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Analysis of the effectiveness of passive fire protection measures

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Passive fire protection is of fundamental importance for the prevention of catastrophic accidents in the process industry, in particular in the case of escalation effects. In the present work, a methodological approach was developed, aimed at the characterization of the performances of passive protection systems, integrating experimental and numerical analysis. Thermal coatings were first characterized under jet fire conditions on laboratory scale, extending the results on pilot scale. A finite elements model was implemented in order analyze experimental results and the complicating factors. The model was extended to large scale tanks, determining the optimal coating thickness and effectiveness for several fireproofing materials.

1. Introduction

Ignition of accidental releases may lead to strong fires able to trigger fired-domino effect escalation, by impinging nearby secondary equipment (CCPS, 2007; Delvosalle, 2003; Lees, 1996). Control and mitigation of consequences are critical in this framework, with the need of safety-based design of layout in order to prevent or, at least, reduce the possibility of domino effect. Among the technological solutions, passive fire protection (PFP) with thermal coatings is a simple and reliable technology (NFPA, 1991). Nevertheless, material testing and characterization at high temperatures is of fundamental importance for the possible PFP utilisation.

The present work was focused on the experimental and analytical investigation of both innovative, based on special fibres, and commercial materials for PFP. A specific laboratory-scale fire test was designed to evaluate the temperature evolution on the surface of the tested specimens. Thus, the resistance of materials to jet-fire impingement was tested, obtaining preliminary indications for the further stage of experiments carried out on larger scale. The pilot-scale test allowed integrating the information on the resistance of the passive fire protection with the behaviour of the protected structure. In particular, 3 m^3 LPG tanks were engulfed by diesel pool fire in order to verify the effectiveness of the protection to avoid the tank rupture. The analysis of the obtained data was integrated with a detailed thermal and mechanical model, based on finite

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elements (FEM). FEM first allowed understanding the experimental outcomes and the effect of coating degradation on the results. Then, the simulation were extended to real scale vessels and tankers. A simplified failure criterion allowed verifying if the rupture of the apparatus could be avoided in a reference lapse of time, needed for fire scenario mitigation, deriving indications for the optimal passive fire protection design.

2. Laboratory scale experimental analysis

2.1 Test set up

A specific experimental facility was built up in order to reproduce on small scale a jet-fire impingement scenario, following a modified ASTM standard (ASTM,1994). An overview of the experimental set up is reported in Fig. 1. Instead of a radiating panel heat source (featured by the ASTM test), a hydrogen jet-fire was preferred, in order to contemplate the effect of convective heat due to the turbulent jet.

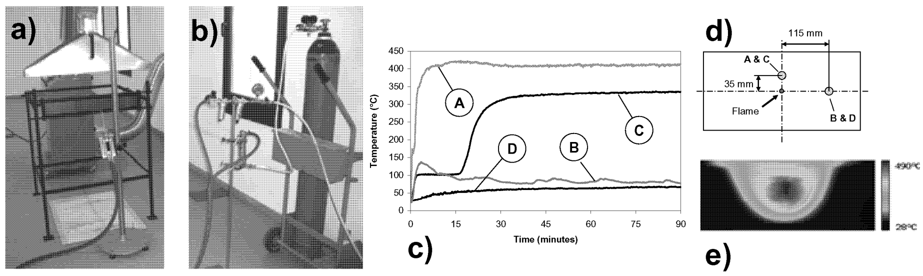

Figure 1 Experimental set up and results: a) specimen holder and burner; b) combustible gas supply system; c) Temperature behaviour of the tested specimens, spots "A" and "B" basalt fibers-epoxy resin composite 3.8 mm thickness; spots "C" and "D" Fendolite® 25 mm thickness; d) relative positioning of the thermocouples; e) Steady state temperature profile on the non exposed side of basalt-based panel during the test.

More details on the test set up are reported in Table 1. A thermocouples set and an infrared camera were used to acquire temperatures in different zones of the tested specimen, evaluating the maximum stationary temperature profile due to flame impingement. Test were carried for 75 minutes, thus indications on the material resistance were obtained for a lapse of time comparable with the intervention times of fire brigades in industrial areas (Molag et al., 2005).

Table 1 Characteristic and details of the laboratory scale fire test.

Feature	Value
Exposed surface of the specimen (mm x mm)	380 x 150
Thickness range (mm)	3-25
Fuel gas flowrate (mg/s) and pressure (barg)	68.2 ; 0.8
Burner diameter (mm)	1
Flame length (mm)	120 mm

2.2 Results

An example of results is reported in Fig. 1. Fig. 1c reports the temperature registration on the non-exposed side of the specimen in different positions behind the flame (depicted in Fig. 1d). A basalt based composite developed by Landucci et al. (2008) was tested and compared with a commercial cementitious material. As it can be noticed, a temperature difference of about 100°C is presented in the middle-part of the specimens (spots "A" and "C"), due to the huge thickness difference among them (the commercial material is 5 times thicker). Moreover, it is worth to notice the temperature-plateau at 100°C in the case of the cementitious material, due to the high water content. The other spots present lower temperature differences, as confirmed by the thermal image reported in Fig. 1e. This was obtained after 40 minutes test on the basalt based material. It clearly appears that the more critical zone is circumscribed (dark central spot), thus the protection is effective in the other parts of the panel.

3. Pilot scale experimental analysis

In order to experimentally implement the protected structure, a pilot scale test was carried out on 3 m^3 LPG tank engulfed by a diesel pool fire (Landucci et al, 2009). This experimental activity was realized in cooperation with TNO (Netherlands Organization for Applied Scientific Research, Apeldoorn, The Netherlands).

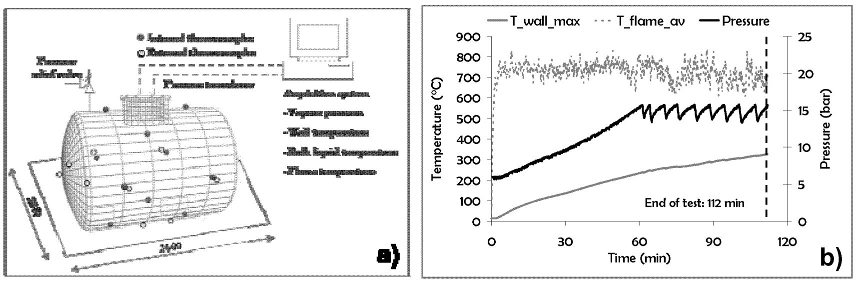

Figure 3 a) Scheme of the experimental set up: disposition of the thermocouples, pressure transducer, PRV and pool sizes (in mm). b) Experimental results: maximum wall temperature (T_wall_max, °C), average flame temperature (T_flame_av, °C), and pressure (bar) as a function of time.

The tested tank was equipped with a heat resistant coating (a commercial intumescing material) and a pressure relief valve (Fig. 3a). The tank kept the integrity for almost 2 hours test, with a maximum wall temperature of 330°C. The temperature and pressure registrations are reported in Fig. 3b. The test demonstrated that PFP is a simple and effective measure to increase the thermal resistance of the structures exposed to fires and to avoid the rupture. Nevertheless, the coating appeared damaged in many spots due to the fire degradation. The entity of the coating damage on the tank behaviour was studied implementing a detailed model thermal and mechanical analysis.

4. Modelling of experimental results

A thermal and mechanical model (Landucci et al., 2009) was developed on the basis of the experimental results, in order to assess the behavior of coated tanks in a simulated fire impingement scenario. The model was based on a finite element approach, which allowed considering both thermal and mechanical loads. The effect of the fluid behavior and the flame impingement were implemented obtaining the temperature distributions on the tank. These results were used as thermal loads, coupled with the ordinary pressure and weigh loads, in the mechanical simulations obtaining stress distributions.

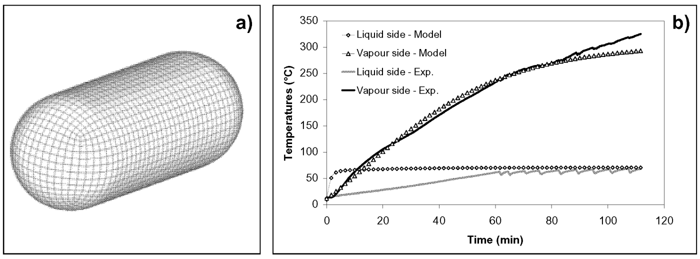

Figure 4 a) FEM Mesh of the coated 3 m^3 tank. b) comparison between the predicted and measured vessel wall temperatures.

The mesh used for the calculations is reported in Fig. 4a, while in Fig. 4b a comparison is realized between the measured and predicted wall temperatures, with good agreement. As it can be noticed, the more critical zone is the side in contact with the vapor phase. Temperatures exceed 300°C, while in the lower part of the vessel temperature are quite lower (about 200°C less). One of the primary aims of the simulations was the determination of the influence of the coating degradation on the results. In particular, a perfect coating was supposed, thus no damages were implemented due to fire exposure. The eventual disagreement between data and calculation results are due to this fundamental assumption. It clearly appears from Fig. 4b that the coating degradation only affects the results in the final part of the testing period (e.g., after 80 minutes). Therefore, only for long-time exposure the coating effectiveness results penalized by degradation.
The use of the FEM allowed also to combine data on the temperature profiles among the tanks with the resulting stress intensity field. This is aimed at the application of a simplified failure criterion expressed as follows for each single point of the tank:

$$f = \sigma \quad (1)$$

where f is the maximum allowable stress of the material function of the material type and of the temperature; σ is the stress intensity in which the thermal dilatation and the other mechanical loads are contemplated.

5. Real scale modelling

Since the results obtained from the modeling approach developed resulted in good accordance with the experimental data available, the simulation were thus extended to large scale tanks for LPG transportation and storage. In particular, a set of case studies of interest was defined, with the data reported in Table 2.

Table 2 Features of the tank tested with large scale FEM.

Item	Road tanker	Tank wagon	Large scale storage
Nominal volume (m^3)	60	110	220
Diameter (m)	2.40	3.04	3.35
Length (m)	13.5	16.04	27.43
Min. wall thickness (mm)	12.2	31.0	31.0
Working pressure (MPa) at 25°C	0.5	0.5	0.5
Design gauge pressure (MPa)	1.82	2.4	1.6
PRV discharge area (m^2)	0.004	0.005	0.01

Table 3 Physical properties of the more common fire proofing materials.

Coating characteristics	Type 1	Type 2	Type 3	Type 4
Definition	Epoxy intumescent	Vermiculite spray	Fibrous mineral wool	Cementitious inorganic formulation
Thermal Conductivity (W/mK)	0.066	0.2	0.38	0.9
Heat capacity (J/kgK)	1172	970	920	1507
Surface emissivity	0.9	0.9	0.9	0.9
Density (kg/m3)	1000	680	100	850

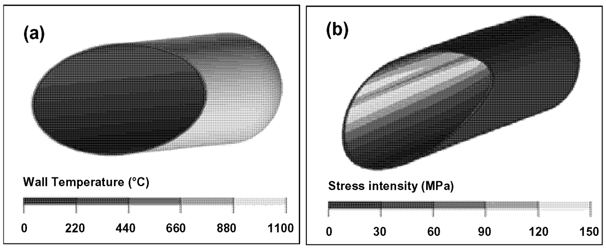

Figure 5 Example of FEM maps obtained for a 60 m^3 road tanker engulfed by a diesel pool fire. Insulating coating: organic intumescing, 40 mm. (a) Temperature map after 100 min (°C); (b) Stress intensity map in the corresponding conditions (MPa).

The tanks were considered with 50% filling level and involved in a total engulfment fire scenario. The heat load was set to 180 kW/m^2 in order to contemplate a strong pool fire impinging the tanks for 100 minutes. Different types of coating were implemented in the analysis, with increasing thicknesses (see Table 4); thermal properties and main features are reported in Table 3. Fig. 5 reports the typical result-maps obtained in the case of a coated 60 m^3 road tanker, engulfed by the flames. The effect of the strong thermal dilatation, caused by the temperature difference among the upper and the lower part of the tank (Fig.5a), is shown in the stress map in Fig.5b. Due to local stress, the interface between liquid and vapor results in the highest stress intensity, identifying a critical zone of the tank. The results allowed estimating the time to failure of vessels, as shown in Table 4, as a function of the coating thickness. Only the coatings with better thermal properties (e.g. type 1 and 2) allowed preventing the tank failure, also for small applied thicknesses. In the case of worse thermal properties (e.g., type 3 and 4) higher thicknesses, and thus payload costs, are required for an effective protection.

Table 4 Results on large scale simulations: time to failure in minutes.

Type of tank	Coating 5 mm Type of coating				Coating 15 mm Type of coating				Coating 40 mm Type of coating			
	1	2	3	4	1	2	3	4	1	2	3	4
60 m^3	100.0	58.3	11.7	5.8	100.0	100.0	50.0	11.7	100.0	100.0	100.0	40.0
110 m^3	100.0	33.3	18.3	13.3	100.0	100.0	100.0	28.3	100.0	100.0	100.0	86.7
220 m^3	100.0	58.3	35.0	16.7	100.0	100.0	100.0	35.0	100.0	100.0	100.0	100.0

6. Conclusions

A methodological approach was developed to evaluate the efficiency and performance of passive fire protection systems. In particular, experimental characterization was preliminary carried out on small scale in order to obtain information about the thermal resistance of coating material. Then the experiments on pilot scale allowed integrating the protection with the structure to protect. Modelling of experimental results was needed to better understand the experimental outcomes and complicating factors, such the coating degradation influence on the temperature profile. The model was extended to large scale tanks in order to obtain indications on the passive protection design, in terms of the minimum required thickness for effective protection.

References

AIChE CCPS, 2007, Guidelines for chemical process quantitative risk analysis, 2nd Ed. AIChE, New York (NY).

ASTM E162-08, 2008,Standard test method for surface flammability of materials using a radiant heat energy source. ASTM International, West Conshohocken (PA).

Delvosalle C., 2003, A methodology for the identification and evaluation of domino effects, Report No. CRC/MT/003. Belgian Ministry of Employment and Labour, Bruxelles.

Landucci G., Rossi F., Nicolella C. and Zanelli S., 2008, Design and testing of innovative composites for passive fire protection, lecture #169 in Int. probabilistic safety assessment and management conference 2008. IAPSAM, Hong Kong (C).

Landucci G., Molag M., Reinders J. and V. Cozzani, 2009, Experimental and analytical investigation of thermal coating effectiveness for 3 m^3 LPG tanks engulfed by fire, J. Hazard. Mater. 161(2-3), 1182-1192.

Lees F.P., 1996, Loss Prevention in the Process Industries, vol 2. Butterworth-Heinemann, Oxford (UK).

Molag M. and Kruithof A., 2005, BLEVE prevention of a LPG tank vehicle or a LPG tank wagon, TNO report R2005/364. TNO, Utrecht (NL).

NFPA, 1991, Fire Protection Handbook 17th edition. NFPA, Quincy (MA).