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The Performance of Inorganic Passive Fire Protections: an Experimental and Modelling Study

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The installation of fireproofing materials on equipment and structures is a widely applied and effective solution for the protection of critical process elements against severe fires, in order to prevent possible damages escalation. The choice and design of fireproofing materials is crucial for granting adequate performances. As a matter of fact, properties such as, among others, thermal conductivity and density change substantially when the material is exposed to severe temperatures. In the present study, a methodological approach, integrating experimental and modelling activities, was proposed. Focus was set on a particular class of PFP: inorganic fireproofing materials. A reference set of commercial PFP materials (rock wool, glass wool, silica blanket, etc.) was selected. Small scale experiments allowed determining the variation of the most relevant thermal properties of the coatings and to obtain detailed correlation models for their description. A finite element model (FEM) was developed in order to reproduce the behaviour of real scale equipment exposed to fire and to provide a sound design of the fire protection system.

1. Introduction

Fire is among the most dangerous accident scenarios that may occur in oil & gas industry. Beside the immediate and direct harms to operators and population, fire may as well cause significant asset damages and trigger more severe secondary scenarios (domino effect) (Mannan, 2005). The cascading events triggered by fire are particularly problematic when involved targets are pieces of equipment containing significant inventories of flammable materials (e.g. pressurized or atmospheric storage vessels as described by Birk (1988), Gòmes-Mares et al. (2008), and Roberts et al. (2000)). Fireproofing materials are a consolidated technique for passive fire protection (PFP) of equipment units and of supporting structures (Di Padova et al., 2011). The effective application of fireproofing requires addressing two practical issues: the identification of the items to be protected and the design of the PFP system in order to meet the desired risk reduction goals. The first issue requires to strike a balance among risk reduction, installation costs and maintenance issues (see e.g. Tugnoli et al. (2012)). The second issue, which is the main subject of current contribution, asks for the evaluation of the protection provided by a PFP in terms of performance in delaying the negative effects of accidental fires. Current practice in rating fireproofing materials does not provide sufficient information about the protection granted to process equipment: for example, the 'time-to-failure' of pressurized vessels containing flammable substances and protected by fireproofing materials, which is fundamental in planning adequate egress and emergency procedures, cannot be predicted from the results of the standardized fire tests.

The current contribution presents the results of a study aimed at a better understanding of the performance of inorganic fireproofing materials in the protection of critical equipment. The study integrates results from experimental and numerical simulation techniques. A reference set of commercial inorganic PFP materials was selected to carry out this study, considering the more widely applied solutions (rock wool, glass wool, silica blanket, etc.) (Malloy, 1969).

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The experimental activity was aimed at the definition of fundamental models to describe the thermo-physical properties of the materials, in particular focusing on the thermal conductivity. Specific simulation models were used to describe heat transfer through the material. The results were validated by lab-scale tests. Next, a Finite Element Model (FEM) simulation was set up implementing the model developed for the fireproofing thermo-physical properties. FEM allowed for the description of the expected behaviour of process equipment exposed to different fire conditions, both considering the effect of the increasing temperature and internal pressure due to the fire exposure. Performance indicators were proposed for the evaluation of PFP behaviour, providing concise representations of the simulation results. The study allowed for a better understanding of the dynamics underlying the effective design for passive fire protection, in particular providing elements for the choice and the design of fireproofing materials.

2. Experimental characterization of PFP materials

2.1 Materials and experimental setup

Four types of fireproofing materials were investigated in current study. The materials represent important categories of commercial PFP: i) silica fibre blanket; ii) rock wool; iii) inorganic aerogel; iv) vermiculite spray.

FEM modelling requires describing the thermo-physical properties of the materials by adequate constitutive equations which take into account the effect of external parameters (temperature, possible thermal degradation, operative conditions). Such data are not commonly available in the commercial literature provided, nor can be easily derived by the results of standard fire tests as UL 1709, ASTM E 119, ASTM E 1529, OTI 95635, or ISO 22899-1. Experimental activity is therefore required to support the definition of such models.

A set of experimental protocols was developed for the assessment of the properties of the selected PFP materials. A fixed-bed tubular reactor was used to study the behavior of the coatings on samples of the order of few grams. A Carbolite HST 12/300 furnace equipped with a W301 controller was used to provide heat to the reactor. The samples were heated using a constant heating rate until a selected final temperature was reached. The tests were carried out under a nitrogen flow, and the samples were recovered after each test for further analysis (weight loss, TGA, density, thermal conductivity, morphological analysis). A scanning electron microscope model JEOL JSM 5600 LV was used for morphological analysis of the materials. A transient plane source instrument (TPS2500S by Hot Disk AB) was used for measurement of the thermal conductivity. The thermal stability of the coatings was investigated by thermogravimetric analysis (TGA Q500 by TA Instruments). Constant heating rate runs performed in nitrogen flow (100 mL/min) allowed exploring the kinetic of possible degradation phenomena. The thermal effects were studied by differential scanning calorimetry (DSC Q2000 by TA Instruments). Further information on the instruments and the techniques are reported elsewhere (Gomez-Mares, et al. 2012a).

A specifically modified ASTM E162 setup was utilized for running medium scale fire tests. These tests were aimed at verifying the property models by the analysis a simple geometry (flat board) representative of real material applications (in particular thickness of the tested sample is compatible with field practice in real installations). Sample boards (460 x 150 mm) of each material were vertically exposed to a 304.8 x 457.2 mm porous gas-operated radiant panel (model RP-1A by Govmark Inc.). The radiant panel face was parallel to the sample. The cold-side (back side) temperature profile of the sample board was monitored using an infrared camera (Thermovision A40M by FLIR systems). Further description of the experimental set-up can be found in (Gomez-Mares, et al. 2012b). At the end of each test the exposed sample boards where recovered and characterized by the analytical techniques described above.

Empirical and semi-empirical relationships were used to correlate experimental data in order to obtain a fundamental model for material properties. Examples of these correlations can be found in (Gomez-Mares, et al. 2012a).

The variation of the operative condition may have significant effects on the properties of the material. For example the left panel of Figure 1 reports the measured variation of the thermal conductivity of a silica blanket sample with compression ratio of the material. As a matter of facts, application of a knitted blanket on process equipment may present several points in which the actual thickness differs from its nominal value. This may occur when the blanket is pinched by supports or squeezed by installation errors, external impacts, etc. This alters the gas to solid ratio in the material and, thus, conductivity. In any case the models should be able to describe the dependence of the properties from the operative conditions, such as the operating temperature and other external factors (e.g. the compression issue described above).

The right panel of Figure 1 reports the average temperature profile over a section of the back side of the panel (i.e., the side of the panel not exposed to fire radiation) from medium scale tests on a silica blanket board. The figure evidences as the temperature rises quickly during fire exposure of the silica blanket, reaching the stationary value in less than 5 minutes. This is due to the low heat capacity provided by the highly porous structure of the material. The thermal conductivity model developed for the blanket shows a significant change of the thermal conductivity with temperature, due to radiative phenomena at high temperature. On the other side, silica blanket is thermally stable and does not undergo the degradation phenomena that are of relevance for other inorganic PFPs (e.g. vermiculite-based lightweight concrete). These information were used in the simulation of the results form the fire tests according to the procedure described in (Gomez-Mares, et al. 2012b). As shown in the figure, experimental data and simulations show a fairly good agreement, validating the proposed approach. Robust simulation results require accuracy of the models describing the fundamental properties of the materials.

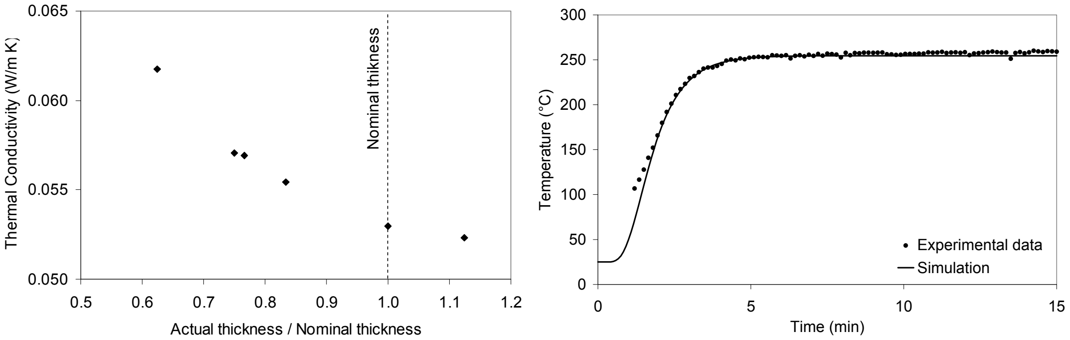

Figure 1: Left panel: measured thermal conductivity for different compression ratios of silica blanket. Right panel: Experimental results and simulation for average temperature of the back side of a silica blanket board (12mm nominal thickness) in medium-scale fire tests.

3. Numerical simulation of vessels engulfed by fires

In order to evaluate the resistance of process equipment engulfed by fire, thus assessing the performance of the applied fireproofing material, a finite element model (FEM) was set up. The FEM was developed on ANSYS^{TM} software, using the ANSYS^{TM}/Multiphysics module. Two types of simulation were carried out. The first type of simulation (thermal-FEM) allowed determining the thermal behaviour of the fired equipment, thus obtaining detailed temperature distributions on the equipment shell and in the fireproofing material layer as a function of time and of external thermal loads. The second type of simulation (mechanical-FEM) allowed evaluating the stress maps on the equipment shell implementing mechanical loads (e.g., due to the internal pressure rise, weight of the structure and of the inner fluid, etc.) together with thermal dilation loads function of the shell temperature, evaluated in the thermal-FEM. In order to simulate the inner fluid behaviour and to obtain input data for the FEM, a lumped parameters models, based on the “thermal nodes” approach (Latha et al., 1992; Moodie, 1988), was used as pre-processor in order to obtain the pressure rise curve together with the dynamic growth in the liquid and vapour temperature. For the sake of simplicity, no complicating phenomena such as liquid stratification were taken into account in the thermal nodes model (Birk and Cunningham, 1996). More details on the model are reported elsewhere (Landucci et al., 2009a).

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 severe fire exposure conditions. A simplified failure criterion was implemented in order to predict the eventual vessel rupture. In particular, comparing the local values of the stress intensity (σ_{eq}), calculated applying the Von Mises criterion, with the local values of the maximum allowable stress (σ_{adm}), which is a function of temperature, the time to failure was assumed 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., 2009b,c).

In order to show the potentiality of the FEM tool a case-study was defined. In particular, the analysis of a vessel with the typical geometrical features of the road tankers used for the LPG transportation in Europe was carried out. The tanker, filled with pure propane (50 % filling level), was simulated under the exposure of an engulfing pool fire. A constant heat load of 140 kW/m^2 was considered on the outer surface of the tank, which was protected with a 12 mm heat resistant blanket made of silica filaments and with a pressure relief valve (PRV) set at 1.7MPa.

The main parameters implemented in the FEM are reported in Table 1, together with the coating and steel thermal properties assumed for the case-study.

Two sets of simulations were carried on in order to study the role of PFP material and the importance of a correct description of its behaviour:

i) Variable coating properties: the silica blanket was simulated implementing the thermal conductivity data provided by the material supplier (Table 2), thus reproducing a more accurate behaviour of the PFP.

ii) Average coating properties: simulation of the tank protected by a layer of coating with constant average properties, as described by Landucci et al. (2009b,c), thus avoiding the implementation of the thermal conductivity function;

FEM simulations were carried out for a total time of 100 minutes, in which no failure was predicted in both cases. Hence, even implementing average conservative properties, the coating was still able to avoid a rapid heat up of the tank thus preventing the rupture.

Table 1: Input data for the FEM simulations: vessel geometry and inner fluid properties calculated with the thermal nodes model

Road tanker properties	Inner fluid properties	Steel properties	Coating properties
Nominal volume: 60 m^3	Average liquid temperature: 52°C	Thermal conductivity: 55 W/(mK)	Thermal conductivity: 0.1 W/mK or Table 2
Diameter: 2.4 m	Average vapour temperature: 171°C	Heat capacity: 460 J/(kgK)	Heat capacity: 1200 J/(kgK)
Length: 13.5 m	Liquid density: 500 kg/m^3	Emissivity: 0.75-0.95	Emissivity: 0.85
Shell thickness: 12.2 mm	Heat transfer coefficient, liquid side: 800 W/(m^{2}K)	Thermal dilatation coefficient: 11.5ppm/K	Thermal dilatation coefficient: 11.5ppm/K
Design pressure: 1.82 MPa	Heat transfer coefficient, vapour side; 12 W/(m^{2}K)	Elastic modulus: 201.5 GPa	Elastic modulus: 1 GPa
PSV area: 0.004 m^2	Initial temperature: 20°C	Density: 7800 kg/m^3	Density: 130 kg/m^3
Material: EN10028-P460NH		Poisson's Ratio: 0.3	Poisson's Ratio: 0.3

Table 2: Thermal conductivity (λ) for silica blanket coating at different temperatures (Insulcon, 2006)

Temperature (K)	323.15	473.15	673.15	873.15	1073.15	1273.15
λ (kW (mK))	4.5×10^{-5}	6×10^{-5}	1.04×10^{-4}	1.72×10^{-4}	2.63×10^{-4}	3.77×10^{-4}

The detailed results of the thermal FEM simulations are reported in the maps shown in Figure 2, in which the temperature profile on a section of the road tanker is shown after 100 minutes simulation. Figure 2a shows the results in the case of variable coating properties, while Figure 2b shows the results obtained in case of average coating properties. In both situations, the lower part of the vessel resulted in the lower temperatures (<100°C), due to the presence of liquid with higher heat transfer coefficient (see Table 1) and cooling effect. Relevant differences were predicted in the behaviour of the top-space of the vessel, in contact with the vapour phase and thus featuring a lower internal heat transfer coefficient (see Table 1). In the case of variable coating properties, the predicted temperature was rather lower than the one predicted with the average maximum value of fireproofing thermal conductivity (more than 70°C °C of difference). The lower temperature increase was due to the gradual growth of the thermal conductivity, compared to the "ideal" protection case assuming a conservative thermal conductivity constant value. Hence a more realistic prediction of the temperature behaviour was carried out.

Figure 3 shows the detailed results of the mechanical FEM simulations (Von Mises stress maps) carried out implementing the temperatures predicted with the thermal FEM (Figure 2). Also in this case, a comparison was made between the simulation with variable and average coating properties; since no failure is predicted by the model, in both cases the maps are shown at 100minues of simulation.

The more critical zone under the mechanical point of view was the interface between liquid and vapour. The upper part, in contact with the vapour phase, experienced higher thermal dilatation than the lower part, in contact with the liquid. This resulted in higher stresses at the interface between the two phases. Also the upper part of the tank was characterized by high stresses, due to the thermal dilatation loads, which significantly increased in the case with average coating properties (see Figure 3b).

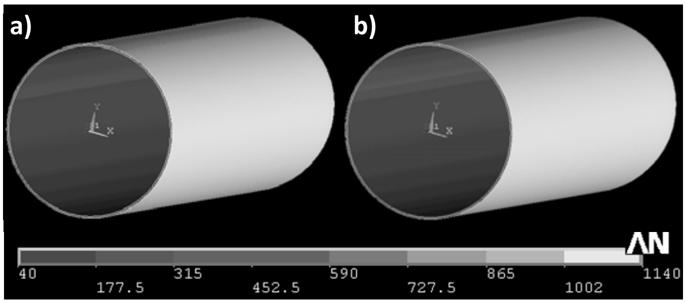

Figure 2: Temperature map (in °C) for the FEM simulations at 100min: a) simulation with variable coating properties; b) simulation with average coating properties.

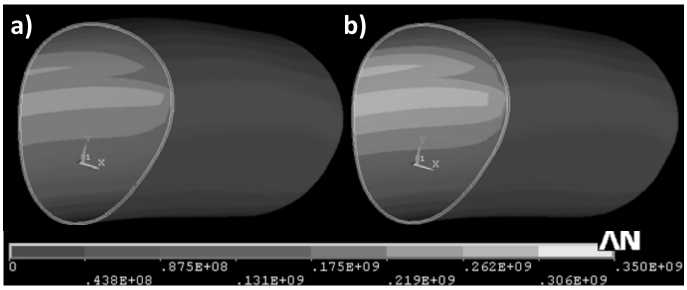

Figure 3: Von Mises stress map (in Pa) for the FEM simulations at 100min: a) simulation with variable coating properties; b)simulation with average coating properties.

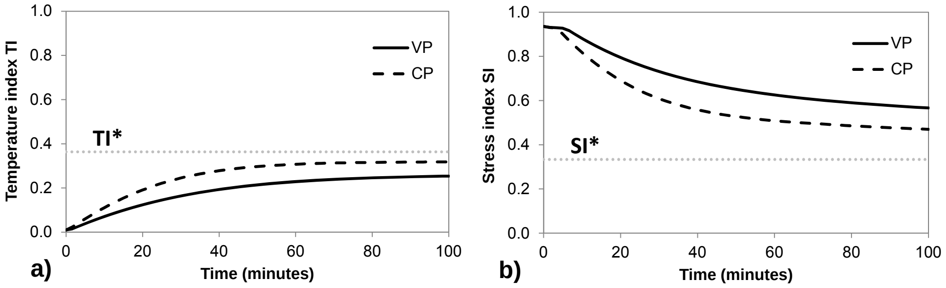

Figure 4: Comparison among the KPIs calculated for each simulation time-step considering constant coating properties (CP) and variable coating properties (VP): a) temperature index TI; b) stress index SI.

Beside the final results on the tank resistance after the fire exposure, the detailed FEM analysis allowed monitoring the dynamic behaviour of the vessel. For this purpose, two specific KPIs (Key Performance Indicators), which definition is reported elsewhere (Landucci et al. 2009b), were calculated allowing for a quantitative and synthetic evaluation of the fireproofing performance.

The first KPI is defined as the "temperature index" (TI) and is based on the assessment of vessel shell temperature gradients. SI represents the ratio among the maximum and minimum temperature on the whole structure (thus including also the fireproofing layer). The second KPI, defined as the "stress index" (SI), takes into account the residual strength of the vessel compared to the design conditions. It is defined as the ratio between a reference value for the residual allowable stress and the maximum allowable stress in the absence of fire. Reference threshold values for both TI and SI were given, respectively TI* and SI* and more details on the KPIs for PFP systems are extensively discussed by Landucci et al. (2009b). The threshold values for the KPIs allowed defining an unsafe region during the fire exposure, where tank shell failure becomes possible.

Figure 4 shows the calculated KPIs for the case with constant coating properties ("CP" curve in Figure 4) and variable properties ("VP" curve in Figure 4). As it can be seen, in both situations, the KPIs approached to the correspondent reference threshold value as the fire exposure time increased. The threshold limit was not reached for both the indexes, even if the TI value for constant coating properties was close TI* (Figure 4a). The analysis of KPIs allows pointing out that assuming constant average properties may lead to too conservative estimations respect to the assumption of a dynamic coating behaviour.

4. Conclusions

A methodology for the evaluation of the protection performance of inorganic PFP materials was presented. The methodology was based on the experimental evaluation of the relevant properties of the materials and the FEM simulation of reference equipment exposed to fire. The methodology was demonstrated in a case-study representative of the hazardous materials transportation in the European framework. The results obtained confirmed that the performance of fireproofing materials in providing effective protection from fire strongly depends on the description of the thermo-physical properties and on the behaviour of the PFP material during fire exposure. Even if characterized by relevant chemical and thermal stability, inorganic coatings may undergo significant changes in their structure and properties when exposed to high temperatures. The methodology developed introduced sound criteria for accounting of these crucial aspects. Altogether, the proposed models can contribute to a more accurate calculation of the time to failure of the protected units and provide reliable information for PFP design and risk assessment activities.

5. Acknowledgments

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