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NUMERICAL ESTIMATION FOR INTUMESCENT THERMAL PROTECTION USING ONE-DIMENSIONAL IHCP

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ABSTRACT

Intumescent coatings are an important group of passive fire protection materials, representing about one third of steel fire protection costs. This insulating system is made of four different chemical compounds that can be classified as: a carbonisation agent, an acid source, a foaming agent and a catalyst. When protecting a steel structure under fire conditions, the intumescent paint is heated, beginning to melt, to bubble and to swell, forming a multi-cellular barrier which decreases the heat transfer from the fire to the substrate. The film behaviour is characterized by an expansion and mass loss, producing a foam char with a geometry that varies from 5 to 200 times its original volume. In order to design this type of protection, the intumescence physical and thermal behaviour must be acknowledged, being the thickness and the effective thermal conductivity the key parameters during this process.

The performance of a commercial water-based intumescent paint is assessed by a set of experimental tests, conducted in a cone calorimeter, which enables the mass loss rate calculation, the substrate temperature and the intumescence thickness variation with time.

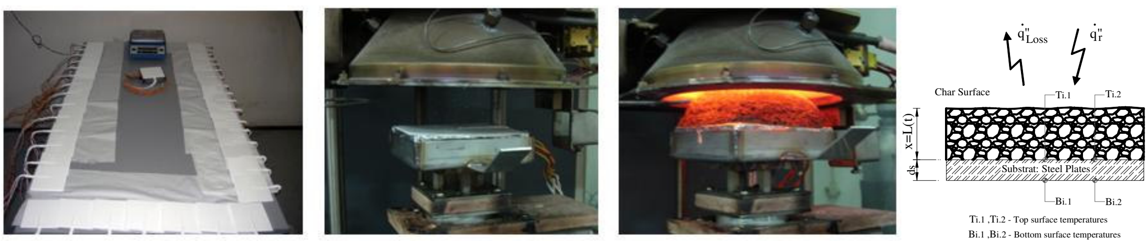

Fig. 1 – Coated steel plates, with fixed thermocouples, cone calorimeter setup and intumescence development.

The samples are made of 100 [mm] squared steel plates, coated in one side with different dry film thicknesses and tested in a cone calorimeter as prescribed by the standard E1354-04 [1], considering different heat fluxes. Substrate temperatures are measured by means of four thermocouples, type k, welded at the plate in the heating side and at the opposite side, at two different positions, see Figure 1. Using discrete frames, obtained from the camera during tests and by image processing techniques, the intumescence profile development was measured over time.

Although the problem of solving energy equation on each side of the intumescence moving boundary is considered as a generalized Stefan problem, in which the moving boundary and the free boundary locations must be determined as part of the proposed problem, [2], in this work the intumescence is treated as one homogenous layer of constant specific mass and constant specific heat. The development of the intumescence may be considered as a one-dimensional heat conduction problem, where the heat flows through the coating layer. The governing equation and the corresponding boundary conditions for the problem are:

$$c\rho \frac{\partial T}{\partial t} = \frac{\partial}{\partial x} k_{eff} \frac{\partial T}{\partial x} \qquad 0 < x < L(t) \tag{1}$$

$$k_{eff} \left. \frac{\partial T}{\partial x} \right|_{x=L(t)} = \varepsilon \dot{q}_r^{''} - h_c (T - T_a) - \varepsilon \sigma (T^4 - T_a^4) \qquad x = L(t) \tag{2}$$

$$k_{eff} \frac{\partial T}{\partial x} = d_s c_s \rho_s \frac{\partial T_s}{\partial t} \qquad x = 0 \tag{3}$$

The solution for the effective thermal conductivity and the temperature field, defined by equations 1-3, may be considered an inverse heat conduction problem (IHCP), being ill-posed, since it will not, in general, have a unique solution. Such problems are extremely sensitive to measurement errors, [3]. The proposed numerical solution is obtained by the finite difference method, considering a single temperature sensor, corresponding to the thermocouple at the plate top surface, and using the function specification method, comparing the single future time step and r future time steps methods, as proposed by Beck, [3].

The intumescence effective thermal conductivity will be estimated by solving the IHCP, considering the influence of: (1) initial dry thickness, (2) incident heat flux, (3) substrate thickness and (4) intumescent coating type.

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