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Performance criteria for the fire safe use of thermal insulation in buildings

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HIGHLIGHTS

- Review on the effect of insulation materials and fire safety in buildings.
- Review of inadequacies of current fire safety methods with insulation materials.
- Failure criteria redefinition based on material characterisation and experiments.
- Methodology for the fire safe design of insulation materials in buildings.
- Performance-based methodology that allows quantitative design of insulation systems.

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ABSTRACT

Building design can be considered as a multi-objective optimisation problem, in which many criteria are considered for determining the most favourable solution. The application of optimisation techniques requires the design criteria to be quantifiable, which sets the baseline for the application of performance-based designs. Sustainability has become the main driver in the built environment during recent decades, with energy efficiency becoming the foremost design criteria and appropriately quantified. By contrast, the approach taken for fire safety is much simplistic, relying on a series of prescriptions based on material classification and "pass–fail" criteria defined in standard fire tests. This results in deficiencies in identification of fire hazards and undermines any attempt at design optimisation. A redefinition of the failure criteria framework based on fundamental understanding of the material behaviour, including the heat transfer controlled processes governing the onset of pyrolysis, can provide a performance-based methodology for the fire safe use of insulation materials in buildings. The different hazards from insulation materials in fire are identified and a set of criteria are defined to identify likely failure modes. A series of highly instrumented large-scale experiments of a construction system involving a common combustible material are referenced to demonstrate the proposed methodology.

1. Introduction

At present, the building design can be considered as a multi-objective optimisation technique, in which many criteria are considered for finding the most favourable solutions. Optimisation techniques are often applied to several criteria such as sustainability (energy consumption [1], life cycle [2] or durability), space-usage and lay-out [3], human comfort (thermal [4], acoustical or visual [5]) or structural design [6]. These are some relevant factors among many others to be considered in the design of buildings.

Under this scenario, energy performance has become the main driver in building design during recent decades, and several changes are expected in construction features and methods. Higher levels of insulation represent one of the main features of energy efficient buildings. As an example of this increasing trend on required higher energy performance, current and expected thermal transmittance (U-value) for the envelope of domestic buildings in the United Kingdom are presented in Table 1. This enhanced performance is required on new and refurbished buildings for the EU Member States by the Energy Performance of Building Directive (EPBD) and the Renewable Energy Directive [7], which indicates a series of requirements for achieving nearly Zero-Energy Buildings by 2020.

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Nomenclature

c_p	specific heat capacity ($J \cdot kg^{-1} \cdot K^{-1}$)
$erfc$	error function
h_T	global heat transfer coefficient of heat losses ($W \cdot m^{-2} \cdot K^{-1}$)
k	conductivity ($W \cdot m^{-1} \cdot K^{-1}$)
L	thickness (m)
$\dot{m}$	mass flow ($kg \cdot s^{-1}$)
t	time (s)
t_p	pyrolysis time (s)
$\dot{q}''$	heat flux ($W \cdot m^{-2}$)
S	surface area (m^2)
T	temperature (K or °C)
U	internal energy ($J \cdot kg^{-1}$)
U	thermal transmittance ($W \cdot m^{-2} \cdot K^{-1}$)
V	volume (m^3)
X	space (m)

Greek letters

α	absorptivity (–)
ρ	density ($kg \cdot m^{-3}$)

Subscripts

B	of thermal barrier
c	characteristic
cr	critical
f	of furnace walls
g	of gas-phase
i	external
ins	of insulation layer
$loss$	losses
p	of pyrolysis
w	of tested sample
∞	of ambient

Acronyms

CO	carbon monoxide
CO_2	carbon dioxide
DTG	differential thermogravimetric analysis
EPBD	energy performance of building directive
FIGRA	fire growth parameter
HRR	heat release rate inside the compartment
MW	stone mineral wool
O_2	oxygen
PIR	rigid polyisocyanurate-based foam
SBI	single burning item test
SMOGRA	smoke production parameter
TGA	thermogravimetric analysis

Most common insulation materials classically used in the European market are polymeric foams (plastics) and inorganic wools. Papadopoulos et al. [8] recognised that inorganic materials and plastic foams respectively represent 60% and 27% of the European market. A more recent study presented by *Rockwool International A/S* in 2011 [9] showed similar trends but with increased percentages for the plastic foams, with stone wool representing 25–30% of the European market, while glass wool had the same representation and plastic foams making up the remaining 40–45%.

Plastic foams are often considered to be the optimum for building design due to their lower conductivity, lower density and the required reduced thermal transmittance (*U*-value) for the building envelope. This is translated into thinner walls, and therefore lower space usage and lighter assemblies. However, current design methods for building design do not consider fire safety as a quantifiable variable in the multi-objective optimisation design, but rather as general prescriptions based on standard testing of materials and products, the performance of which is evaluated as a material classification and as pass–fail criteria. Increased criticism has been raised about certain aspects of standard fire testing during recent decades [10,11]. These are mainly related to the fact that knowledge from first principles is, in general, not widely applied in the fire safe design of buildings.

Many other drawbacks of the predominantly prescriptive methodology can be mentioned. The most important one, which has also been previously identified by many authors [12,13], is that results from standard fire testing are not representative of real fires, and in some cases do not correspond to the most onerous scenarios and failure modes that might be experienced in a real building. Indeed, many studies have shown that results obtained from a specific test are rarely widely applicable to other scenarios [14]. As recognised by Drysdale [11], results obtained by standard testing must be generalised and applied with care, since these strongly depend on the apparatus and procedures followed. Therefore, extrapolation of results requires a fundamental understanding of material behaviour which may be hard to come by. This is where standard testing often fails, since extrapolation to real scenarios and reliance on rating systems from simplified tests may not be justified.

This scenario contrasts with multiple concerns raised about the intense use of insulation materials in buildings by the fire safety community [15,16]. Two approaches are commonly presented for discussion:

The first one is based on the concern about using combustible[1] materials within the boundaries of the compartmentalisation. Compartmentalisation is the last and most crucial system for controlling fire spread through a building. The use of combustible materials raises a series of possible issues with regard to fire safety. More severe fire behaviour might be expected if combustible materials contribute to the fire inside the compartment, resulting in heat release contribution and likely longer fire duration. This larger severity might lead to important issues outside the compartment, such as a likely premature collapse of the boundaries which may then trigger internal or external fire spread. A simultaneous issue is represented by the generation of toxic species released by the pyrolysis or combustion of pyrolysates.

The second approach is based on the effect that insulating walls might have on the fire behaviour due to lower heat losses to the exterior, therefore increasing the thermal feedback to the fire and burning fire load.

A methodology based on material characterisation from first principles is proposed to address the design of insulation materials for buildings, with the aim that the different hazards and associated risks can be quantified, and then reduced or mitigated. In order to set out this methodology, a discussion is firstly presented on what current standard test methods for fire safety design are measuring, which identifies the inadequacy of this framework for insulation materials. This is followed by an analysis of the expected behaviour of insulation materials from a heat transfer perspective. A series of highly instrumented large-scale experiments of a

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[1] The term combustible used in this manuscript shall be interpreted as the ability of an organic compound (gas or solid) to oxidise rather than a classification given by standard fire testing.