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Methodology for estimating pyrolysis rates of charring insulation materials using experimental temperature measurements

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ABSTRACT

This paper presents the application of a simplified method to estimate pyrolysis rates from rigid closed-cell cellular plastics by means of experimental temperature measurements. These materials are extremely effective in meeting energy efficiency goals in buildings and their safe use should also be enabled and optimised by undertaking comprehensive fire safety analyses. The proposed methodology consists of determining the mass loss as a function of the thermal evolution by applying a mass conversion directly using thermogravimetric data under non-oxidative conditions. In order to verify this simplified method, an experimental programme based on 100 mm thick samples of rigid polyisocyanurate foam was conducted using a Cone Calorimeter, obtaining measurements of mass loss and temperature within the core of the material. A Monel plate was used on top of the sample in order to represent a simpler boundary condition by eliminating the smouldering process of the charred material. Although the pyrolysis rates using this methodology did not provide a perfect fit with experimental data, they showed similar trends, with a slightly delayed prediction but still accurate magnitude. This methodology presents potential for fire safety engineering applications in two domains: (1) as a complementary technique to improve the interpretation of results from standard and ad-hoc testing, and (2) as a design technique for the evaluation of potential heat release contribution and gaseous emissions of assemblies incorporating insulation materials.

1. Introduction

During recent decades sustainability has become one of the main drivers in building construction, resulting in highly thermally efficient buildings. Several techniques may be used to achieve the stringent energy efficiency requirements defined by the Energy Performance of Buildings Directive [1], e.g. thermal insulation within the building envelope, increased levels of air tightness, efficient heat recovery of the ventilation systems, reduction of thermal bridging and/or more efficient windows [2]. The intense use of thermal insulation is one of the primary targets due to the large surface area of the building envelope and the architectural aspirations. As a result, low thermal transmittances (*U-values*) are required, which can only be achieved by significantly increasing the thickness of insulation used.

Due to the multi-criteria nature of building design, stringent *U-values* clash with other desired design criteria such as efficient space usage and cost. Despite the large diversity of insulation materials in the market [3], under this competitive scenario closed-cell plastic foams have become an easy and cost-effective solution because of their relatively low thermal conductivity. The most common closed-cell insulation foams at present being used are rigid polyisocyanurate foams, commonly known as PIR, and phenolic foam. These materials are often provided as boards with a foil-facing on the surface and used for framing construction or masonry cavity walls; alternatively they can be embedded directly within linings, e.g. sandwich panels or structural insulated panels (SIPs) [4].

Despite the fact that these materials are extremely effective in meeting energy efficiency goals, their use should be also enabled and optimised by undertaking a comprehensive fire safety analysis, i.e. systems including insulation materials should be optimised while still ensuring life safety and property protection.

1.1. Fire performance of closed-cell plastic insulation materials

The fire performance of these materials has been studied by several authors at different scales [5–19]. Generally, these types of plastics are

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Nomenclature

k	thermal conductivity (W m^{-1} K^{-1})
c	specific heat capacity (J kg^{-1} K^{-1})
f	non-dimensional fraction of remaining mass (–)
i	number of element (–)
j	number of time step (–)
k	number of exposure area (–)
L	thickness (m)
m	mass (g)
$\dot{m}$	mass flow (g s^{-1})
$\dot{m}''$	mass loss rate per unit area (g s^{-1} m^{-2})
N	maximum number of finite differences (–)
q	heat (W)
t	time (s)
S	surface area (m^{-2})
T	temperature (K or °C)
x	distance (m)
Y	yield (g g^{-1})

Greek letters

α	absorptivity/emissivity (–)
ΔH_c	effective heat of combustion (J kg^{-1} K^{-1})
Δt	time step (s)
Δx	finite difference thickness (m)
ρ	density (kg m^{-3})

Subscripts

0	initial
cr	critical
i	of the difference i
net	net/conductive
P	pyrolysis
z	species

Acronyms

HRR	heat release rate
MLR	mass loss rate
PIR	rigid closed-cell polyisocyanurate foam
SIP	structural insulated panel
TC	thermocouple
TGA	thermogravimetric analysis
U-value	thermal transmittance

classified either as thermoplastics or thermosets. Thermoplastics (e.g. expanded polystyrene) exhibit melting behaviour, while thermosets (e.g. polyisocyanurate or phenolic foam) exhibit a charring behaviour, leaving a carbonaceous residue after pyrolysis. A complete description of the different mechanisms of thermal decomposition for these polymers is described by Witkowski et al. [5]. These mechanisms result in different fire performance, with a charring behaviour being more desirable due to the positive effect of the char layer on the reduction of the pyrolysis rate. Several authors have focussed their research at the material scale (e.g. thermogravimetry), looking at polymer formulations that promote larger residue generation and endothermic reactions in the solid-phase [6–8]. These techniques of flame retardancy have been largely covered by Hull and Kandola [9]. However, the majority of research has focussed on the macroscopic material behaviour using bench-scale testing, thus concentrating on the ignition mechanism and release of heat from these materials [10–19]. More extensive experimental work covering different scales can be found in Refs. [12,18].

Recently published work showed the relation between the thermal degradation at the material scale linked to the heat transfer phenomena within the solid material [20]. Rigid closed-cell polyisocyanurate and phenolic foam showed similar behaviour, i.e. materials that experience pyrolysis and char formation. The char layer reduces the heat transport to the pyrolysis front resulting in a slower propagation and lower pyrolysis rate. Typically, this insulating effect of the surface char layer limits the heating of virgin foam to several degrees per minute. Experimental results showed that this char is however highly vulnerable to surface oxidation (smouldering). The smouldering process was shown not to be self-sustaining due to the large heat losses under the specific experimental conditions. In addition, the closed-cell structure of the polymer restricted the air flow through the foam which was shown to be a key factor to limit self-sustaining smouldering [20]. In end-use conditions, the insulation materials are typically covered by a lining or a physical barrier, thus limiting the contact with the air, unless they are introduced in partial fill cavity walls. As a result, this smouldering behaviour is not expected under real fire conditions.

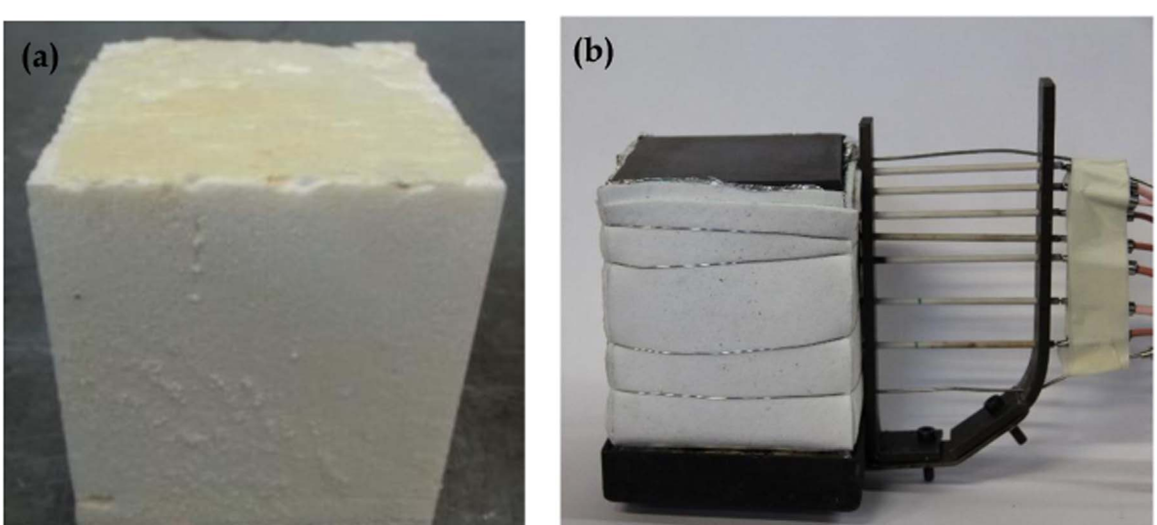

Fig. 1. (a) PIR sample prepared for testing. (b) PIR sample wrapped in aluminium foil and ceramic paper with metallic plates and thermocouples inserted into the centre of the sample through ceramic tubes. A special holder was designed to keep the thermocouple horizontal during the insertion.