for measuring the dynamics of the phase transformation of the contained liquid when the associated vessel is subjected to a direct fire. Such technique is known as Particle Image Velocimetry (PIV) and represents an advanced method to get information to calibrate mathematical approaches. That is, computational fluid dynamics computer programs can be calibrated through the data obtained from this experimental technique, as the size, location and speed of the phase-change bubbles can be acquired.

The problem of modelling the behavior of a confined liquid fluid when its container is subjected to a direct fire, is described in this paper though the results of a destructive test that aimed at assessing the potential effect that insulation coats on the vessel as well as the installation of pressure relief valves, have on the time variation of the temperature and pressure within the tank, when subjected to an external heat source. Results reveal the drastic effect of the thermal coating to decrease the rate at which the temperature rises within the tank, and the effect of the pressure relief valve to delaying the failure of the tank. However, this pressure relief device did not avoid the eventual failure of the tank.

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