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Analysis and Testing of Fibrous Passive Fire Protection Material for Fireproofing of Equipment Units

Raffaela Moricone, Alessandro Tugnoli*, Valeria Villa, Valerio Cozzani

[a] Dipartimento di Ingegneria Civile, Chimica, Ambientale e dei Materiali Alma Mater Studiorum – Università di Bologna, Bologna, via Terracini n.28, 40131 Bologna, Italy
a.tugnoli@unibo.it

Fire is one of the most frequent accident scenarios in process facilities and it may be responsible of severe escalation scenarios: flames and heat radiation can damage equipment units, support structures, and piping with consequent loss of containment of hazardous materials. Mitigation measures are acquiring increasing importance in the design of the facilities with the goal of reducing the probability of domino effect. Passive Fire Protection Materials (PFP), properly applied, contributes to the protection of industrial equipment against accidental fires. PFP delays the heating of the protected metal and vessel contents, allowing increased time for other mitigation measures. The present contribution focuses on the measurement and modeling of some key properties for the assessment of the performance of fiber fireproofing materials. The results of the experimental activities were used to develop heat transfer models in fire-like conditions applicable to Finite Element Modeling (FEM) simulations for advanced fire and safety analysis. Particular attention was devoted to the development of a unified model for effective thermal conductivity able to account for the role of operative conditions (temperature, deformation of the fireproofing, etc.).

1. Introduction

Passive Fire Protection can be defined as an insulating system used to protected industrial equipment against accidental fire, avoiding the rapid increase of temperature in the protected items and the decrease of the mechanical properties of the structural components. While fireproofing is a well known technique, several issues for the practical application are still active object of active research: identification of fireproofing zones in a plant (see e.g. Di Padova et al., 2011; Tugnoli et al., 2012), definition of effective maintenance and inspection strategies (see e.g. Mannan, 2005; UKOOA, 2007), analysis of the protection performance (see e.g. Gomez-Mares et al., 2012a; Landucci et al., 2009a; Argenti and Landucci, 2013), effects on material corrosion and aging (see e.g. Roberts et al., 2010; UKOOA, 2007), etc. In particular, the advanced modeling of protected equipment items exposed to fire (e.g. Birk et al., 2006; Landucci et al., 2009b) requires a detailed description of the properties of the material. Thermal conductivity and degradation resistance during fire exposure are among the most important characteristics to be defined for a PFP material in these cases. The severe conditions of fire exposure cause, in any case, a variation of the physical properties of the insulation material that needs to be accounted for (Gomez et al., 2012b).

Present study is based on collecting experimental data and on modelling the behavior of PFP materials, evaluating the characteristics of the thermal protection provided by one of the more common inorganic insulating material: the silica wool. The changes in the physical properties were investigated by high temperature tests on laboratory scale. Several experimental techniques (thermogravimetric analysis (TGA), Hot Disk method (TSP), etc.) were combined in order to obtain relevant data. In order to describe the thermal properties of the insulating materials a simple approach to the modelling of heat transfer in a fibrous medium was considered. In the following, the theoretical model used to describe effective thermal conductivity is presented, the results from an experimental campaign on a reference material are reported and compared with the model preditions providing a validation of the method. Finally a simple case study application is discussed, presenting a possible application of the results.

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2. Heat transfer model

Heat transfer through fibrous insulation involves combined modes of heat transfer (conduction and radiation) in different phases (Zhao et al., 2009). If a one-dimensional geometry is considered, the heat transfer by conduction and radiation through a board of insulating material can be described by the following partial differential equation (Gomez et al., 2012b):

$$\begin{cases} \rho \cdot cp \dfrac{\partial T}{\partial t} = \dfrac{\partial}{\partial x}\left(k \dfrac{\partial T}{\partial x} \right) \\ T(x,0) = T_0 \\ k \dfrac{\partial T}{\partial x}(0,t) = -\sigma_B (\varepsilon \cdot T_{flame}{}^4 - \varepsilon \cdot T(0,t)^4) \\ k \dfrac{\partial T}{\partial x}(L,t) = -M'' \cdot cp_M \dfrac{\partial T_M}{\partial t} - h_{in}(T_M - T_{in}) \end{cases} \tag{1}$$

Where T_0 is the initial temperature, and the other boundary condition refer to the case of a direct flame radiation on the hot side of the board (T_{flame} is the temperature of the flame, ε the surface emissivity, σ_B the Stefan-Boltzmann constant) and convective exchange with the fluid in the vessel on the cold side of the board (h_{in} convective exchange coefficient, T_{in} temperature inside the vessel, M'' mass per unit area of the metal wall of the vessel, T_M temperature of the metal wall).

The effective thermal conductivity (k) can be expressed considering the fibrous thermal insulation as a semi-transparent disperse medium consisting of a fiber skeleton and air filling the gaps between fibers. Several energy transportation mechanisms occur: conduction in the fiber skeleton, conduction or/and convection in the gas phase, thermal radiation through the gas phase (Lee and Cunnigton, 2000). Hence, an effective thermal conductivity can be defined as for Eq(2).

$$k = k_{conduction} + k_{convection} + k_{radiatior} \tag{2}$$

The theoretical and experimental evidence shows that for materials with density $\rho > 20$ kg/m^3 it is possible to neglect the contribution of convection (Lee and Cunnigton, 2000). The modeling for the other terms of Eq(2) are discussed in the following.

2.1 Radiation

Radiative energy transfer in heterogeneous and porous media has been the topic of several reviews. In many approaches, the governing equations are derived by using the principle of energy conservation. This approach is acceptable if the size of the system is much larger than the wavelength of the radiation and it results in the classical radiative transfer equation (RTE) which is widely used for solving radiative heat transfer problems in absorbing, emitting and scattering media. The Rosseland diffusion approximation is a methods frequently used to solve the RTE for optically think dispersed media. According to the method, the radiative flux (q_r'') can be expressed as an equivalent diffusion process (Siegel and Howell, 1992):

$$q_r'' = -\frac{16 n^2 \sigma_B}{3\beta} T^3 \frac{\partial T}{\partial x} \tag{3}$$

Where β is the extinction coefficient, which is the product of extinction mass and sample bulk density, n is refraction index, and σ_B is the Stefan-Boltzmann constant (Bailis and Sacadura, 2000). For porous and fibrous materials the extinction coefficient is typically determined by Eq(4) (Hendricks and Howell, 1996). If the fiber diameter is large enough, the refraction index can be assumed the same as for the material from which the fibers are made (Hager et al., 1967).

$$\beta(L,\varphi) = \frac{c_e}{L}(1 - \varphi) \tag{4}$$

where c_e is a constant parameter depending on the interaction between fibers, L is the characteristics length and φ is porosity. The approach assumes a statistically isotropic medium.

2.2 Gas conduction

Daryabeige (2002) has reported that the exchange of heat from gas molecules to bounding solid surfaces is influenced by the system pressure in the rarefied and transition regimes. The gas conductivity term is determined according to the “Theory of Temperature Jump” (Kennard, 1938) in Eq(5).

$$kg = \frac{2kg0}{\Phi + \Psi\left(\frac{2-a}{a}\right)\left(\frac{2}{\gamma+1}\right)\left(\frac{1}{\Pr}\right)Kn} \tag{5}$$

which *kg0* is the air thermal conductivity, the parameter *α* is accommodation coefficient (*α* =1), *γ* and *Pr* are specific heat ratio and Prandtl number respectively. The parameters *Φ* and *ψ* depend on Knused number (*Kn*) calculated from Kennard (1938) with Eq(6).

$$Kn = \frac{\lambda}{L} = \left(\frac{K_B T}{\sqrt{2}\pi d_g^2 P}\right) \bigg/ \left(\frac{\pi}{4}\frac{D_f}{fv}\right) \tag{6}$$

In the same equation, the gas molecular free path *λ* is a function of the Boltzmann constant (K_B), the gas collision diameter (d_g), and the pressure (*P*) (Williams and Curry, 1993). The characteristic length *L* for gas conduction in fibers is calculated as a function of the fiber diameter (D_f) and the solid fraction ratio (*fv*). The latter term is defined as the ratio of density of fibrous insulation to the density of fiber parent material (Daryabeige, 2002). The parameters *kg0* (T), *Pr*(T) and *γ*(T) are usually known from the literature.

2.3 Solid conduction

The empirical model for predict solid conduction of fiber insulating used in this study is reported in Eq(7).

$$ks = Fsks^* fv^b \tag{7}$$

Fs is a global parameter that relates the microscale geometric effects of fiber matrix with the bulk dimensions (Williams et al., 1993) and *b* is power varying between 1 and 3 (Verschoor et al., 1952). The fiber solid conduction *ks** , which is thermal conductivity of bulk fiber material, has been estimated by the following fourth-order polynomial (Touloukian et al., 1970):

$$ks^* = 0.3628 + 8.473\times10^{-3}T - 1.687\times10^{-5}T^2 + 1.58\times10^{-8}T_3^3 - 4.528\times10^{-12}T^4 \tag{8}$$

2.4 Thermal conductivity: gas and solid conduction

Different ways of modeling the interaction between solid and gas conduction have been proposed by various researchers; several of them are derivations of the Maxwell equation (Wang et al., 2006). In this study two options were considered: the Parallel model and the Bhattacharyya model. The first one is shown in Eq(9) (Kantoroviche and Bar-Ziv, 1999).

$$k_{conduction} = fvks + (1 - fv)kg \tag{9}$$

The second one is shown (Daryabeige, 2002) in Eq(10).

$$k_{conduction} = ks\frac{kg - ks}{1 + \frac{fv}{1+fv}\left[1 + z\frac{kg-ks}{kg+ks}\right]} \tag{10}$$

with coefficient *z* equal to 5/6 considering half of the fibers being random and the other half being normal to the direction of heat flow.

3. Experimental approach

3.1 Material studied

The fireproofing material studied in current investigation was a silica blanket supplied by Insulcon. It consists mainly of silica glass fibers, with silicon dioxide and aluminum dioxide as main components (97%) and some binders as minor components. The specimens used in the current study were sections cut from a commercial roll, having a nominal thickness of 12 mm and an apparent density ρ_{app} equal to 0.122 g/cm^3.

3.2 Experimental apparatus

A TGA Q500 thermogravimetric analyzer from TA Instruments was used to study if thermal degradation was significant for the material. Thermal program of the tests consisted in a temperature ramp with a constant heating rate (10 °C/min) up to a final temperature of 800 °C; pure nitrogen (100 mL/min) was used as purge gas. The use of an inert atmosphere is justified by the typical fire conditions, where the oxygen availability in contact with the analyzed material is limited by the combustion.

A transient plane source instrument (TPS2500S, by Hot Disk AB) was used for measurement of the thermal conductivity. This system is designed for measuring the thermal transport properties of a sample, i.e. thermal conductivity, thermal diffusivity and specific heat, applying the transient plane source technique. Further information on the equipment and on the experimental procedures adopted are reported elsewhere (Jannot et al., 2010).

3.3 Parameter estimation

The constant parameter (c_e) in extinction coefficient and the solid conduction term (exponent b and parameter Fs) were not know and were estimated using parameter estimation techniques. The estimate method was based on least-squares minimization of the difference between measured (k_m) and predicted effective thermal conductivities (k_p) for the insulation samples as for Eq(11).

$$S = \sum_{i=1}^{n} \left[k_m(i) - k_p(i, c_e, b, Fs)\right]^2 \tag{11}$$

subject to the following physical constraints: c_e>2 , 1 ≤ b ≤ 3 (Williams and Curry, 1993) and 0 ≤ Fs ≤ 1 (Wang et al., 2006).

4. Results and discussion

4.1 4.1 Thermal degradation of the material

The degradation of the selected PFP reference sample material were investigated using TGA. The results evidence a moderate weight loss (±10%) mostly due to water evaporation and degradation of binders present in the material. Hence the change in the material properties due to material degradation was neglected in the thermal conductivity model, considering the material thermally stable.

4.2 Thermal conductivity: experimental data

The thermal conductivity of the PFP material was measured on a sample of thickness 12 mm, which corresponds to the nominal thickness of the blanket. Figure 1 shows the experimental values of the thermal conductivity measured between room temperature and 700 °C.

4.3 Validation of effective thermal conductivity model

The effective thermal conductivity models introduced above were applied to the description of the experimental data. Figure 2 shows the effect of the model choice on the results. The figure also evidences that the two models used for gas/solid conduction interaction yield very similar results. Therefore the Parallel Model, which is mathematically simpler, was selected as model of choice.

As it can be observed, when the temperature increases, changes in the contribution to thermal conductivity take place for each heat transfer mechanism. In particular, the contribution of the radiation mechanism increases at high temperatures and becomes the predominant phenomena above 600 °C. Moreover, gas conduction is higher than solid conduction. Silica knitted blankets can be deformed, reducing the thickness of the insulation past the nominal value, by even moderate compression loads. In order to provide a validation of the developed model, the model parameters estimated in the temperature dependent tests of Figure 1 were used to predict the effect on thermal conductivity of the deformation by compression at a fixed temperature. The results are reported in Figure 2 for room temperature.

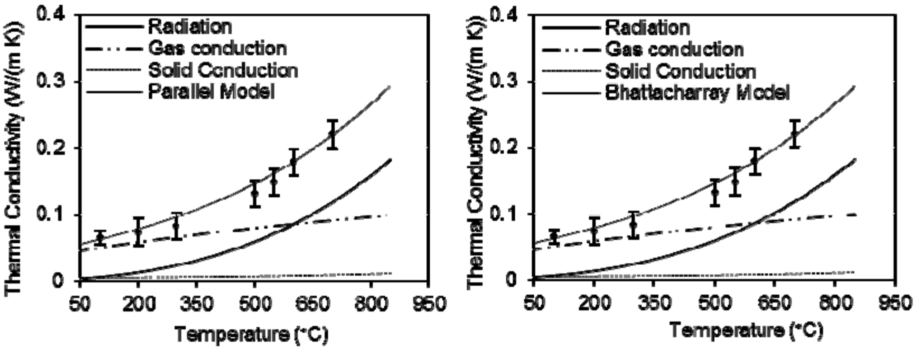


Figure 1: Effective Thermal conductivity model and Experimental data between room temperature and 700 °C. (a) Parallel model for gas and solid conduction; (b) Bhattacharyya model for gas and solid conduction.

The same figure reports the experimental measures obtained for samples mechanically compressed up to the desired thickness ratio. The deformation allowed to change material porosity between 0.9 and 0.81, resulting in variation of thermal conductivity up to 20 % of the value at nominal thickness. The good agreement between experiment and model results suggest the validity of the model and its flexibility in predicting different operative conditions for simulation purposes.

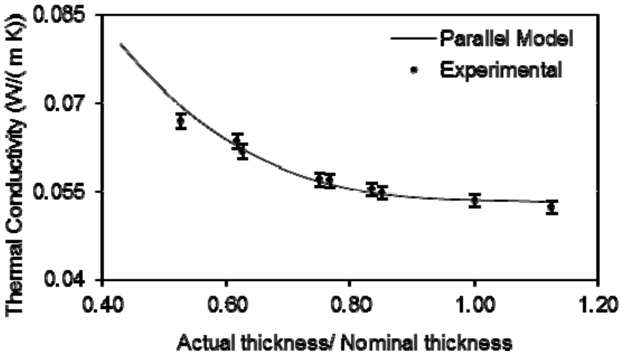
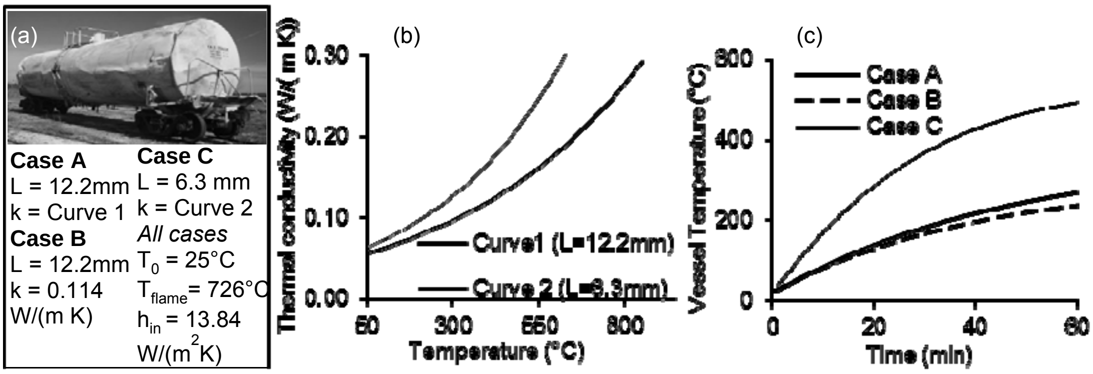


Figure 2: Calculated and measured thermal conductivity for different compression ratios at 25 °C

4.4 Case study

The case study presented here conceders the case of impact damage to an inorganic PFP system installed on a vessel wall. In these systems the silica blanket is usually protected by a thin metal sheet, that provides water tightness and also works as thermal shield during fire exposure. External impacts may deform the metal sheet, squeezing the inorganic fiber underneath (see in Figure 3a an example for a railcar). In case of fire the PFP system will operate in conditions quite different than intended design: in particular both insulation thickness and effective thermal conductivity are affected. The developed model allowed to explore the effect of thickness reduction of the effective thermal conductivity (Figure 3b). It can be observed that deformations halving the thickness of the insulator lead to moderate variation of thermal conductivity (up to 20 % in the temperature range of interest).

The developed conductivity model is applied to the simulation of a section of the PFP system applied on a tank wall. Three cases are considered, as detailed in Figure 3. The comparison of the case A and B evidences the importance of an accurate description of the conductivity behaviour of the blanket: if a constant value is assumed for the conductivity (k = 0.114 W/m^2 is the value at the average material temperature of 375 °C) a significant under-prediction of the temperature of the vessel is experienced (Figure 3c). On the other hand, the material deformation has a dramatic effect on the protection performance, as evident from the comparison of curves A and C in Figure 3c, though the analysis of the results shows that a major role is played in this case by the reduction of the material thickness. Altogether these kind of analysis would not have been possible in absence of a flexible model for description of thermal conductivity as the one developed in current study.



Case A
L = 12.2mm
k = Curve 1
Case B
L = 12.2mm
k = 0.114 W/(m K)
Case C
L = 6.3 mm
k = Curve 2
All cases
T_0 = 25°C
T_{flame}= 726°C
h_{in} = 13.84 W/(m^{2}K)

Figure 3: Case study: (a) example of PFP deformation accident; (b) simulated thermal conductivity for two deformed thickness of the blanket; (c) simulated protected wall temperature in the three cases analyzed.

5. Conclusion

A methodology to evaluate and model the thermal insulation properties of inorganic PFP materials was presented in current contribution. The methodology is based on integration of experimental and theoretical results. The approach allowed to model the protective behavior of a silica blanket, accounting for the change of physical properties occurring because of temperature and deformation of the material. The developed model may be applied to other fibrous and porous materials, supporting a better description of the time to failure of the protected items and therefore providing a more reliable information on the PFP expected performance, limiting the need of expensive large scale experimental tests.

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