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Global modelling of fire protection performance of intumescent coating under different cone calorimeter heating conditions

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ABSTRACT

This paper presents a mathematical model to simulate the expansion process and global behaviour of intumescent coating applied to a steel plate under different cone calorimeter heating conditions. A mathematical expression has been found to relate the local rate of expansion of intumescent coating to the local rate of mass loss, rate of temperature change and temperature. Comparing the recorded expansion process of intumescent coating under cone calorimeter heating exposure, this modelling method has been found to give accurate results of the expansion–time relationship for the product tested. The thermal conductivity of expanding intumescent coating was modelled based on treating intumescent coating as a homogeneous porous media. The predicted steel temperatures were found to be in excellent agreement with experimental results from the cone calorimeter tests with different steel plate thicknesses and intumescent coating thicknesses under two different heat fluxes.

1. Introduction

Structural steel is widely used in modern structural construction all over the world. It is an important and prime requirement of building regulations for steel-framed buildings to have sufficient fire resistance and one way to achieve this requirement is to apply passive fire protection to the structural steel [1]. Thin film intumescent coatings have become the dominant choice for passive fire protective materials because of their many advantages including: flexibility and ease of usage for both on- and off-site applications, light-weight, thin and attractive appearance, and high standard finish.

Intumescent coating is inert at room temperature but intumesces up to 100 times its initial thickness when exposed to heat, forming a cellular charred layer of low conductivity foam. The foam layer protects the substrate steel from a fire, reduces the rate of temperature rise in the steel, and prolongs its load bearing capacity. The assessment of fire protective intumescent coatings is generally performed by means of standard fire resistance tests [2], which is an unrealistic fire scenario due to the temperature–time relationship of the fire being fixed and forever increasing in temperature with time. There is now a demand from the structural fire engineering community to consider more realistic fire conditions, in which the fire temperature–time relationship is defined in terms of the geometry of the compartment, available ventilation, amount of combustible material and the characteristics of the compartment boundaries. Intumescent coating is a reactive material and its thermal properties are dependent on the heating condition and hence on the type of fire exposure. Therefore, the thermal properties of intumescent coatings, particularly thermal conductivity, obtained from standard fire tests may not be consistent and reliable under a different set of fire exposure conditions. On the other hand, it is not feasible, or cost effective, to conduct numerous fire tests under different realistic fire exposure conditions. Therefore, developing a modelling approach, in which different fire exposure conditions can be incorporated, is preferred.

The expansion of intumescent coating under heat is rather complicated, involving a complex mixture of gas, liquid and solid phases and with many variables being extremely difficult to measure. To date, the majority of previous research studies into the behaviour of intumescent coatings have been experimental based and mainly focused on understanding the effects of different formulations to help manufacturers develop products to pass the standard fire resistance rating test [3–5]. Very few studies have been conducted to investigate the performance of intumescent coatings under different fire conditions, with very limited success in modelling. The modelling efforts may be classified into three types according to the level of complexity.

(1) At the simplest level, without considering the complex physical and chemical behaviour of intumescent coating [6,7], a simple

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Nomenclature

A	pre-exponential factor (s^{-1})
a	unit surface area (m^2)
C	specific heat capacity ($J\,K^{-1}kg^{-1}$)
C_{trap}	trapped gas coefficient
d	bubble size (m)
e	emissivity
E	activation energy ($kJ\,mol^{-1}$)
h	convection heat transfer coefficient ($W\,m^{-2}$)
H	heat of pyrolysis per unit mass of material ($J\,kg^{-1}$)
K	reaction rate constant
m	mass (kg)
n	number of elementary layers in the coating
P	gas pressure (Pa)
Q	cone calorimeter heat flux ($kW\,m^{-2}$)
R	universal gas constant ($J\,mol^{-1}\,K^{-1}$)
t	time (s)
T	temperature (K)
W	mean gas molecular weight
x	coordinate along coating thickness (m)
y	coordinate along steel thickness (m)
Y	mass fraction
$\dot{g}$	mass flow rate of gas per unit area ($kg\,s^{-1}\,m^{-2}$)

Greek letters

β	trapped gas ratio during swelling
ΔH	decomposition heat in an elementary layer
Δt	time step (s)
Δx_i $(i=1,n)$	thickness of coating element layer (m)
Δy	thickness of steel element layer (m)
ε	void fraction
λ	thermal conductivity ($W\,m^{-1}\,K^{-1}$)
ρ	density ($kg\,m^{-3}$)
σ	Stefan–Boltzmann constant ($W\,m^{-2}\,K^{-4}$)
v	stoichiometric coefficient

Subscripts

c	coating
C	char
g	gas
s	solid
S	steel
S_1, S_2, S_3	reactive components
G_1, G_2, G_3	gas products from S_1, S_2, S_3

thermal analysis is carried out to determine the temperature dependent effective thermal conductivity of the intumescent coating based on standard fire tests or cone calorimeter tests. These studies are restricted to specific fire conditions, together with specific steel and coating thicknesses. It would be grossly inaccurate to extrapolate the results from these studies to different applications.

(2) At the most complicated level, intumescent coating behaviour may be studied from fundamental microscopic level of chemical reaction, individual bubble generation, growth, movement, interaction with other bubbles and collapse [8–10]. This type of study requires many assumptions which will be difficult to validate, extensive input data that will be difficult to quantify and extremely demanding computational effort which will not be practical to implement. So far this type of modelling has been limited to the early stage of intumescencing and has not been validated.

(3) The study presented in this paper will follow an intermediate approach in which the focus is on measurable global chemical and physical quantities of intumescent coating, with the chemical reactions being coupled with thermal analysis [11–18]. An example of this approach was adopted by Di Blasi [11,12], in which the chemical reactions of an intumescent coating were described by three independent global reactions: melting, swelling and charring. The degradation of the intumescent coating components were described by the Arrhenius kinetic law and the volume expansion was associated with mass loss. The effects of endothermic/exothermic chemical reactions and the energy loss due to gas escaping were taken into consideration. This method is attractive because the complex chemical reactions and bubble mechanisms are simplified so the heat and mass transfer process can be calculated using global physical/chemical properties.

All the existing intermediate level studies have many limitations, the most critical one being that an 'expansion factor (ratio)' should be provided as input to determine the final coating thickness. However, in reality, the expansion ratio spans a wide range and is the most singular important factor affecting the thermal properties of intumescent coating [11–18]. Indeed, the expansion ratio should be a model output instead of a prescribed input. By introducing an empirical relationship based on mass loss, Griffin [18] proposed an alternative method. However it is not clear whether the relationship proposed by Griffin would be applicable for different fire scenarios, since only one fire condition was explored. This paper builds on the research of Di Blasi [11,12] and Yuan [19,20], but presents a new model to allow the intumescent coating expanding process to be accurately predicted for different heating conditions. Experimental validation of the model was performed using the authors' test results from a cone calorimeter, which is an instrument widely adopted to measure many materials fire properties because it allows small-scale heating tests to be performed in a timely and cost-effective manner. Cone calorimeter can produce a stable heating source of different heat fluxes, thus allowing the effects of heating condition on intumescent coating to be investigated.

2. Theory and mathematical model

It is generally accepted that intumescent coating is composed of three active components (acid source, blowing agent, and charring agent) bound in a binder polymer [21–23]. When exposed to a heating source, several reactions are triggered almost simultaneously but in an appropriate sequence. First the coating melts and forms a viscous fluid; the acid source breaks down to yield a mineral acid as a catalyst, which then takes part in the charring reaction to yield the carbon char and at the same time the blowing agent decomposes to release a large amount of gaseous products, part of which is trapped in the coating to cause the molten matrix to swell. As the temperature increases, the mixture is solidified; finally, the carbon char further oxidises leaving a residual protective multi-cellar insulating layer.

The major assumptions in this model are

(1) Heat and mass transfer occurs in one-dimension only, being vertical to the surface of substrate. Fig. 1 shows a schematic of the coating system, which consists of a steel substrate and an