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Experimental and numerical investigation of passive fire protection for pressurized tanks engulfed by fires

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This work is aimed at presenting a methodology for the assessment of Passive Fire Protection (PFP) systems performance. Specific experimental data allowed the characterization of selected commercial PFP materials. The results were used as input data to simulate the behavior of real scale tanks engulfed by fire. A comparison was thus realized between protected and non protected tanks, evaluating the possible tank failure due to thermal exposure.

1. Introduction

Accidental fires may impinge equipment and pipes, leading to their thermal collapse and to accident escalation triggered by fire (Lees, 1996; CCPS, 2000). The resulting secondary events may be far more severe than the primary fire, especially when pressurized storage or transport units are involved, resulting in severe domino accidents (Landucci et al., 2009a). Passive fire protection (PFP), which consists in systems able to limit the temperature rise of equipment involved in fires, may be a robust and effective solution to reduce the probability of fire escalation (SCI, 1992; Molag et al., 2005). The assessment of the behavior of the material exposed to fire is a critical issue for determining the effectiveness of the PFP system. As a matter of fact, thermal coatings may undergo degradation that may cause the variation of key physical properties during prolonged fire exposure. Though the degradation, in terms of weight losses and devolatilization, may be an inherent part of the protective action of the coating (for example in the case of intumescing coatings), the progressive deterioration of the material may lead to a decrease inof the effectiveness of the protection (Landucci et al., 2009b).

In the present study, an approach to the assessment of the effectiveness of passive fire protection is presented. The approach is based on the combination of experimental results and finite element modelling (FEM), which allowed estimating the behavior of real scale pressurized tanks engulfed by fires.

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2. Methodological approach

The proposed approach for the assessment of coating performances is based on the following main steps:

1. Selection of reference PFP materials
2. Characterization of PFP behaviour to fire exposure (*experimental*)
3. Application of PFP on real scale vessels (*FEM simulations*)

Several reference materials, both organic and inorganic formulations, were selected among those more commonly used for PFP in Oil&Gas processing and storage facilities. The experimental analysis was aimed at the assessment of the dynamic behavior of the thermal coating exposed to fire. The critical phases of the devolatilization and degradation processes were identified by thermo-gravimetric analysis (TGA). This allowed the systematization of the available coatingd data of the coating, in order to identify adescribe the dynamic function to describe of the PFP performance during fire exposure.

The results obtained were implemented in a finite elements model (FEM), in order to simulate the behavior of insulated tanks engulfed by fire. The implemented dynamic behavior of the coating also allowed investigating on the resultant degradation effect. A simplified failure criterion allowed combining the temperature and stress distribution for the time to failure evaluation of the structure, thus obtaining significant elements to evaluate the performance of the thermal protection.

3. Characterization of the PFP systems behavior

The dynamic behavior of the PFP during fire exposure was described by a step function (i.e. consecutivesuccessive phases characterized by constant properties). The step function was preferred since: *i)* it clearly identifies distinct phases in the PFP performance (e.g. expansion, devolatilization, etc.); *ii)* it is suitable for use of generic/average information on the PFP properties (e.g. thermal conductivity, thickness, etc.); *iii)* it can be easily implemented in finite elements model set-ups. Thermal analysis techniques at laboratory scale were applied for the definition of the transition temperatures among the phases of PFP behavior. In the current study, the use of thermo-gravimetric technique (TGA) is demonstrated on samples taken from two among the selected PFP materials (Table 1). The samples (about 10mg each) were scanned at a constant heating rate (10°C/min). Some significant results obtained in experimental runs are reported in Figure 1.

The single phases of PFP behavior were identified integrating the available information from the material provider and the literature with the results of TG runs. For example, the organic intumescent material undergoes several significant weight losses that can be correlated to three main phases: i) unexpanded material, ii) expanded material, iii) degradation. The transition temperatures relative to each phase were identified from the weight profile (Table 1). A reference value for the thermal conductivity was associated to each phase, resorting to literature data set (Liley et al., 1999; Fjellerup et al., 2003, Insulcon, 2009). The results of the analysis for the materials are summarized in Table 1. Though all the PFP materials show some degree of weight loss in TGA experiments, these are not always be associated to significant change in the PFP critical properties (thermal conductivity, thickness, etc.). However, as in the case of the silica filaments, the temperature can be assumed for discretization of the conductivity function.

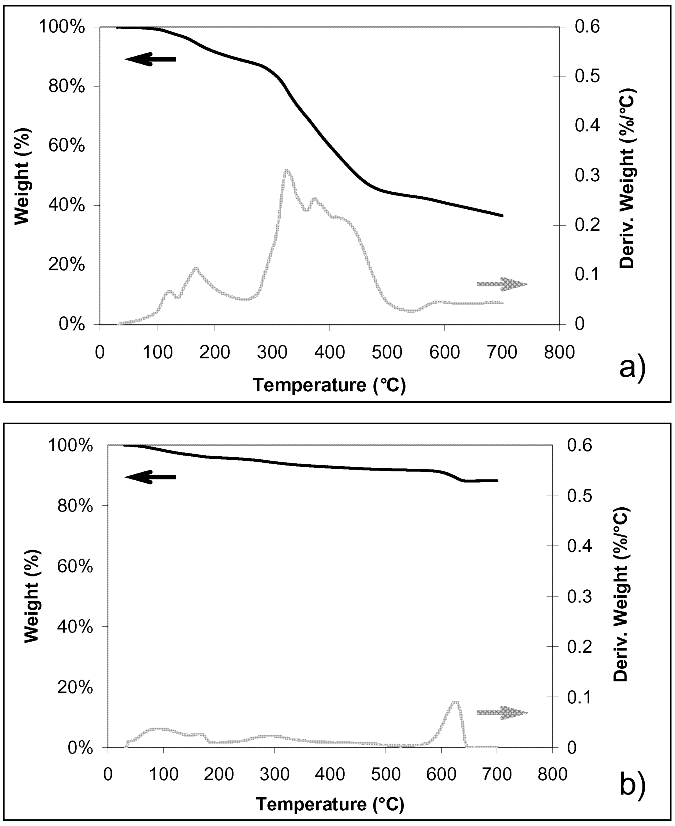

Figure 1 TGA results for the three selected materials. a) Organic intumescent, b) Silica filaments.

Table 1 Step function defined for coating performance. n.d.: not defined

	Organic intumescent		Silica filaments	
Phase	***T_c (°C)***	***K (W/mK)***	***T_c (°C)***	***k (W/mK)***
I	10÷270	0.28	10÷560	0.07
II	270÷510	0.066	>560	0.29
III	>510.	0.22	n.d.	n.d.

4. Simulation of the protected vessel behavior

4.1 FEM set up

The experimental results were implemented in the simulation of real scale pressurized tanks engulfed by fires. For this purpose, a finite element model (FEM) was implemented on ANSYS™ software, using the ANSYS™/Multiphysics module divided in two main frameworks. The first sub-model allows the detailed calculation of the temperatures on the vessel shell as a function of time and of external thermal loads. In the second sub-model, the simulation of the transient stress field is carried out, implementing the local temperatures, evaluated in the previous step, as thermal loads and adding the other loads present on the vessel shell (internal pressure, weight, etc.). The FEM was used to perform detailed simulations of the radiation mode, of the wall temperature and of the stress over the vessel shell under pool fire full engulfment conditions. The local values of the stress intensity (σ_{eq}), calculated applying the Von Mises criterion, may be thus compared with the local values of the maximum allowable stress (σ_{adm}), which is a function of the temperature, according to ASME codes (ASME, 1989). A simplified failure criterion (ASME, 1989) was adopted to calculate vessel time to failure (ttf), assuming the ttf as the time when the increasing σ_{eq} equals σ_{adm}. Further details on the FEM set up and validation are reported in previous publications (Landucci et al., 2009a,b)

A case-study representative of the European transportation of HazMat was defined to exemplify the methodology application. In particular, a 95 m^3 rail tank wagon, complying to RID regulations (the standards ruling the European rail transportation of HazMat) was simulated with the described FEM tool. A full engulfment fire scenario was considered with a constant heat load (180 kW/m^2) on the outer surface of the tank. The main parameters implemented in the FEM are reported in Table 2.

Table 2 Input data for the FEM simulation

Tank wagon properties	Inner fluid properties
Nominal volume: 95m^3	Fluid: Propane
Geometry: horizontal cylinder	Average liquid temperature: 70°C
Diameter: 3.1 m	Average vapor temperature: 170°C
Length: 15 m	Liquid density: 585 kg/m^3
Thickness: 16 mm	Heat transfer coefficient, liquid side: 400 W/m^2K
Filling level: 80%	Heat transfer coefficient, vapor side*: 6-140 W/m^2K
Material: high yield carbon steel	Initial temperature: 10°C
PSV area: 0.008 m^2	
Design pressure: 2.5 MPa	

* Low value for protected case, high value for not protected case.

An organic intumescent coating, 10 mm thick, was supposed to be installed on the outer surface of the tank. According to the results of the experimental analysis (Table 1), the three phases were implemented in the simulation, on the basis of the activation temperature T_c. The coating thickness was supposed to expand his thickness up to 2.5 times in phase I, according to experimental results (Landucci et al., 2009b). After the working phase (phase II), the degradation phase (phase III) was thus included. In order to evaluate the entity of the degradation effect on the results, the “ideal” coating behavior was also simulated, considering a sudden expansion up the final value with constant thermal conductivity and no degradation (thus, considering only phase II among the whole simulation). Moreover, the non-protected case was simulated.

4.2 FEM results

An example of FEM results is reported in Figure 2, in which the temperature and stress maps are shown at the end of simulation (100 minutes) in the case of protected tanker, with the 3-phases coating behavior implemented. As it can be seen in Figure 2a, the highest temperatures are in contact with the vapor phase (about 350°C), while the wall in contact with the liquid presents extremely lower temperatures (about 92°C). This is due to the difference in the inner heat transfer coefficient.

The highest stress region is at the interface between liquid and vapor (Figure 2b). In this zone, the stress is increased by additional thermal tensions due to the temperature difference between the upper and lower part of the tank (more than 250°C).

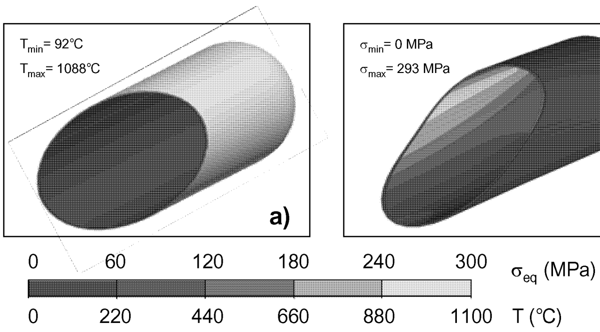

Figure 2 Example of thermal (a) and mechanical (b) FEM results for a 95m^3 LPG tanker fully engulfed by the fire (heat load: 180kW/m^2) with thermal protection. Temperatures in °C and stress in Pa, end of simulation: 100 min.

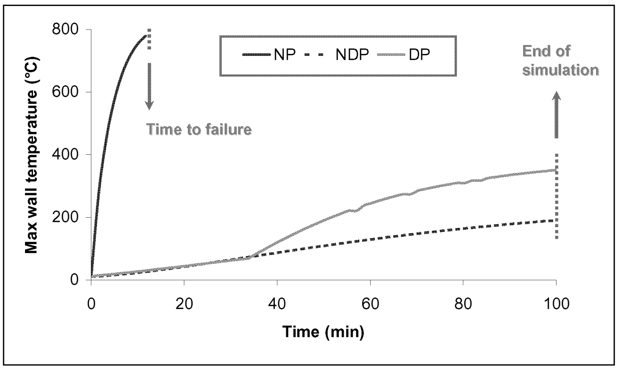

Figure 3 Maximum wall temperature profile (in °C) for non coated tankers (NP); tankers with "ideal" coating (no expansion and no degradation NDP); coating with expansion and degradation implementation (DP).

The coating avoided the tank rupture for all the simulation time (100 minutes), while in the non protected case, the tank collapse was predicted in 13 minutes. The coating resulted crucial in reducing the vessel wall heat up, as shown in Figure 3. As it can be

seen, the temperature in the non protected case my rise up over 750°C in a very short time, increasing the inner pressure, and leading to tank failure.
Nevertheless, significant differences may be found between the "ideal" and the degraded coating behavior (labeled respectively as NDP and DP in Figure 3). When phase II ends, a higher temperature is calculated in the second case, due to higher thermal conductivity, indicating a less effective protection (see Figure 3). Therefore the experimental characterization of the dynamic behavior of the thermal protection resulted crucial for a correct modeling of the coating performance.

5. Conclusions

In the present work a methodological approach for the assessment of PFP systems performance was developed. Experimental aend numerical analyses were combined in order to simulate the effect of the coating thermal activation and degradation in real scale fire scenarios. The more common product for PFP were selected and tested with TG analysis, evidencing the critical phases of the thermal behavior. The results were implemented in a FEM, which simulated real scale tankers engulfed by fires, with and without thermal protection installed. The protection resulted critical to enhance the tanker fire resistance, but an evident negative effect of the coating degradation was evidenced and quantified with the simulations, providing important indication for the PFP system design.

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