CHEMICAL ENGINEERING TRANSACTIONS
VOL. 57, 2017

A publication of
AIDIC
The Italian Association
of Chemical Engineering
Online at www.aidic.it/cet

Guest Editors: Sauro Pierucci, Jiří Jaromír Klemeš, Laura Piazza, Serafim Bakalis

ISBN 978-88-95608- 48-8; **ISSN** 2283-9216

DOI: 10.3303/CET1757045

Experimental Analysis of a Pressurized Vessel Exposed to Fires: an Innovative Representative Scale Apparatus

Ian Bradley[a], Giordano E. Scarponi[b], Frank Otremba[c], Valerio Cozzani[b], Albrecht M. Birk[d]

[a] University of Edinburgh, UK
[b] LISES - Dipartimento di Ingegneria Civile, Chimica, Ambientale e dei Materiali, Alma Mater Studiorum - Università di Bologna, Italy.
[c] Bundesanstalt für Materialforschung und -prüfung (BAM), Berlin
[d] Department of Mechanical and Materials Engineering, Queen's University, Kingston, Ontario Canada
I.Bradley@ed.ac.uk

One of the most critical safety issues concerning the transportation and the distribution of hazardous materials, is the possible occurrence of accidental fires affecting transport vessels, leading to the heat up and consequent failure with catastrophic effects. Therefore, since the early seventies, numerous field studies and laboratory scale tests were carried out on pressurized tanks, in order to simulate fire impingement conditions with the aim of increasing the understanding of such scenarios and improving the safety in this field. However, the detailed assessment of the inner fluid behaviour during fire exposure in terms of velocity, temperature and boundary layer determination was never object of detail investigation. This is critical for the development and validation of advanced modelling tools such as computational fluid dynamic (CFD), which is aimed at predicting vessel pressurization rate, time to failure and to support detailed safety and external emergency studies.

With the aim of providing experimental data suitable for supporting the advanced modelling of fired vessels heat up and consequent pressurization, an innovative fire test set-up was designed for the present research work. Initial tests were carried out using water as operative fluid. The fire conditions, heated area, test fluid and filling degree can be varied among tests in order to investigate the influence of these parameters on the thermal and velocity profile in the tank lading.

In the present work, the experimental set up is described and some preliminary results obtained during commissioning tests are summarized. The capabilities of the present apparatus in providing advanced results to support the evaluation of the behaviour of fired pressurized tankers are discussed.

1. Introduction

The study of accident scenarios involving pressure vessel exposed to fire has received particular attention in the last few years (Argenti and Landucci, 2015; Argenti et al. 2014; Scarponi et al., 2017). The pressurization rate of fire engulfed pressure vessels is understood to be driven by the degree of thermal stratification within the fluid component of the vessel contents (Birk and Cunningham 1996; Hadjisophocleous et al. 1990). The thermohydraulic behaviour of liquid and vapor inside a vessel during fire engulfment is a topic that has received intermittent investigation over the past 40 years. Knowledge of the importance of thermal boundary layer development and transport has led to the development of a number of zone or integral models that seek to account for this (e.g. Johnson 1988, Ramskill 1988; Beynon et al. 1988; Venart 1986), however the ambition of developing a reliable three-dimensional numerical model remains incomplete. Validation of numerical models also remains a challenge due to limitations in the body of supporting experimental data. Although pressure and bulk temperature data is available, detailed experimental data on the boiling characteristics and boundary layer fluid properties for typical vessel geometry and fluid content combinations remains scarce. This papers describes a test apparatus designed to investigate such characteristics and presents a selection of initial results from a first round of tests.

Please cite this article as: Bradley I., Scarponi G.E., Otremba F., Cozzani V., Birk A.M., 2017, Experimental analysis of a pressurized vessel exposed to fires: an innovative representative scale apparatus, Chemical Engineering Transactions, 57, 265-270 DOI: 10.3303/CET1757045

2. Experimental equipment

Figure 1: The test equipment shown with an example fire.

The tests were performed at the BAM technical safety test site (Droste et al., 2011), in the state of Brandenburg, Germany. The test facility used was the same one used to study the pressurization of full containment pressure vessels under contract with the US DOT Federal Railroad Administration in 2014 (Bradley et al., 2015; Birk et al., 2016). One of the main advantages of this facility is the large degree of flexibility, both in the size of objects it can test and the fire configurations that can be developed.

The apparatus consists of a 1.016 m outer diameter vessel with a total volume of 2.6 m^3. The ends of the tank are 2:1 semi-elliptical heads and the vessel wall thickness 7.4 mm. The tank is cut in two ends: the “test end”, with a volume of 1.9 m3, and the “camera end”, with a volume of 0.7 m3. The test end is engulfed in fire generated through a low speed burners array, fuelled by liquid propane to reproduce an engulfing pool fire scenario, as shown in Figure 1. The test end is instrumented with wall and lading thermocouples and pressure transducers. The thermocouples inside the tank lading are positioned at varying distances from the wall at a number of measuring stations. The majority of thermocouples are close to the wall, in order to characterize the thermal boundary layer and thermal stratification of the liquid phase. Directional flame thermometers are installed on the external wall to measure fire conditions. Work was undertaken to characterize the fire throughout the commissioning tests using directional flame thermometers, water cooled calorimeters and infra-red thermography. This work is shortly to be published separately.

The two ends are separated by a sheet of 19mm toughened low-iron glass. It is held between two flanges, as shown in Figure 2, using a solid-state gasket to allow pressurization of the vessel to over 5 bar. Cameras positioned in the camera end record the behaviour of the fluid in the test end. This can provide visual information about both the boiling occurring close to the wall and the flow field. A custom built pressure compensation system is implemented to equalize the pressure in the two ends, in order to preserve the integrity of the glass window during pressurization and depressurization. The test end has manual and remotely operated vent valves, in addition to a 2” SCH60 flange for future compatibility with laser based velocity measuring techniques. A schematic diagram of the equipment is shown in Figure 3.

Figure 2: The equipment end showing glass held in position. The supply tank for pressurization of the equipment end is visible to the right.

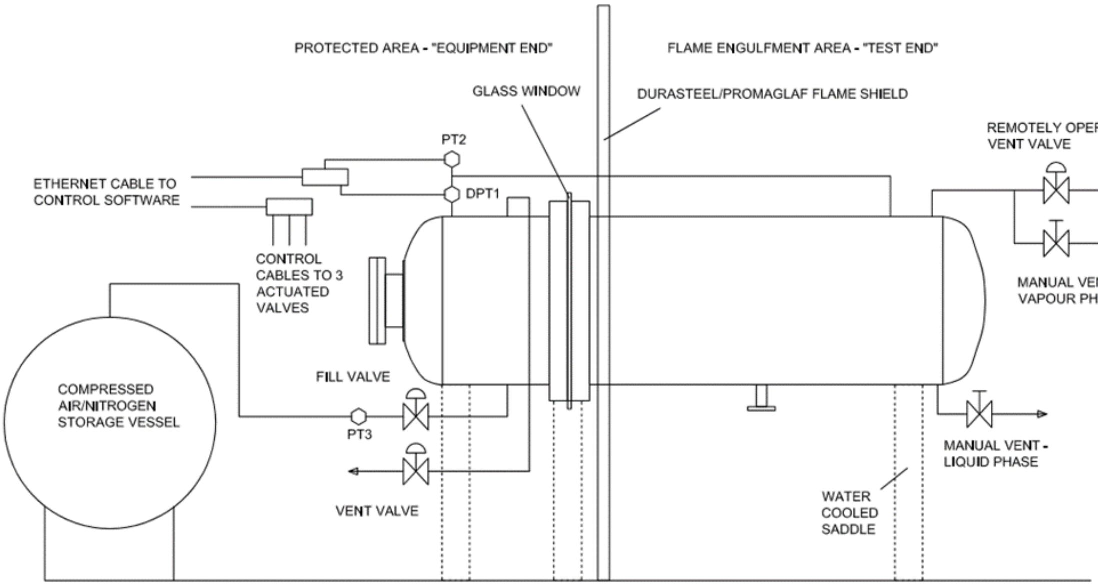

Figure 3: A schematic diagram of the equipment set-up.

3. Commissioning Test Series

An initial series of commissioning tests were performed in June 2016. Water was the test fluid and only a limited vessel surface area was exposed to fire. The primary purpose of the tests was commissioning of the equipment and finalization of the thermocouple type and locations for a subsequent test series. A selection of the tests is listed in table 1, with the prefix c denoting the test as part of the commissioning series (to distinguish them from future tests). During the commissioning phase the opportunity was taken to investigate the effect of changing the location of localized heating in relation to the vessel test fluid surface height. The heated zone is described in terms of the width (along the axis of the vessel), the number of sides exposed, and the height from the bottom of the vessel to the top of the heated area (measured to the equivalent height directly above the bottom of the vessel and ignoring the curvature). In tests up to c10 the total surface area heated remained constant (it extended to the bottom of the vessel in test c6 and c10, but did not in tests c7 and c8). From tests c11 onwards the patch extended to the bottom of the vessel in all cases.

Table 1: List of commissioning tests

Test number	Liquid surface height (filling percentage)	Heated area			
		Sides	Width	Height	Total
C6	0.7 m (74 %)	1	0.5 m	0.65 m	0.706 m^2
C7	0.7 m (74 %)	1	0.5 m	0.70 m	0.713 m^2
C8	0.7 m (74 %)	1	0.5 m	0.75 m	0.720 m^2
C10	0.7 m (74 %)	1	1.0 m	0.65 m	1.420 m^2
C11	0.7 m (74 %)	1	1.0 m	0.75 m	1.440 m^2
C13	0.7 m (74 %)	2	1.0 m	0.65 m	2.825 m^2
C14	0.7 m (74 %)	2	1.0 m	0.75 m	2.880 m^2
C18	0.92 m (96 %)	2	1.0 m	0.75 m	2.880 m^2

4. Test Results and discussion

The sample tests described in this paper were intended to recreate conditions representative of a vessel with a localized defect in a fire protection material or system exposed to a non-engulfing hydrocarbon pool fire. The tests reported herein were primarily intended as commissioning tests, and some differences exist between tests, including leaks which result in lower pressurization rates being measured. These differences are not reported in detail here, but consequently, the test results should not be relied upon to draw firm quantitative conclusions. Despite this, tentative conclusions can be drawn from trends observed.

An example of the results from a commissioning test are given in Figure 4. The tests were not fully instrumented; however, three types of thermocouples were placed at varying distances from the vessel wall at a height of 0.6m above the vessel bottom. Figure 4 shows the results for the 1.5mm type K ungrounded thermocouples, with the legend giving the distance from the wall for each. The curves clearly show that the temperature drops quickly moving from the wall towards the bulk of the liquid. This result suggest that, with an appropriate positioning of the thermocouples with respect to the wall, it will be possible to characterize the behaviour of the thermal boundary layer.

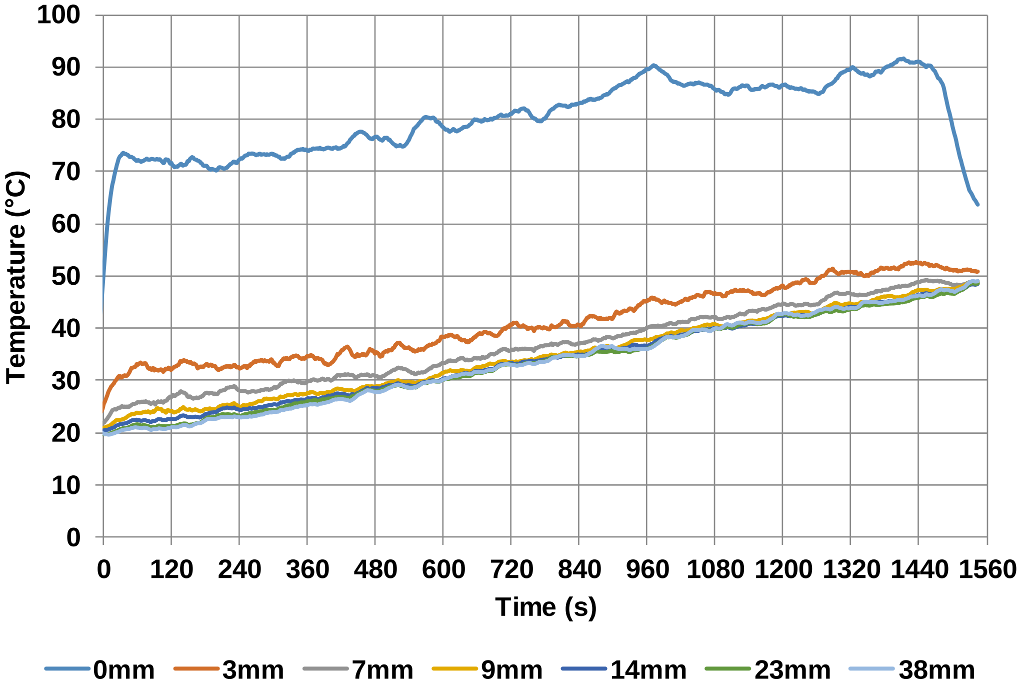

Figure 4: The (30s time-averaged) temperatures and pressures for test 18c. The legend indicates the distance of the thermocouple from the inner wall of the tank.

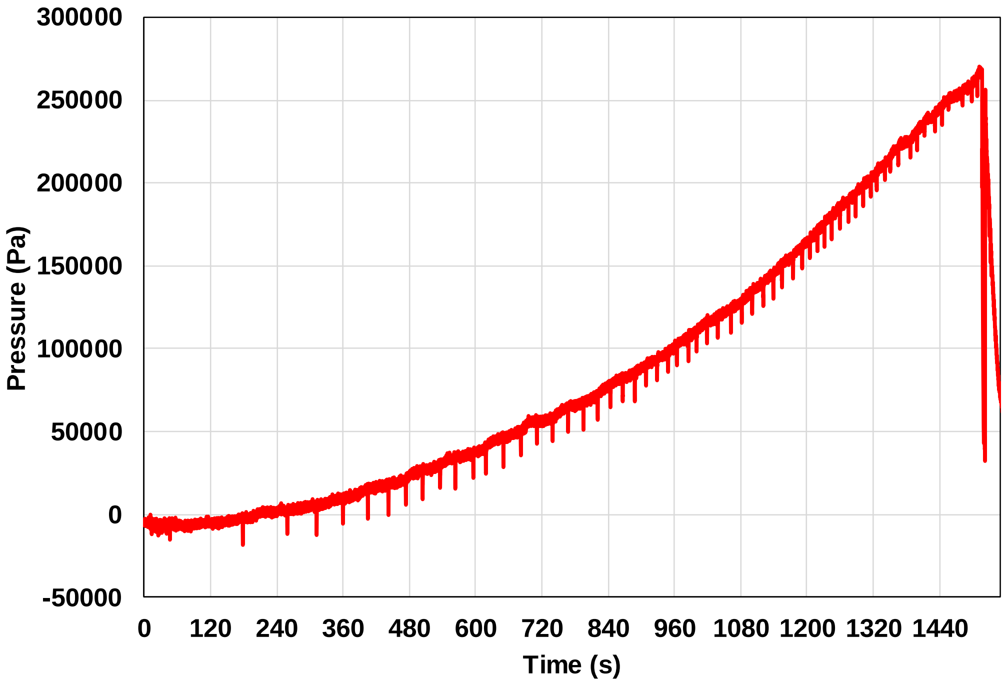

Figure 5: Pressure rise for test 18c.

Going to consider the pressurization rate, Figure 5 shows the pressure curve obtained in test c18. The downwards spikes correspond to the moments in which the pressure compensation system opens the line connected to the compressed air storage vessel in order to equalize the pressure in the two ends.

Table 2 reports the pressurization rate obtained in the different tests, together with the heated surface area and the relative position of the unprotected zone with respect to the liquid level. Comparing the measurements from test c13 and c14, the pressurization rate obtained in the first test is more than 6 times than the value registered in the latter one (69 Pa/s against 11.5 Pa/s). Since it appears not credible that an increment of just a 2 % of the heated surface area was responsible for such an increase in the pressurization rate, this results seems to suggest that an exposure of just 0.05 m of vessel wall above the liquid level to fire can increase the pressurization rate significantly.

However, it should be warned that this tentative conclusion would require validation through repeat testing, including exposure of a large area of vessel to fire to increase the overall pressurization rate and reduce the influence of natural variation of measurement associated with large outdoor fires.

If the results here can be replicated both experimentally and through modelling, it would lead to the conclusion that two dimensional (single- or multi-) zone models are likely to be conservative when predicting the pressurization rate of vessels with local insulation defects exposed to fire conditions.

Table 2: Maximum pressurization rate obtained for the different tests

Test number	Heated area	h_{HA} - h_L *	Maximum pressurization rate
c6	0.706 m^2	- 0.05 m	Negligible
c7	0.713 m^2	0.00 m	Negligible
c8	0.720 m^2	+ 0.05 m	Negligible
c10	1.420 m^2	- 0.05 m	Negligible
c11	1.440 m^2	+ 0.05 m	115 Pa/s (1 psi/min)
c13	2.825 m^2	- 0.05 m	11.5 Pa/s (0.1 psi/min)
c14	2.880 m^2	+ 0.05 m	69 Pa/s (0.6 psi/min)
c18	2.880 m^2	- 0.17 m	345 Pa/s (3 psi/min)

*h_{HA} = heated area height, h_L = liquid surface height. Height is intended as the vertical distance from the bottom of the tank

5. Conclusion

A novel deign of test equipment has been commissioned to investigate thermal stratification and boiling during fire exposure of pressure vessels. Extensive temperature measurements and video of the internal conditions during fire exposure are possible, and the equipment has been designed for future compatibility with laser-based velocity measurement techniques. It is expected to generate data large quantities of data that will be of use in validation of two- and three-dimensional CFD models for the prediction of pressure vessel behaviour in fire. Future work will seek to characterize the boundary layer conditions in detail for a range of test fluids, fill levels and fire-induced thermal boundary conditions.

Initial tests undertaken during commissioning may indicate that fire exposure of the vessel wall just above the liquid level can have a notable influence on the pressurization rate, by increasing the degree of superheat. Further experimental and modelling work is required to confirm and quantify this effect, or to rebut this conclusion.

Acknowledgments

The author expresses thanks to Akzonobel and Promat for their generous support of the project. Also to Jörg Borch and Thilo Hilse at BAM for the considerable assistance they provided.

Reference

Anderson C.E., Townsend W., Zook J., Cowgill G., 1974, The effects of fire engulfment on a rail tank car filled with LPG, US DOT FRA1974.

Argenti, F., Landucci, G., 2015, Quantitative evaluation of the safety barriers to prevent fired domino effect, Chemical Engineering Transactions, 43, pp. 2377-2382. DOI: 10.3303/CET1543397

Argenti, F., Guerrini, L., Rossi, F., Landucci, G. 2014, Experimental and numerical characterization of fireproofing materials based on ASTM E162 standard, Chemical Engineering Transactions, 36, pp. 367-372. DOI: 10.3303/CET1436062

Beynon, G.V., Cowley L.T., Small L.M., Williams I., 1988, Fire engulfment of LPG tanks: HEATUP, A predictive tool, Journal of Hazardous Materials, 20, 227-238.

Birk A.M., Cunningham M.H., 1996, Liquid temperature stratification and its effect on BLEVEs and their hazards, Journal of Hazardous Materials, 48, 219-237.

Birk, M. A., Otremba, F., Borch, J., Bradley, Ian and Bisby, L., 2016, Fire Testing of Total Containment Pressure Vessels, Chemical Engineering Transactions, 48, pp. 277–282. DOI: 10.3303/CET1648047.

Bradley I, Birk A.M., Otremba F., Gonzalez F., Prabhakaran A., Bisby L. 2015, Development and characterization of an engulfing hydrocarbon pool fire test for Hazardous Materials Pressure Vessel, Proceedings of the 1sft Conference on Fire and Blast (CONFAB) Glasgow.

Droste B., Ulrich A., Borch J., 2011, Brand new fire test facilities at 'BAM Test Site Technical Safety'. Packaging, Transport, Storage & Security of Radioactive Material 22.4, 195-199.

Gonzalez F., Prabhakaran A., Robitaille A., Booth G., Birk A.M., Otremba F., 2015, Rail Tank Car Total Containment Fire Testing: Planning and Test Development, ASME Joint Rail Conference JRC 2015-5764, San Jose, USA.

Hadjisophocleous G.V., Sousa A.C.M., Venart J.E.S., 1990, A study of the effect of the tank diameter on the thermal stratification in LPG tanks subjected to fire engulfment, Journal of Hazardous Materials, 25, 19-31.

Johnson M.R., 1988, Tank Car Thermal Analysis, Vol 1 User Manual, Vol 2 Technical Documentation, US DOT Report1998.

Ramskill P.K., 1988, Description of the ENGULF computer codes -- Codes to model the thermal response of an LPG Tank either fully or partially engulfed by fire, Journal of Hazardous Materials, 20, 177-196.

Scarponi G.E., Landucci G., Tugnoli A., Cozzani V., Birk A.M., 2017, Performance assessmento of thermal protection coatings of hazardous material tankers in the presence of defects, Process Safety and Environmental Protection, 105, pp. 393-409

Venart J.E.S., 1986, Tank car thermal response analysis -- Phase II.