Fire Safety Journal 81 (2016) 74–84

Contents lists available at ScienceDirect

Fire Safety Journal

journal homepage: www.elsevier.com/locate/firesaf

Assessment of the thermal conductivity of intumescent coatings in fire

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ARTICLE INFO

Article history:
Received 24 September 2015
Received in revised form
12 January 2016
Accepted 27 January 2016
Available online 13 February 2016

Keywords:
Intumescent coatings
Thermal conductivity
Expansion
Prediction
Different fire conditions
Steel temperature

ABSTRACT

This paper presents the results of the detailed assessment of a method that can be used to predict the intumescent coating behaviour and thermal conductivity under different conditions (changing steel section factor, intumescent coating thickness and fire condition). The basis of this method is the analytical solution of Amon and Denson (1984) [1] for predicting bubble growth under pressure under an idealised condition, which has previously been extended by the authors to non-uniform temperature field and temperature-dependent viscosity of intumescent melt. This paper demonstrates the accuracy of the predictive method to quantify the expansion process of intumescent coatings under different fire conditions, by comparing the temperatures of intumescent coating protected steel plates under different fire conditions with the fire test results of Zhang et al. (2012) [18]. The method is then applied to assess how the intumescent coating expansion and effective thermal conductivity are affected by changing the coating thickness, the steel thickness and the fire condition including smouldering fire. The results indicate that the expansion ratio of intumescent coating decreases, and hence the effective thermal conductivity increases, as the rate of heating increases. Therefore, the intumescent coating thermal conductivity obtained from the Standard fire exposure can be safely used for slower realistic fires, but would produce unsafe results for faster fires.

1. Introduction

Steel dominates the UK construction market and is widely used worldwide to construct modern, stylish and architecturally attractive structures. Due to the high thermal conductivity of steel and the rapid loss of strength and stiffness of steel at elevated temperatures, fire attack can cause significant damages to steel structures. Therefore, fire protection is often necessary to protect steel structures against fire exposure. Among the many different types of passive fire protection materials (i.e. plaster boards, sprayed materials, and intumescent coatings), thin film intumescent coatings have become the preferable option owing to their many advantages such as flexibility, good appearance (aesthetics), light weight and fast application.

Intumescent coatings are inert at room temperature, but can swell up to 100 times the original thickness when being exposed to heat from the fire attack. It is the massively expanded thickness that protects the substrate steel structure from the fire attack.

Despite their widespread use, there is a lack of understanding of how intumescent coatings behave in fire. The majority of the previous research studies may be divided into two categories: studies by chemists to invent new ingredients and their mixture to pass the specified regulatory testing conditions, or studies by fire protection engineers based on phenomenological observations of the overall performance. There is very little link between studies of these two groups of researchers. As a result, there is still little understanding of how the physical and chemical changes (studied by chemists) would affect the fire protection performance (concerns of fire protection engineers) of intumescent coatings.

At high temperatures, intumescent coatings release gases. The released gases then expand due to high pressure. How intumescent coatings expand is the most important quantity that affects their fire protection performance. The expansion process clearly depends on the coating thickness, but also the speed of chemical reaction depends on the rate of heating. Therefore, it is expected that the fire protection performance of intumescent coatings will depend on the fire condition, the protected steel substrate (thickness) and the amount of coating used which all affect the rate of heating.

However, although intumescent coating expansion is the most important quantity, due to the complexity of intumescent coating behaviour, there has been very little research devoted to predicting the expansion of intumescent coatings. Of the existing research studies that have attempted to incorporate the expansion of intumescent coatings into the model of quantifying their fire protection performance, most have assumed the expansion as input data. Of the studies that have attempted to predict intumescent coating expansion, Butler [3] and Butler et al. [4] have

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http://dx.doi.org/10.1016/j.firesaf.2016.01.011
0379-7112/

tried to simulate the expansion process at the microscopic level. However, the detailed methodology of this model is not available and the simulation results have only demonstrated the feasibility of such an approach. Zhang et al. [18,19] have developed a mathematical model to simulate the expansion process and global behaviour of intumescent coatings. In this approach, they assume that most of the gases produced in the intumescent coating are lost to the environment. The remaining amount is trapped in the intumescent coating and expands as ideal gas under the atmospheric pressure without any consideration of pressure equilibrium inside the coating. They relate the trapped gas (hence the local rate of expansion) to the local temperature and rate of temperature change. Although their comparison of model prediction results with their cone calorimeter and furnace fire test results suggests good accuracy, this model is based on many assumptions that do not reflect the physical and chemical behaviour of intumescent coatings.

Because of this lack of a simple and reliable model to predict the expansion behaviour of intumescent coatings, hence their fire protection performance, the current method of assessment for intumescent coatings in the current Eurocode (EN 13381-8:2013) [7] treats the intumescent coating as a chemically non-reactive material because it assumes that the intumescent coating thermal conductivity is temperature dependent only and the rate of heating (due to different fire exposure condition, different coating thickness, different steel section factor) has little effect.

The above assumptions of the current assessment method are clearly not correct. A more reliable method for the assessment of intumescent coatings should be developed. Recently the authors [8] extended the analytical solution of Amon and Denson [1] for bubble expansion under pressure to quantify the expansion process of intumescent coatings. It has been found that with suitable modifications and input reaction data (mass loss, viscosity), the Amon and Denson [1] model is applicable. The validation of the model is based on comparison of the intumescent expansion process and the maximum expansion ratio between the calculation results and the test results of Zhang et al. [18,19] under different cone calorimeter heating and furnace fire testing conditions. In this comparison, the measured steel temperatures were used as input data. However, due to the limited number of tests, it is not possible to examine in detail the influences of changing the various design conditions on the behaviour and thermal conductivity of intumescent coatings. These design conditions include the fire temperature-time curve, the intumescent coating thickness and the steel section factor. The purpose of this paper is to address this deficiency, by conducting an extensive series of parametric studies, using the analytical method based on the Amon and Denson [1] model.

2. Procedure

The aim of this research is to assess the accuracy of a predictive method that can be used to quantify the effects of changing different design parameters on the behaviour and thermal conductivity of intumescent coatings. To achieve the aim of this research, the following procedure is applied:

(1) Obtaining the effective thermal conductivity of intumescent coating for different rates of temperature increase. This will be done by assuming a uniform temperature field in the coating. The thermal conductivity of the coating will be expressed as the effective thermal conductivity, calculated for the original coating thickness. Temperature rates of 1 °C/min to 100 °C/min (near the fire exposure surface) will be used.
(2) The effective thermal conductivities of the coating are then be used to calculate the protected steel temperatures using the equation in EN 1993-1-2 [6] for protected steel sections. Two schemes will be used; one assuming that the entire intumescent coating is a single layer and one dividing the intumescent coating into multi-layers. The calculation results will be compared with the fire test results of Zhang et al. [18] to check the validity of the model.
(3) Using the analytical method, a parametric study will be carried out to systematically calculate the protected steel temperatures under different fire temperature-time curves, using different steel section factors and different coating thicknesses.
(4) Using the protected steel temperatures calculated from (3), the effective thermal conductivity of the intumescent coating with non-uniform coating temperature distribution will be calculated, through inverse solution of the protected steel temperature equation according to EN 13381-8:2013 [7].

In this paper, the intumescent coating is water based and is the same as used by Yuan [17] and Zhang et al. [18,19]. To predict the intumescent coating expansion, it is necessary to have the input data of mass loss, viscosity and surface tension of the intumescent coating. Figs. 1–3 present the required input data for the intumescent coating used.

3. Effective thermal conductivity of intumescent coating

The intumescent coating char can be treated as a porous material. According to Yuan [17], the apparent thermal conductivity (related to the expanded thickness) of the coating is:

$$\lambda^{*}=\lambda_s\frac{\frac{\lambda_g}{\lambda_s}\varepsilon^{\frac{2}{3}}+1-\varepsilon^{\frac{2}{3}}}{\frac{\lambda_g}{\lambda_s}\left(\varepsilon^{\frac{2}{3}}-\varepsilon\right)+1-\varepsilon^{\frac{2}{3}}+\varepsilon} \tag{1}$$

where ε is the volume fraction (or porosity), λ_g is the thermal conductivity of the gas within the pore (or bubble) and λ_s is the thermal conductivity of the solid part of the porous structure. After full expansion, there is very little solid left in the coating char and the thermal conductivity of the solid has little influence on the thermal conductivity of the coating. For simplicity, a value of 0.5 W/mK may be used [17].

Porosity (ε) is defined as the fraction of the total volume occupied by the bubbles to the total volume of the char. If the expansion ratio of the intumescent coating is E, then the porosity is

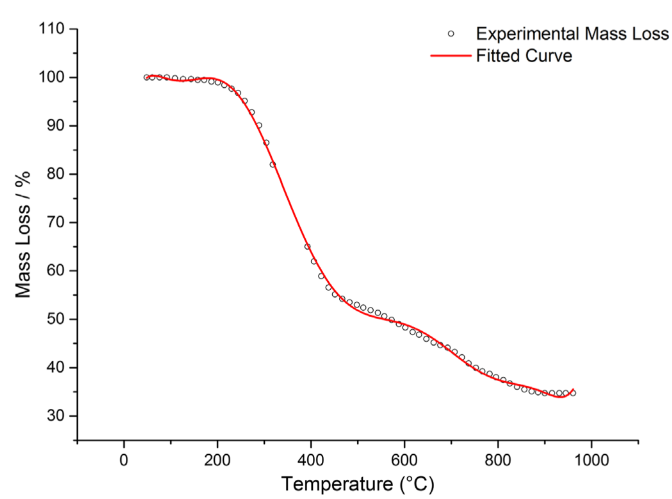

Fig. 1. Mass conversion (loss) data as a function of temperature [19].