Proceedings of the ASME 2023
Pressure Vessels & Piping Conference
PVP2023
July 16-21, 2023, Atlanta, Georgia

PVP2023-107249

ON THE QUANTIFICATION OF ACCIDENTAL GAS RELEASE FROM PRESSURIZED VESSELS

Annalisa Rosti[1,2], Emanuele Brunesi[2], Filippo Dacarro[2], Paolo Dubini[2], Alessandra Marino[3], Giorgio Nosenzo[4], Gerard J. O'Reilly[5]

[1]University of Pavia, Pavia, Italy
[2]European Centre for Training and Research in Earthquake Engineering (Eucentre), Pavia, Italy
[3]Istituto Nazionale per l'Assicurazione contro gli Infortuni sul Lavoro, Rome, Italy
[4]Independent Researcher, Italy
[5]Scuola Universitaria Superiore IUSS Pavia, Pavia, Italy

ABSTRACT

NaTech accidents may pose significant risk to human safety, not only for potential structural and non-structural damage but also considering the possible release of hazardous substances into the environment. In the context of risk-based management of industrial facilities, the detection and quantification of accidental release of toxic substances from pressurized pipelines and tanks are thus of primary concern. Based on these considerations, this paper presents a simplified analytical model for assessing the accidental release of gas from pressurized vessels. Taking advantage of pressure and temperature measurements acquired by fiber-optic (FO) sensors, the proposed model allows for quantifying the mass outflow rate, averaged in a given time window, and for estimating the leakage area. To this end, the model is capable of identifying the time at which the discharge process starts and following its evolution over time. The capability of the proposed analytical model is demonstrated by comparing predictions with results from several experimental tests, specifically carried out for simulating the release of gas from a vessel, pressurized at different initial pressure thresholds and equipped by FO sensors. Estimates from the developed analytical model can be also exploited for assessing concentrations of chemicals in the industrial plant and simulating their spatial diffusion over time, thus supporting the generation of environmental health risk maps.

Keywords: NaTech accidents; fiber-optic sensors; pressurized vessels; pipelines; gas release; environmental health risk.

1. INTRODUCTION

The impact of a natural hazard on industrial facilities can lead to the release of hazardous materials (hazmat) potentially triggering secondary events, such as fires and explosions, with possible severe consequences on both humans and the environment ([1]; [2]). Besides structural and non-structural damage potentially initiated by natural hazards, the exposure to hazardous materials as a result of NaTech incidents can pose significant risk to human health with both short- and long-term consequences.

Detection and quantification of the accidental release of toxic substances from pressurized vessels and pipelines are thus essential for risk-based management of industrial facilities at risk of NaTech events. In this context, optical fiber sensing technology has huge potential for industrial applications (e.g. [3]; [4]; [5]; [6]). Fiber-optic sensors boast several advantages over traditional sensor technologies, such as being durable and light weight, immunity to electromagnetic fields, high accuracy, capability of covering long distances, and good embeddability even in harsh environments, although they may become more expensive – than traditional sensors – in some cases. Fiber-optic sensors permit real-time measuring physical parameters (e.g. strain, pressure, temperature), enabling to detect potential damage or possible leaks from pressurized components (e.g. [7]; [8]). On the other hand, quantification of the accidental discharge rate from pressurized components requires understanding of the discharge process and of the evolution of the physical properties of the gas (e.g. [9]; [10]; [11]).

This paper presents an extensive experimental-analytical study on the quantification of accidental gas release from pressurized components typical of industrial facilities. A simplified analytical model is developed for quantifying the

Copyright © 2023 by ASME

accidental gas release from a pressurized vessel, in terms of average mass outflow rate and leak area. A test-bed is specifically assembled for experimentally simulating the accidental gas release from a pressurized vessel, instrumented by FO sensors. Information collected during the experimental tests is processed both to provide input data required by the proposed analytical model and to verify the suitability of the model to be used in various industrial risk-based applications. Comparison of the estimates of the proposed model, coupled with data acquired by FO sensors, with those obtained by alternative instrumentation shows the adequacy of the developed analytical model for accidental gas release quantification. Results from this work highlight both the suitability of FO sensor technologies for leakage detection and of the proposed analytical model for assessing the accidental release of harmful substances. This underlines the suitability of their coupling for risk mitigation and management in industrial facilities following hazardous events. The presented experimental test-bed and analytical model were developed and extensively used within the ROSSINI Project ([12]; [13]), for simulating and quantifying accidental gas release within a case-study industrial plant at risk of NaTech disasters.

2. A SIMPLIFIED ANALYTICAL MODEL FOR ACCIDENTAL GAS RELEASE QUANTIFICATION

A simplified analytical model is developed for the quantitative assessment of accidental gas release from pressurized components typical of industrial facilities. The proposed model specifically focuses on the discharge process of a pressurized vessel for quantifying the average mass outflow rate and the leak exit area, following accidental gas release. These estimates are essential for risk-based management in industrial plants at risk of NaTech accidents. On one hand, they allow for detecting accidental release of toxic substances in the facility; on the other, they represent some of the input data required by atmospheric dispersion models (e.g. [14]).

Modeling the discharge process is difficult, as the vessel undergoes depressurization as the gas is released, with continuous change of gas density, pressure and temperature. Simplifying assumptions are thus fundamental for easily assessing the gas' release rate. The proposed analytical model assumes that the gas in the vessel is thermally and calorically perfect. The average velocity of the fluid in the vessel is assumed to be negligibly small with respect to the leak velocity and contribution from gravitational potential energy is also neglected. The leak area is modeled as a converging nozzle, discharging to the surrounding environment at the generic pressure (P_B) equal to the atmospheric pressure (P_{atm}), with isentropic and quasi-unidimensional flow (e.g. [15]; [16]). The discharge process is physically described by referring to a control volume, corresponding to the vessel volume, V, pressurized at the initial pressure value P_0 and with initial temperature T_0.

Based on the equation of mass conservation and referring to the control volume, the variation of the gas mass in time (dm/dt) is given by the difference between the mass inflow ($\dot{m}_{in}$) and outflow ($\dot{m}_{out}$) rates:

$$\frac{dm}{dt} = \dot{m}_{in} - \dot{m}_{out} \qquad (1)$$

In this study, the mass inflow rate ($\dot{m}_{in}$) is zero, as no gas flow enters the vessel.

Taking advantage of the equation of state of a hypothetical ideal gas, the mass of the gas in the vessel, m, can be written as:

$$m = \frac{PVM}{RT} \qquad (2)$$

where P and T are the gas pressure and temperature, V is the vessel volume, R is the universal gas constant, M is the molar mass of the gas.

By modeling the opening of the leak as a converging nozzle (e.g. [16]), the mass outflow rate ($\dot{m}_{out}$) can be evaluated based on Eq 3, depending on sonic (Eq 3a) or subsonic conditions (Eq 3b):

$$\dot{m}_{out}(t) = \begin{cases} A_t P(t)\sqrt{\dfrac{kM}{RT(t)}} \cdot \sqrt{\left(\dfrac{2}{k+1}\right)^{\frac{k+1}{k-1}}} & (a) \\ A_t P(t)\sqrt{\left(\dfrac{2k}{k-1}\right)\dfrac{M}{RT(t)}\left(\dfrac{P_B}{P(t)}\right)^{\frac{2}{k}}\left[1-\left(\dfrac{P_B}{P(t)}\right)^{\frac{k-1}{k}}\right]} & (b) \end{cases} \qquad (3)$$

where A_t is the leak area, $P(t)$ and $T(t)$ are pressure and temperature of the gas in the vessel, respectively, P_B is the ambient pressure, k is the gas specific heat ratio, M is the gas molar mass and R is the universal gas constant.

In case of accidental hazmat release, direct use of Eq 3 for quantification of the release rate is however prevented, as the leak area is unknown. Based on this consideration, the proposed analytical model first quantifies the total mass of gas out of the tank (m_{out}) in the reference timespan, by benefitting from real-time pressure and temperature measurements from FO sensors. At a given time instant, t, the total mass of gas out of the vessel (m_{out}) is calculated as difference between the mass of the gas initially in the vessel (i.e. at the time instant t_0), m_0, and the mass of gas in the vessel at the time instant t, $m(t)$.

Taking advantage of the ideal gas law, the total mass of gas out of the vessel (m_{out}) at a given time instant, t, is expressed as:

$$m_{out}(t) = m(t_0) - m(t) = \frac{P_0VM}{RT_0} - \frac{P(t)VM}{RT(t)} \qquad (4)$$

The generic time instant, t, refers to the time instant at which one assesses the average mass outflow rate. For instance, it may refer to the emptying time, identified when the pressure of the gas in the vessel achieves the ambient pressure.

Known the total mass of gas out of the tank (m_{out}), the mass outflow rate averaged in a predefined time window, $\dot{m}_{out,avg}$, can be computed.

Copyright © 2023 by ASME

Based on the evolution of the mass of gas out of the tank provided by Eq 4, the instant mass outflow rate, $\dot{m}_{out}$, can be approximated as:

$$\dot{m}_{out} = \frac{\Delta m_{out}}{\Delta t} \quad (5)$$

An estimate of the exit area, A_t, can be obtained by equating Eqs 3 and 5.

3. QUANTIFICATION OF ACCIDENTAL GAS RELEASE THROUGH EXPERIMENTAL TESTS

The accidental gas release and the consequent discharge process of a pressurized vessel were experimentally simulated by assembling an ad-hoc test apparatus (Figure 1). The test-bed mainly consisted of an approximately 1 cm-thick steel vessel, pressurized by nitrogen, selected given its non-toxic, non-flammable and non-combustible properties. The vessel was charged by nitrogen reservoir bottles, by using a manual valve for regulating the speed of the charge and discharge process (Figure 1).

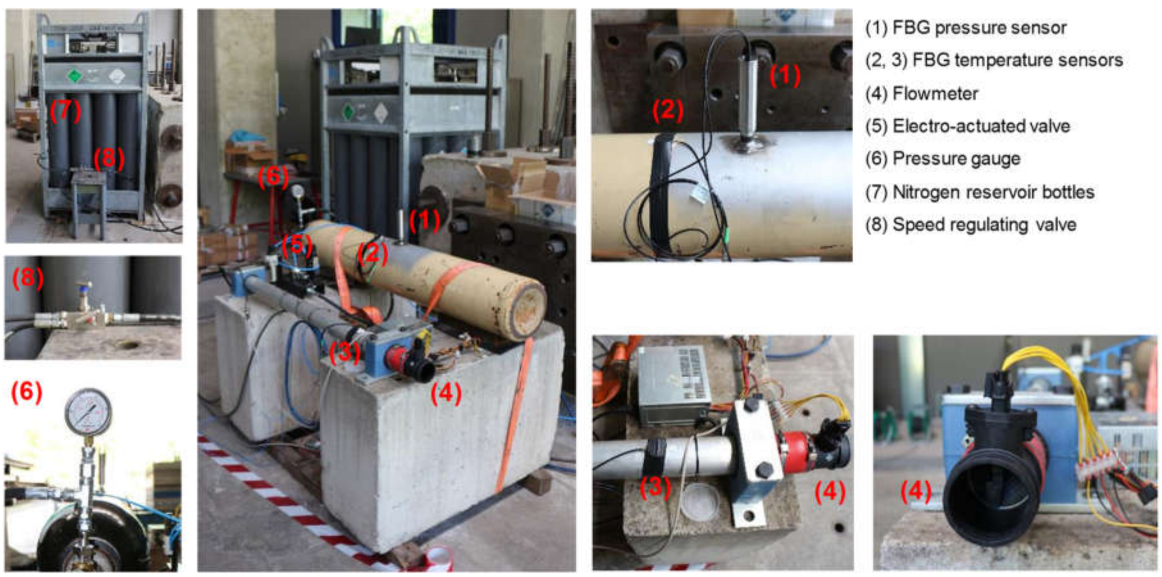

FIGURE 1: TEST-BED FOR THE EXPERIMENTAL SIMULATION OF THE ACCIDENTAL GAS RELEASE.

The test-bed was equipped by FO Fiber Bragg Grating (FBG) sensors for instantaneously monitoring pressure and temperature of the gas in the vessel and detecting potential pressure and temperature drops due to gas release. One FBG pressure sensor (Sylex P-05) was installed on the vessel to monitor the pressure of the gas inside the vessel (Figure 1, 2). Two FO surface temperature sensors (Sylex STS-03) were used for temperature measurements. One temperature sensor was installed on the outer surface of the tank, whereas the other one was placed on the outer surface of the exit pipe (Figure 1, 2). The FO pressure sensor has pressure range of 1-100 bar and an operating temperature range from -20°C to +60°C. The FO temperature sensors have a temperature range from -20°C up to +60°C. All FBG sensors were connected to an optical sensing conditioner unit (Micron Optics Sm130-500) by standard optical cables and connectors (Figure 2).

An air-mass flowmeter was installed at the end of the exit pipe allowing for directly measuring the mass outflow rate during the discharge process of the vessel. Accidental gas release was simulated by an electro-actuated valve, allowing the system to release nitrogen in the environment through the exit pipe (Figure 1).

Several experimental tests were carried out for simulating the accidental gas release from the vessel. The vessel was pressurized at different initial pressure thresholds ranging from 20 up to 100 bar, with an increment of 10 bar. Two alternative increasing opening areas (i.e. $A_{t,1/4}$ and $A_{t,1/2}$) of the valve were considered for simulating the accidental gas release. In the following, results from experimental tests considering exit area of $A_{t,1/2}$ are presented. Real-time measurements acquired by FBG sensors during the experimental tests were post-processed to obtain the evolution of gas pressure (Figure 3a) and temperature (Figure 3b) over time. In the figures, the different colors refer to the different thresholds at which the vessel was initially pressurized. Results show the gradual depressurization of the vessel (Figure 3a). Temperature of the gas in the vessel does not show a significant reduction over time, with a maximum decrease of the initial value lower than 30% (Figure 3b).

 Copyright © 2023 by ASME

(a)

(b)

(c)

FIGURE 2: FBG PRESSURE (SYLEX P-05) SENSOR (a); FBG TEMPERATURE (SYLEX STS-03) SENSOR (b); MICRON OPTICS SM130-500 CONDITIONER UNIT (c).

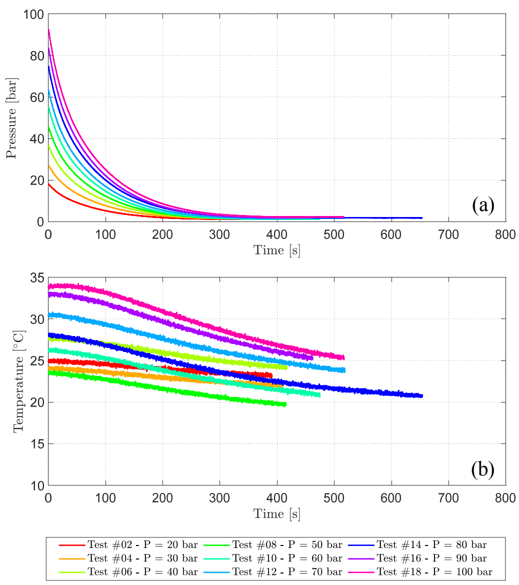

FIGURE 3: PRESSURE (a) AND TEMPERATURE (b) MEASUREMENTS ACQUIRED BY FBG SENSORS DURING THE EXPERIMENTAL DISCHARGE PROCESS OF THE VESSEL.

4. VALIDATION OF THE ANALYTICAL MODEL

Results from the experimental tests were exploited for testing the capability and appropriateness of the simplified analytical model to be used for accidental gas release quantifications. Experimental validation of the analytical model was performed with respect to the evolution of the mass of gas out of the tank over time and of the instant mass outflow rate, evaluated by alternative instrumentation (i.e. flowmeter). The suitability of the proposed analytical model to estimate the leak area was also verified.

Figure 4 shows the evolution of the mass of gas out of the tank (m_{out}) over time. The black line corresponds to estimates obtained by the proposed analytical model (Eq 4) fed by pressure and temperature measurements acquired by FO sensors. The red line is obtained by integrating the instant mass outflow rate measurements of the flowmeter. The dashed horizontal black line refers to the mass of gas initially in the vessel. A good agreement of the results obtained from the proposed analytical model coupled with FO sensors' measurements with those obtained by the flowmeter can be observed (Figure 4).

In Figure 5, the evolution of the instant mass outflow rate obtained by coupling the simplified analytical model (Eq 5) with FO sensors' real-time data (black line) is plotted against the one directly measured by the flowmeter (red line). As also shown by the experimental tests, pressure has higher contribution than temperature to the estimated gas outflow. A rather good match can be observed for all the different experimental tests, exception made for the initial steps of high-pressure tests where the outflow is slightly more disturbed. Nonetheless, the difference is of up to 20% and it is shown to reduce with time.

Copyright © 2023 by ASME

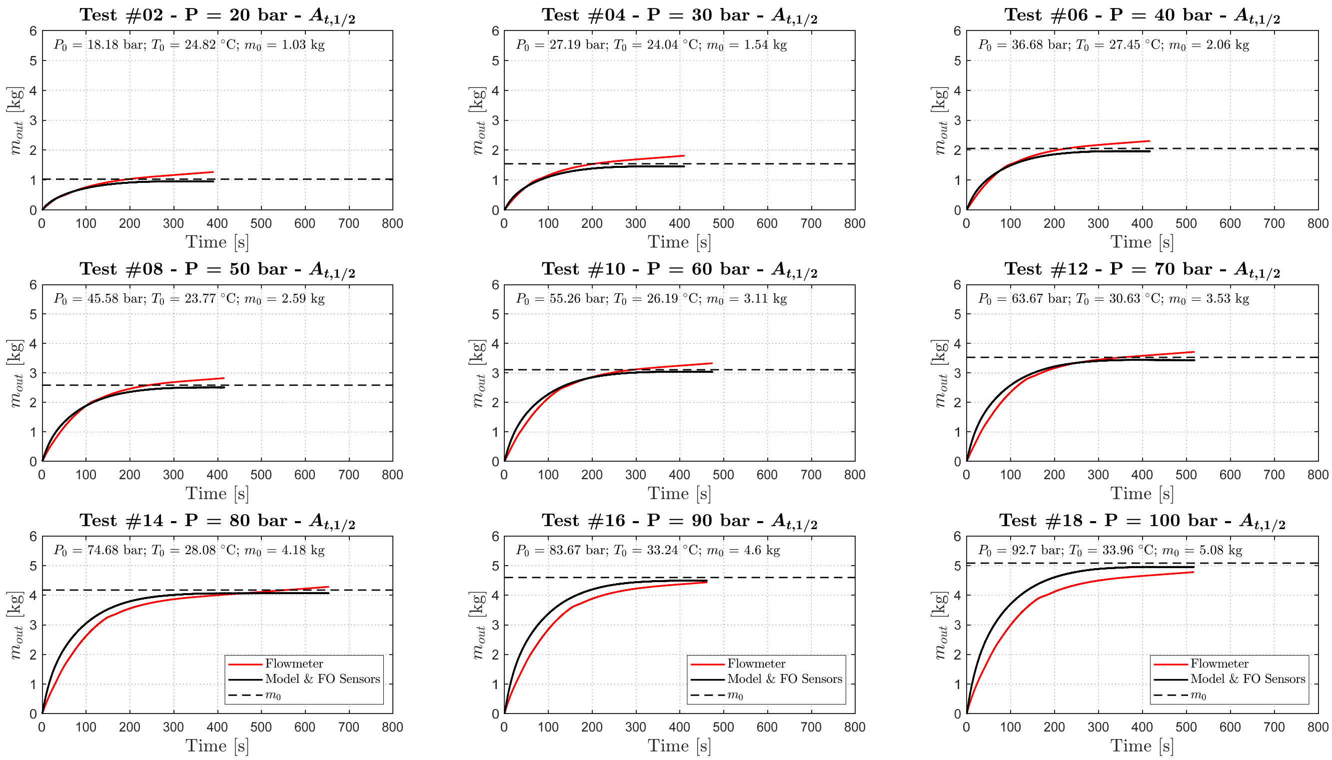

FIGURE 4: COMPARISON OF THE TREND OF THE MASS OF GAS OUT OF THE TANK (m_{out}) AS A FUNCTION OF TIME, OBTAINED BY COUPLING THE PROPOSED ANALYTICAL MODEL WITH FBG SENSORS' MEASUREMENTS (BLACK LINE) WITH THE ONE DIRECTLY MEASURED BY THE FLOWMETER (RED LINE).

Copyright © 2023 by ASME

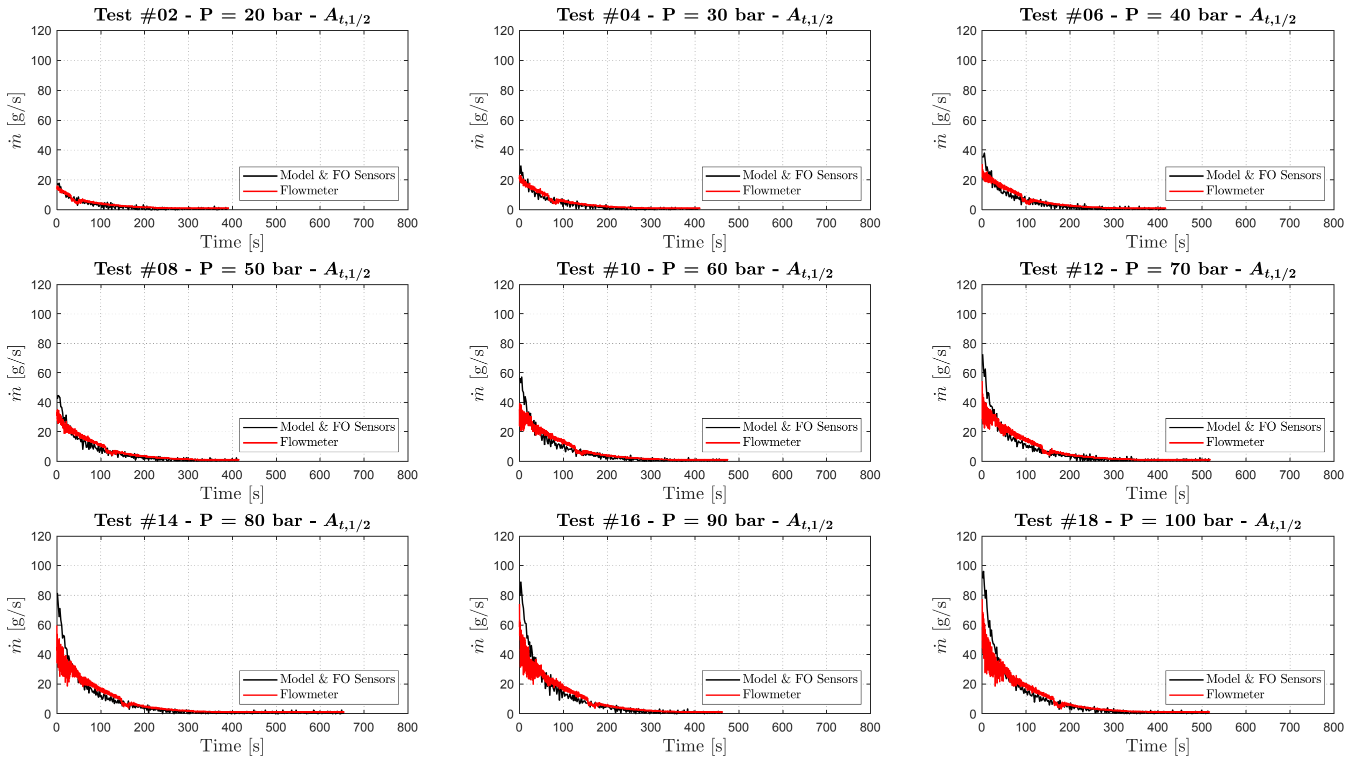

FIGURE 5: COMPARISON OF INSTANT MASS OUTFLOW RATE RESULTING FROM COUPLING THE PROPOSED ANALYTICAL MODEL WITH FBG SENSORS' MEASUREMENTS (BLACK LINE) AND DIRECTLY MEASURED BY THE FLOWMETER (RED LINE).

For each experimental test, Figure 6 shows values of the leak area (A_t) estimated by the proposed analytical model. Estimates of the exit area tend to be horizontally aligned as a function of the different thresholds of the initial pressure and well-approximated by a horizontal regression line (i.e. mean of the values obtained at the various experimental tests). These findings underline the suitability of the simplified analytical model in the context of accidental gas release quantifications.

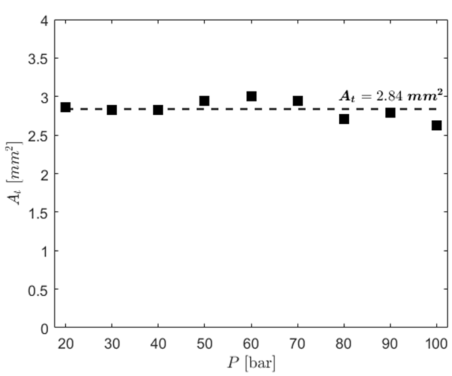

FIGURE 6: ESTIMATE OF THE LEAK AREA FOR DIFFERENT THRESHOLDS OF THE INITIAL PRESSURE IN THE VESSEL.

5. SUMMARY AND CONCLUSIONS

This paper presented an experimental-analytical study on the quantification of accidental gas release from pressurized vessels typical of industrial facilities. A simplified analytical model was developed for quantifying the accidental gas release, in terms of average mass outflow rate and leak area. The analytical study was complemented by several experimental tests simulating the accidental gas release from a pressurized vessel. To this aim, an ad-hoc test-bed, mainly consisting of a vessel pressurized at different initial pressure thresholds and equipped by FO sensors, was set up. The experimental tests provided necessary information for both feeding the proposed analytical model, using FO sensors' measurements as main input data, and to test its capability for accidental gas release the quantifications. By exploiting real-time data acquired by fiber-optic sensors, the proposed analytical model is indeed able to follow the evolution of the discharge process, and it quantifies the leak area and the average mass outflow rate in a predefined time window. The capability of the proposed analytical model to assess accidental gas release was verified by comparing the results obtained at the different steps of the proposed analytical framework with those obtained by alternative instrumentation. Results highlighted both the suitability of FO sensor technologies for leakage detection and the adequacy of the simplified analytical model for assessing

Copyright © 2023 by ASME

the accidental release of toxic substances, suggesting the appropriateness of their coupling for risk mitigation and management in industrial facilities ([12]; [13]).

ACKNOWLEDGEMENTS

This work was carried out under financial support from the ROSSINI Project, funded by INAIL (Italian national institute for workplace insurance) under the call "BRiC 2019".

REFERENCES

[1] Girgin S, Necci A, Krausmann E (2019) Dealing with cascading multi-hazard risks in national risk assessment: the case of Natech accidents. *International Journal of Disaster Risk Reduction*, 35, 101072.

[2] Krausmann E, Cruz AM (2013) Impact of the 11 March 2011, Great East Japan earthquake and tsunami on the chemical industry. *Natural Hazards*, 67: 811-828.

[3] Udd E, Spillman WB (2011) Fiber Optic Sensors: an introduction for engineers and scientists. *John Wiley & Sons.* ISBN 978-0-470-12684-4.

[4] Alwis L, Sun T, Grattan KTV (2016) Developments in optical fibre sensors for industrial applications. *Optics & Laser Technology*, 78: 62-66.

[5] Marino A, Ciucci MM (2019) Smart approach to integrated natural risks management for industry 4.0. In: Niezrecki C, Meyendorf NG, Gath K, editors. *Smart Structures and NDE for Energy Systems and Industry 4.0, SPIE*. DOI: 10.1117/12.2513764.

[6] Paolacci F, Quinci G, Nardin C, Vezzari V, Marino A, Ciucci M (2021) Bolted flange joints equipped with FBG sensors in industrial piping systems subjected to seismic loads. *Journal of Loss Prevention in the Process Industries*, 72: 104576.

[7] Li HN, Li DS, Song GB (2004) Recent applications of fiber optic sensors to health monitoring in civil engineering. *Engineering Structures*, 26(11): 1647–1657.

[8] Hou Q, Jiao W, Ren L, Cao H, Song G (2014) Experimental study of leakage detection of natural gas pipeline using FBG based strain sensor and least square support vector machine. *Journal of Loss Prevention in the Process Industries*, 32: 144-151.

[9] Luo JH, Zheng M, Zhao XW, Huo CY, Yang L (2006) Simplified expression for estimating release rate of hazardous gas from a hole on high-pressure pipelines. *Journal of Loss Prevention in the Process Industries*, 19: 362-366.

[10] Woodward JL (2009) Validation of two models for discharge rate. *Journal of Hazardous Materials*, 170: 219-229.

[11] Kanes R, Basha A, Véchot LN, Castier M (2016) Simulation of venting and leaks from pressure vessels. *Journal of Loss Prevention in the Process Industries*, 40: 563-577.

[12] O'Reilly GJ, Shahnazaryan D, Nafeh AMB, Ozsarac V, Sarigiannis D, Dubini P, Dacarro F, Gotti A, Rosti A, Silvestri D, Brunesi E, Mascetti S, Ducci M, Carletti D, Ciucci M, Marino A (2022a) Utilization of a Sensor Array for the Risk-Aware Navigation in Industrial Plants at Risk of NaTech Accidents. *Proceedings of the Volume 5: Operations, Applications, and Components; Seismic Engineering; ASME Non-destructive Evaluation, Diagnosis and Prognosis (NDPD) Division*. Las Vegas, Nevada, USA. July 17–22, 2022. V005T08A015. ASME. https://doi.org/10.1115/PVP2022-84014.

[13] O'Reilly GJ, Shahnazaryan S, Dubini P, Brunesi E, Rosti A, Dacarro F, Silvestri D, Mascetti S, Ducci M, Ciucci M, Marino A (2022b) Risk aware navigation in industrial plants at risk of NaTech accidents. *International Journal of Distaster Risk Reduction,* https://doi.org/10.21203/rs.3.rs-2311786/v1.

[14] US EPA (1995) User's guide for the Industrial Source Complex (ISC3) dispersion models. U.S. Environmental Protection Agency, EPA-454/B-95-003a.

[15] Dutton CJ, Coverdill RE (1997) Experiments to study the gaseous discharge and filling of vessels. *International Journal of Engineering Education*, 13(2): 123-134.

[16] Guo X, Tan W, Liu L, Liu C, Zhu G (2021) Experimental study of liquified gas dynamic leakage behavior from a pressurized vessel. *Process Safety and Environmental Protection*, 151: 20-27.

 Copyright © 2023 by ASME