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Design Tool for the Definition of Thermal Barriers for Combustible Insulation Materials

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Abstract

Previous work has demonstrated that the main and initiating hazard from combustible insulation materials is the onset of pyrolysis. This paper presents a methodology for designing thermal barriers for combustible insulation in buildings, which represent the main measure to control this hazard. A series of potential design tools are developed in order to determine the relationship between the different design parameters, and therefore, define the optimum thickness and thermal properties from the thermal barrier for a series of fire inputs.

Introduction

At present, the use of insulation materials in the built environment is drastically increasing due to requirements for improved energy performance of buildings around the world. However, most of the insulation materials used in the European market comprise of plastic organic foams such as polyurethane, polyisocyanurate, phenolic foam or expanded polystyrene, which by definition are combustible. Since these materials are characterised by their low thermal inertia, very modest amounts of energy are required for achieving the onset of pyrolysis at the surface. Thus, the main hazard from combustible insulation materials is represented by the onset of pyrolysis, resulting in the significant release of flammable volatiles. Previous work has demonstrated that this is to be considered as the main and initiating hazard from combustible materials [1, 2], which may be represented as a critical temperature, equivalent to the concept of ignition temperature in solids [3, 4]. Control measures for this hazard lie in the design of effective non-combustible thermal barriers to delay the arrival of the thermal wave at the insulation layer. A tool for the quantitative design of barrier parameters, such as thickness and thermal properties as a function of heat flux inputs from the fire, is proposed herein. This approach will allow for the performance-based design of building assemblies to be carried out on the basis of a particular failure criterion defined for thermal insulation materials [1].

Design strategy

The safe use of insulation materials in assemblies lies in assuring that the onset of pyrolysis - conservatively defined by the authors as a critical temperature [3] - is not achieved by its surface. The instant at which the surface of the insulation achieves the critical temperature is defined as the critical time, which is particular to specific conditions of heat exposure and material properties of the thermal barrier and insulation. Therefore, the goal from performance-based designs of assemblies is to guarantee no involvement of the insulation to heat release contribution or generation of toxic effluents for a specific time, judiciously determined by the practitioners.

The definition of the problem that allows prediction of the critical time is based on the resolution of the heat of conduction equation for two media in contact, represented in Fig. 1, and defined in Eqs. (1) to (5):

$$\dot{q}_{net}'' = -k_b \cdot \frac{\delta T}{\delta x} \Big|_{x=0^+} \quad \text{for } x = 0 \quad (1)$$

$$\frac{\partial \left(k_b \cdot \frac{\delta T}{\delta x} \right)}{\partial x} = \rho_b \cdot c_b \cdot \frac{dT}{dt} \quad \text{for } 0 < x < L_b \quad (2)$$

$$-k_b \cdot \frac{\delta T}{\delta x} \Big|_{x=L_b^-} = -k_i \cdot \frac{\delta T}{\delta x} \Big|_{x=L_b^+} \quad \text{for } x = L_b \quad (3)$$

$$\frac{\partial \left(k_i \cdot \frac{\delta T}{\delta x} \right)}{\partial x} = \rho_i \cdot c_i \cdot \frac{dT}{dt} \quad \text{for } L_b < x < L_b + L_i \quad (4)$$

$$-k_i \cdot \frac{\delta T}{\delta x} \Big|_{x=L_b+L_i} = \dot{q}_{loss}'' \approx 0 \quad \text{for } x = L_b + L_i \quad (5)$$

where \dot{q}_{net}'' is the net heat flux, k_b , ρ_b , c_b and L_b and k_i , ρ_i , c_i and L_i are the thermal conductivity, density, specific heat capacity and thickness of the barrier and the insulation respectively, and \dot{q}_{loss}'' are the heat losses at the rear surface of the insulation.

Then, the design process shall aim to advise on selecting suitable barriers, which corresponds to a rational optimisation of the barrier thermal properties and thickness. This approach allows for different combinations of materials to reach an equivalent level of fire safety, represented by a given critical time for specific conditions of heat exposure.

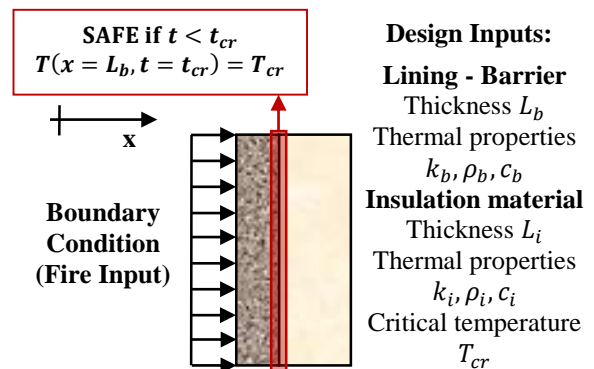


Fig. 1. Problem definition for the methodology based on the control of the pyrolysis onset

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On the definition of design tools

A discussion on the methodology fundamentals for the definition of design tools that would allow optimising the thickness and thermal properties of the barrier is presented here. Generic analytical solutions are explored, and uncertainties and further steps are detailed.

Methodology parameters

A description of the parameters that determine the design methodology is given below:

- The **critical time** (t_{cr}), defined as the moment at which the critical temperature of the insulation material is obtained for specific fire inputs. The critical time represents a conservative time below which no contribution to the heat release rate from the flammable insulation can be guaranteed.
- The **fire inputs**, which define the boundary condition (\dot{q}_{net}'') for specific heat exposures. A discussion on the adequate definition will be presented below. Probabilistic approaches can be incorporated to allow a wide range of heat exposures to be considered.
- The **insulation critical temperature** (T_{cr}), **thickness** (L_i), and **thermal properties** (k_i , ρ_i , c_i). These variables are fixed for the definition of the specific tools which are unique to these properties. Indeed, the thermal evolution of the barrier is strongly dependent on the material properties of the insulation layer (back face boundary condition).
- The **barrier properties** such as **thickness** (L_b), **thermal conductivity** (k_b), **density** (ρ_b) and **specific heat capacity** (c_b). These variables can be optimised or simply fixed in order to estimate the critical time at which the critical temperature is achieved for certain conditions of heat exposure (fire inputs).

Understanding the relationship between the different methodology parameters is crucial for an adequate design of thermal barriers. Although numerical analyses could be applied by designers to solve the specific problem defined in Eqs. (1) to (5) for any particular scenario, a simple tool that represents the direct solution would be more ideal due to its simplicity. An approach based on dimensionless parameters will be developed for achieving the problem solution, which is applicable for thermally thick regimes.

The boundary condition

The resolution of the afore-formulated problem requires the accurate definition of the boundary condition, which represents the input parameter from the fire. However, the definition of heat inputs from real fires remains as one of the greatest challenges yet to be solved by the scientific community.

The classic compartment fire framework defines the evolution of the fire as a pre-flashover (combustible controlled) and a post-flashover regime (ventilation controlled). These regimes have been discussed by

Harmathy [5] and Thomas *et al.* [6] who described them as ventilation controlled (*Regime I*) and fuel-surface-controlled (*Regime II*). A review for the fire safe design of buildings has recently been presented by Torero *et al.* [7], emphasising the need for understanding the dynamics of fire under *Regime II*.

The distinction between these regimes is based on the geometry of the compartment and the mechanisms of mass and energy transfer related to this. The burning rate in *Regime I* is controlled by the static pressure difference within the compartment. For this case, the heat release (burning rate) in the compartment can be assumed to be constant once the thermal equilibrium is achieved and is determined by the available flow of oxygen. The thermal equilibrium will eventually be achieved since the characteristic times of the gas-phase are much shorter than the characteristic times of heat transfer to the boundaries. Then, the temperature in the gas-phase reaches a roughly constant value and thus the variation of energy in the compartment is null. As a result, the net heat to the boundaries can be defined as noted in Eq. (6), independently of the thermal properties of the material:

$$\dot{q}_{net} = \dot{q}_{fire} - \dot{q}_{out} + \dot{q}_{air,in} \quad (6)$$

where \dot{q}_{net} is the net heat transferred to the boundaries, \dot{q}_{fire} is the heat release rate inside the compartment, \dot{q}_{out} is the energy lost by the mass transfer of fire gases leaving the compartment and $\dot{q}_{air,in}$ is the energy gained by the mass transfer of fresh air introduced in the compartment. This expression may be obtained by applying the energy conservation equation and by assuming that the variation of energy within the compartment is zero.

However, if *Regime II* is considered, the dynamic pressures generated by the fire dominate over the static differential pressures [7] and therefore, the framework based on classic quasi-cubic compartments is no longer applicable. This fire regime is usually considered as the pre-flashover fire stage for quasi-cubic compartments (<150 m³), but is clearly applicable to compartments with higher volume or low height-floor area ratio, which are more frequently found in modern construction [8, 9]. Then, the transient heat transfer to the boundaries plays an important role and the net heat flux to the boundaries cannot be determined independently of the thermal properties of the boundary element.

A simplified expression that considers an effective irradiation \dot{q}_r'' and a lumped global heat transfer coefficient of losses h_T can be used to determine the boundary condition of the fire, defined as:

$$\dot{q}_{net}''(t) = \alpha \cdot \dot{q}_r''(t) + h_T \cdot (T_0 - T_s(t)) \quad (7)$$

where α is the absorptivity, T_0 and $T_s(t)$ are the initial and temporal evolution of the surface temperature, respectively.

It has previously been recognised that there is a high level of uncertainty in an accurate definition of realistic boundary conditions from the fire. However, a pragmatic approach could consider a range of possibilities as fire inputs based on Eqs. (6) and (7). This approach gives the opportunity for quantitative and probabilistic analyses that consider different heat exposures in the pre-flashover

stage to be performed, and thus no contribution to the heat release rate from flammable insulation materials can be guaranteed.

Common material properties

The present study requires data of thermal properties which are characteristic of typical linings. The typical ranges of thermal properties for a selection of materials are listed in Table 1 below.

Table 1. Range of thermal properties at ambient temperature from a selection of type of materials extracted from CIBSE [10]

| Material | Thermal conductivity range /W·m ⁻¹ ·K ⁻¹ | Density range /kg·m ⁻³ | Specific heat capacity range /J·kg ⁻¹ ·K ⁻¹ |
|---------------------------|--|-----------------------------------|---|
| Brick | 0.30 – 1.31 | 1000–2000 | 800 – 921 |
| Cement / plaster / mortar | 0.08 – 1.50 | 350–2100 | 840–1340 |
| Ceramic / clay tiles | 0.52 – 1.803 | 1120–2000 | 840 – 850 |
| Concrete blocks / tiles | 0.20 – 1.35 | 620–2240 | 840–2040 |
| Concrete, cast | 0.08 – 1.70 | 200–2000 | 840 – 880 |
| Masonry | 0.19 – 1.40 | 470–2200 | 840 |
| Stone | 0.35 – 3.49 | 1300–2880 | 710–1470 |

In this paper, a generic PIR insulation foam is used for the development of these tools. Conservative properties obtained from previous work [3] are presented in Table 2 below.

Table 2. Properties of a generic PIR foam [3]

| Thermal conductivity /W·m ⁻¹ ·K ⁻¹ | Density /kg·m ⁻³ | Specific heat capacity /J·kg ⁻¹ ·K ⁻¹ | Critical temp. /°C | Thickness /mm |
|--|-----------------------------|---|--------------------|---------------|
| 0.06 | 31 | 1500 | 300 | 100 |

Non-dimensional solution for a constant net heat flux

The relationship between the methodology parameters is explored for the case scenario where the net heat flux is a constant value. The exact analytical solution for the temperature distribution within the semi-infinite plate, given a constant net heat flux, is provided by *Incropera et al.* [11], noted in Eq. (8) below:

$$(T(x, t) - T_0) \cdot \frac{k}{q} = \left[\sqrt{\frac{4\kappa t}{\pi}} \cdot \exp\left(-\frac{x^2}{4\kappa t}\right) - x \cdot \operatorname{erfc}\left(\frac{x}{\sqrt{4\kappa t}}\right) \right] \quad (8)$$

where x is the position, t is the time, T_0 is the initial temperature, q is the constant net heat flux, κ is the thermal diffusivity and erfc is the complementary Gaussian error function defined as:

$$\operatorname{erfc}(w) = 1 - \frac{2}{\pi^{1/2}} \cdot \int_0^w \exp(-u^2) \cdot du \quad (9)$$

If a non-dimensional analysis is pursued, the definition of the similarity variable η is required, which is given as:

$$\eta = \frac{x}{\sqrt{4\kappa t}} \quad (10)$$

Taking Eq. (10) and rearranging terms in Eq. (8), the non-dimensional solution for the temperature at the barrier-insulation interface ($x = L_b$) can be expressed as:

$$\frac{k \cdot (T_{cr} - T_0)}{q \cdot L_b} = g(\eta) = \frac{\exp(-\eta^2)}{\sqrt{\pi} \cdot \eta} - \operatorname{erfc}(\eta) \quad (11)$$

This non-dimensional solution is represented in Fig. 2, and corresponds to the assumption of the semi-infinite plate. This solution represents the case of a barrier with the same thermal properties as the insulation being protected.

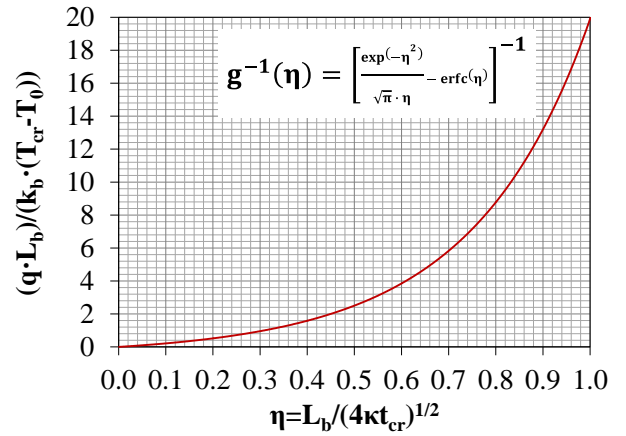


Fig. 2. Non-dimensional solution for a constant heat flux for the semi-infinite plate

The non-dimensional solution for the scenario corresponding to the actual problem, i.e. with different thermal properties in barrier and insulation, is expected to be an alteration of the solution for the semi-infinite plate. However, if this correlation is pursued, a series of numerical analyses need to be carried out.

Results from parametric analyses considering insulation properties such as the PIR noted in Table 2, and a barrier thickness from 5 to 100 mm, thermal conductivity from 0.05 to 4.05 W·m⁻¹·K⁻¹ and volumetric heat capacity from 31·1,500 to 2,500·2,500 J·m⁻³·K⁻¹ are presented in Fig. 3 as a function of the volumetric heat capacity (i.e. the product of density and specific heat capacity). A clear trend equivalent to the analytical solution of the semi-infinite plate, but displaced towards higher values of the dimensionless parameter $\eta = \frac{x}{\sqrt{4\kappa t}}$, is observed. The data points from higher volumetric heat capacities seem to converge, while the data points from low volumetric heat capacities (lower than the insulation) have greater dispersion along the η -axis. This dispersion is produced for values of the barrier thermal conductivity in the vicinity of the insulation. Indeed, the points on the left of the semi-infinite plate regression correspond to a

thermal conductivity which is lower than that of the insulation, while having the same volumetric capacity.

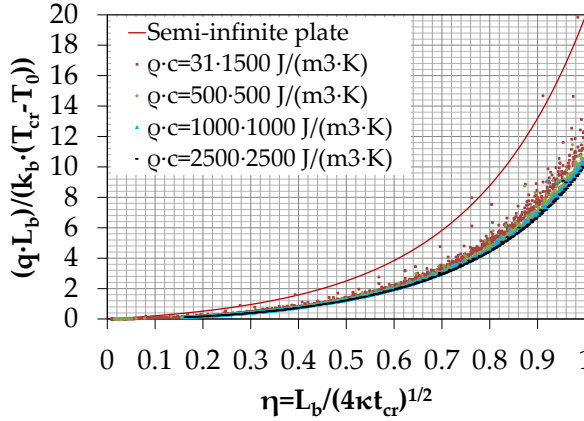


Fig. 3. Non-dimensional solution for a constant heat flux for the semi-infinite plate and real

Therefore, it is important to determine the limits of applicability of the obtained generic solution, which is clearly identified to be a function of the volumetric heat capacity and thermal conductivity.

Non-dimensional solution for a constant radiant heat flux with a constant heat transfer coefficient of losses

The exact analytical solution for the temperature distribution within the semi-infinite plate given a constant radiant heat flux \dot{q}''_r and a heat transfer coefficient h_T as defined in Eq. (7), is given by the expression noted below provided by *Carslaw and Jaeger* [12]:

$$(T(x, t) - T_0) \cdot \frac{h_T}{\alpha \cdot \dot{q}''_r} = \left[\operatorname{erfc}\left(\frac{x}{\sqrt{4kt}}\right) - \exp\left(\frac{h_T}{\sqrt{k\rho c}} \cdot x + \frac{h_T^2}{k\rho c} t\right) \cdot \operatorname{erfc}\left(\frac{h_T \cdot t^{1/2}}{\sqrt{k\rho c}} + \frac{x}{\sqrt{4kt}}\right) \right] \quad (12)$$

If a non-dimensional analysis is pursued, the definition of the similarity variable η is required as noted in Eq. (10), and θ as noted below:

$$\theta = \frac{h_T \cdot t^{1/2}}{\sqrt{k\rho c}} \quad (13)$$

By considering Eqs. (10), (12) and (13), and rearranging terms, the non-dimensional solution for the temperature at the thickness $x = L_b$ can be expressed as:

$$\frac{(T_{cr} - T_0) \cdot h_T}{\alpha \cdot \dot{q}''_r} = g(\eta, \theta) = \operatorname{erfc}(\eta) - \exp(2 \cdot \theta \cdot \eta + \theta^2) \cdot \operatorname{erfc}(\theta + \eta) \quad (14)$$

The non-dimensional solution depends on two parameters, θ and η ; thus the graphic representation of this is expected to include a combination of both so as to determine the variable $\frac{(T_{cr} - T_0) \cdot h_T}{\alpha \cdot \dot{q}''_r}$. A graphic representation of this is plotted in Fig. 4 below. As shown previously, this solution would be applicable for

barriers with the same thermal properties as the insulation being protected.

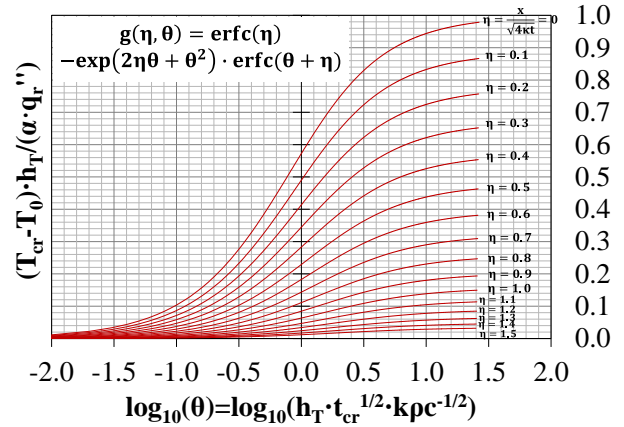


Fig. 4. Non-dimensional solution for a constant heat flux for the semi-infinite plate

As with the constant heat flux boundary condition, the non-dimensional solution for the general definition of this particular case is expected to have a dependency on the thermal conductivity and volumetric heat capacity. This is shown in Fig. 5, where differentiated iso- η curves for barriers with different volumetric heat capacities are displayed.

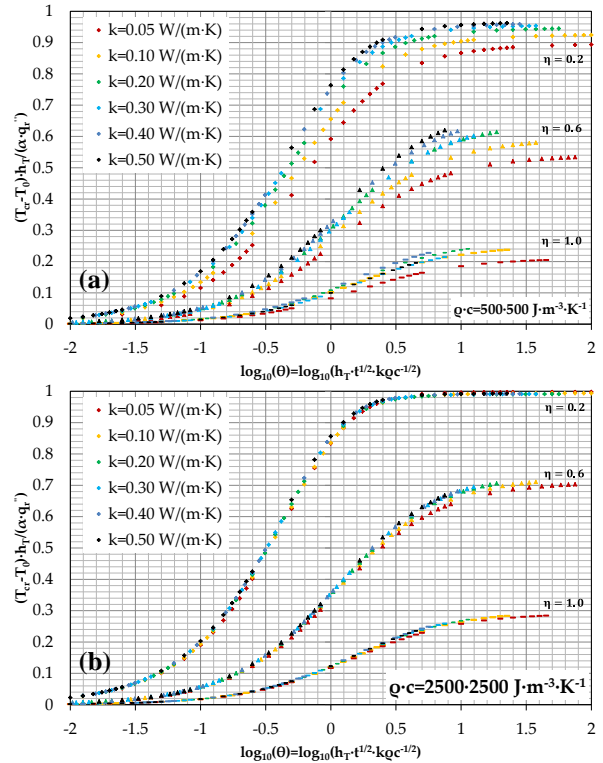


Fig. 5. Non-dimensional heat transfer solution for a constant radiant heat flux with a cooling coefficient for different thermal conductivities and volumetric heat capacities: (a) 500·500 J·m⁻³·K⁻¹ (b) 2500·2500 J·m⁻³·K⁻¹

Moreover, it is clearly shown that the conductivity does not have a significant effect for the case with high volumetric heat capacity, while the convergence for a

lower volumetric heat capacity is observed beyond a specific conductivity.

Therefore, unless a lumping function is found, a generic solution may not be achievable as for the case with a constant net heat flux. This indicates that if simplistic approaches are pursued, practical design tools could be specific to the thermal barrier as well, depending on its thermal properties.

Methodology uncertainties

The presented methodology includes a series of uncertainties, essentially related to material properties of the thermal barrier and the conditions of heat exposure:

- With regard to the thermal barrier, experimental work needs to be performed towards validating the proposed methodology, and thus reduce the level of uncertainty. The current use of standard testing as pass-fail criteria does not provide means for performance-based designs [1], and thus the use of further instrumentation in these testing methods, accompanied with a rational assessment of the material behaviour and properties, could provide valuable sets of data points for the methodology validation.
- With regard to the fire inputs, further work is required in order to provide likely conditions of heat exposure from real fires. As discussed previously, despite the fact that this might be a limitation, a range of possible solutions could be used. In any case, guidelines are further required on the sensible selection of fire scenarios.

Conclusions and further work

A series of potential tools for the quantification of optimum thickness and thermal properties of barriers for flammable insulation materials have been presented. These tools are provided as a function of different hypotheses for the definition of input parameters from the fire. These input parameters are referred either to the net heat flux or to a radiant heat flux with a heat transfer coefficient of losses. Despite the fact that these tools are in early stages of development (since they refer to constant values of heat flux), approximated quantifiable solutions could be obtained.

Additionally, the dependence of these charts on the thermal properties of the element behind the barrier or lining has been investigated. The singularity of the presented solutions is only applicable for a certain range of thermal conductivities, depending on the volumetric heat capacity. However, the impact of these limitations is expected to be low since typical barrier elements generally show values of thermal conductivity higher than the limit. Particular solutions for these cases are provided in the generated tools.

Further work is required in order to identify a lumping factor that could extend the range of application of these solutions into a unique generic solution. Additionally, the extension of this work to variable functions of heat flux is required as well as including endothermicity of the barrier material into the analysis. Further experimental

work is required so as to validate the applicability of these tools and reduce the uncertainty in barrier quantification.

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