THE EFFECT OF ELEVATED TEMPERATURE EXPOSURE ON THE THERMAL BEHAVIOUR OF INSULATED MASONRY WALLS

K.J. Kontoleon[1,*], T.G. Theodosiou[1], M. Saba[2], K. Georgiadis-Filikas[1], I. Bakas[1], E. Liapi[1]

[1] Laboratory of Building Construction & Building Physics, Department of Civil Engineering, Faculty of Engineering, Aristotle University of Thessaloniki, Gr-54124, Thessaloniki, Greece

[2] CIEL Laboratory, Department of Civil & Environmental Engineering, University of Balamand, Lebanon

(*kontoleon@civil.auth.gr*)

ABSTRACT

The main objective of this study is to assess the thermal behaviour of insulated masonry walls subjected to a fire action with reference to the standard time-temperature curve (EN1991-1-2). This forcing condition can affect substantially the development of temperatures through the examined building configurations. Nevertheless, the impact of fire exposure relies to a large extent on the position, the thickness and the flammability of the studied thermal insulation layer (EPS). In addition, this work is extended to address and analyse the effect of hollow clay-brick elements as regards the thermal emissivity of air cavity surfaces. Reported results stress the influence of these issues on the developed temperatures of the unexposed surface. It is important to note that temperature profiles in this region indicate the fire resistance of masonry walls, with respect to the insulation criterion (I). In this context, a transient thermal model is introduced to unveil numerically the fire performance of the considered masonry walls (finite element method, FEM). A three-dimensional finite-element analysis is carried out to handle the fundamental heat transfer mechanisms, as well as to define the geometry of masonry walls, the properties of materials and the prevailing environmental conditions. To conclude, the findings of this investigation highlight the fire response of insulated masonry assemblies subjected to controlled temperature variations.

KEYWORDS

Fire exposure; Hollow clay-brick; Insulation flammability; Masonry wall; Thermal emissivity.

1. INTRODUCTION

In fire protection on of the most reliable and traditional fire protection measures is the effective compartmentation of rooms with building elements that can sustain the thermal exposure of the fire and block it from spread. This passive measure is actually yet another property requirement that the classic building elements should fulfil. Concurrently, thermal insulation has become one of the most important properties of wall elements, because of the global need to reduce energy consumption in buildings. Many of the thermal insulation layers used in building construction are burnable and could affect the fire response of the wall assembly.

Wall assemblies have been researched and optimized against thermal insulation requirements. Wall elements based on clay hollow-bricks introduce the need for cavity

optimization which plays a significant role in thermal response. The influence of the emissivity of cavity surfaces has been analysed under conventional environmental conditions [1-3]. Previous results have shown how coating the internal surface of the cavity leads to a significant reduction of radiative heat exchange. Another work has specified the performance of clay masonry walls under fire action [4-5]; results emphasise to the key parameters that define their fire-resistance.

The present study aims to analyse the thermal performance of insulated masonry walls settled with hollow clay-bricks and insulated with burnable thermal insulation. The investigation draws upon the challenges and opportunities of assessing the impact of the standard time-temperature curve (EN1991-1-2) on the thermal behaviour of masonry, focusing primarily on the role of the insulation layer and radiation heat transfer through brick cavities. The research gaps in this emerging field are identified, including: the effect of the insulation characteristics, such as position, thickness and flammability, as well as the emissivity of hollow clay-bricks. The following sections will briefly describe and demonstrate the trend of temperature variations, under a variety of insulation /masonry solutions.

2. INFLUENCE OF FIRE ACTION IN TERMS OF TEMPERATURE DEVELOPMENT

In general, physical processes involving temperature variations through solids and fluids depict a transient heat flow. In that event, the rate of heat flow is directly linked to the shown temperature fluctuations on the nearby environment.

From this perspective, it is clear that studying the exposure of building elements to fire actions (rapid increase of temperatures) advocates an even more complex procedure. Although this topic appears to be analogous, there are several additional points that should be addressed; accordingly, temperature dependencies of material thermal properties and phase change processes or decomposition (melting and gasification), affect the entire transient problem.

3. DYNAMIC THERMAL ANALYSIS

3.1 Configuration of masonry walls

As shown in Figure 1 (a), analysed building configurations correspond to insulated masonry walls. The masonry wall consists of clay hollow-bricks, which are connected with cement mortar. The thickness of each brick unit is 25 cm and the thickness of the bond between bricks and mortar is 1 cm. Apart from that, the insulation layer is considered as unexposed or exposed, with reference to the fire action, while its thickness is taken d_{EPS} = 5 cm or d_{EPS} = 10 cm. At last, both sides of the brick wall are covered with 1.5 cm thick lime mortar.

The layout of the cross section of a brick unit is given in Figure 1 (b); the design of hollow cores is illustrative of brick layers in the Southern part of Europe. The pattern by which brick units are organised, as well as the layout of brick cavities, can affect heat transfer processes through the masonry.

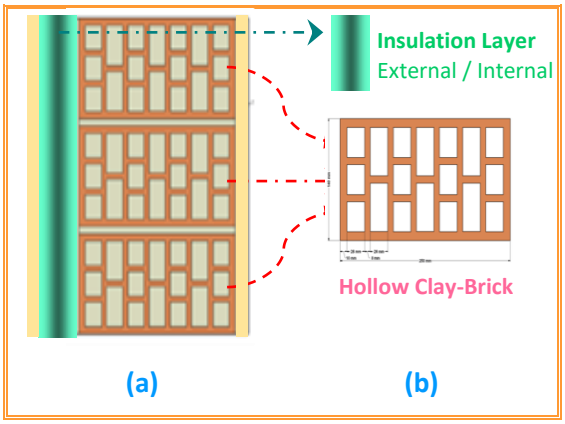

Figure 1. Outline of analysed masonry walls.

3.2 Properties of masonry wall materials

The thermophysical properties of: (a) the clay material of brick units forming the masonry wall, (b) the brick bonding – cement mortar, (c) the insulation layer of expanded polystyrene – *EPS* and (d) both coatings – lime mortar, are listed in Table 1 [6]. Furthermore, three values of the thermal emissivity coefficient of the clay material on hollow-brick cavity surfaces are assumed (ε = 0.10, ε = 0.50 and ε = 0.90).

Table 1. Thermophysical properties of involved masonry materials at 20 °C.

Material	λ [W/(m·K)]	ρ [kg/m³]	C_p [J/(kg·K)]
Clay	0.800	2000	1000
Cement mortar	1.400	2000	1000
Insulation - EPS	0.035	30	1500
Lime mortar	1.400	2000	1000

The EPS of the thermal insulation layer is a burnable thermoplastic material and its properties are affected by elevated temperatures. The EPS insulation is always covered by another non- or difficult burnable layer in order to be protected against ignition according to local fire protection requirements. EPS is stable until 100°C but after that enters in a glass transition phase and above 110 °C undergoes rapid thermal degradation [7]. The inflated EPS beads lose their volume and at 150 °C have returned to their initial diameter. At 160 °C EPS is a viscus liquid and no longer can be categorized as a solid insulating board. Above 278 °C starts the vaporization of EPS.

For this study the thermal conductivity of EPS is displayed on Figure 2. Thermal conductivity is taken as 0.035 W/(m·K) until 150 °C and above this limit is being rapidly increased until 10000 W/(m·K) at 200 °C. This linear increase will expedite the heat transfer through the material and virtually remove it from the heat transfer calculation. This numerical treatment will introduce a non-linear thermal behaviour of the wall element to approximate the liquification and vaporization of the insulation layer above 150 °C. The possible ignition of the vapours of EPS is not treated and it is not part of the scope of this study.

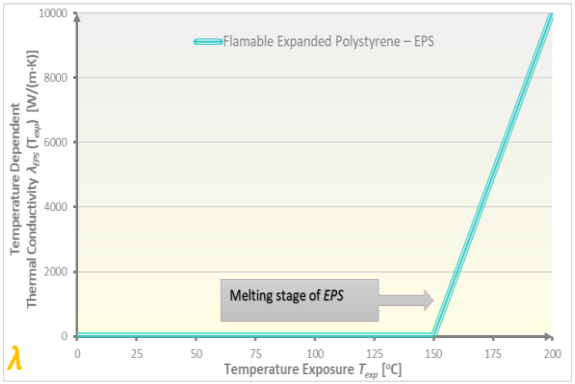

Figure 2. Thermal conductivity of EPS as a function of temperature progress due to fire.

3.3 Environmental conditions – Fire action

Gas temperatures in the vicinity of the fire exposed masonry wall can be depicted by using nominal temperature-time curves according to EN1991-1-2 [8] (Standard ISO-834 Fire Curve). In this study the standard temperature-time curve is taken as the current forcing condition (Figure 3):

$$T_{fire}(t) = 20+345\cdot\log_{10}(8\cdot t+1) \ [^{o}C] \qquad (1)$$

Then again, the air temperature in the limit of the unexposed surface of the masonry wall is considered to be steady:

$$T_{air}(t) = 20 \ [^{o}C] \qquad (2)$$

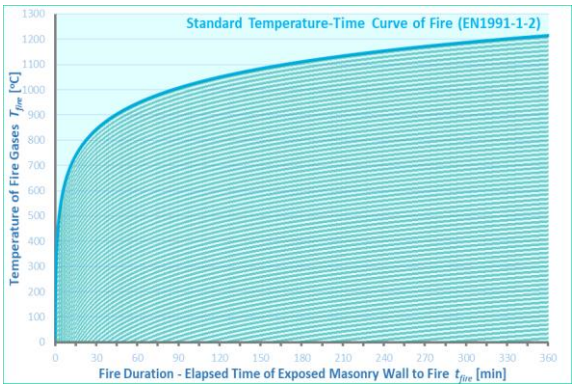

Figure 3. Gas temperatures due to fire action.

3.4 Methodology – Modelling & simulation

To carry out the thermal problem solving of insulated masonry walls it is necessary to designate the geometry of their assembly, the thermophysical properties of associated building materials and, definitely, the controlled temperature variations of the surrounding environment.

For the aims of this study, a finite element methodology (FEM) and a capable simulation program (COMSOL Multiphysics [9]) are utilised to analyse heat transfer mechanisms (Figure 4). Thus, the main processes of heat transfer are:

- Conduction regarding solid wall sections.
- Free convection within air cavities.
- Long-wave radiation on cavity surfaces.
- Convection and radiation on boundaries.

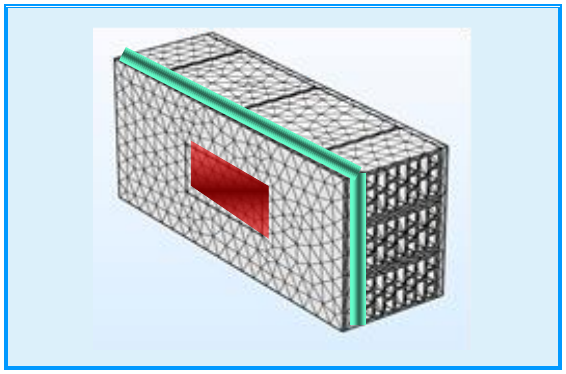

Figure 4. Three-dimensional modelling and meshing sequence of heat transfer effects via COMSOL Multiphysics.

4. RESULTS AND DISCUSSION

The main objective of this paper is to determine the thermal behaviour of insulated masonry walls subjected to a certain fire action (Standard ISO-834 fire curve). Analysed masonry wall scenarios take into account different positions and thicknesses of the insulation layer, as well as different values of the thermal emissivity of air cavity surfaces within clay hollow-bricks. Consequently, a total of twelve masonry wall configurations are comprehensively examined (Table 2).

Table 2. Data sets of analysed masonry walls, with regard to the position/thickness of EPS and the emissivity of the clay material.

No.	d_{EPS} [cm]	ε [-]
	1st Set of masonry wall configurations Unexposed insulation layer	
1	5	0.10
2	5	0.50
3	5	0.90
4	10	0.10
5	10	0.50
6	10	0.90
	2nd Set of masonry wall configurations Exposed insulation layer	
7	5	0.10
8	5	0.50
9	5	0.90
10	10	0.10
11	10	0.50
12	10	0.90

Simulation software findings exposing the effect of the aforementioned parameters, on the temperature variations of masonry walls subjected to fire (EN1991-1-2), are presented in the following subsections. To accomplish this goal, all numerical analyses are carried out via COMSOL Multiphysics simulation software. The duration of the analysis is considered to be 6 hours.

4.1 Masonry walls subjected to ISO-834 fire curve – Unexposed insulation layer

The graphs in Fig. 5 (a) and (b) delineate the temperature variations due to fire, on the non-exposed surface, for a masonry wall with an insulation layer positioned on the unexposed side of its structure.

In Fig. 5 (a), the thickness of the insulation layer is assumed to be d_{EPS} = 5 cm. As seen, a low value of emissivity (ε = 0.10) appears to be valuable in terms of temperature increase. Therefore, for the entire period of this analysis the maximum temperature does not exceed 25 °C. This implies, that heat fluxes through the region of air cavities are immensely diminished. Nevertheless, this trend regarding temperature variations is not similar for ε = 0.50 and ε = 0.90. A higher value of emissivity results to a dominant heat

bridge that accelerates the heat flow towards the unexposed surface of the masonry wall. Subsequently, for ε = 0.50 and ε = 0.90 the insulation layer retains the temperature rise bellow 25 °C for a period of 4.3 hours and 3.5 hours, respectively.

Moreover, Fig. 5 (b), refers to a thickness of the insulation layer d_{EPS} = 10 cm. The thermal response of these configurations has followed a similar trend; for ε = 0.50 and ε = 0.90 the exposed temperatures are below 25 °C for a period of 4.4 hours and 3.6 hours, respectively. Hence, the effect of the insulation thickness is shown to be slight, with reference to the rise of temperature values.

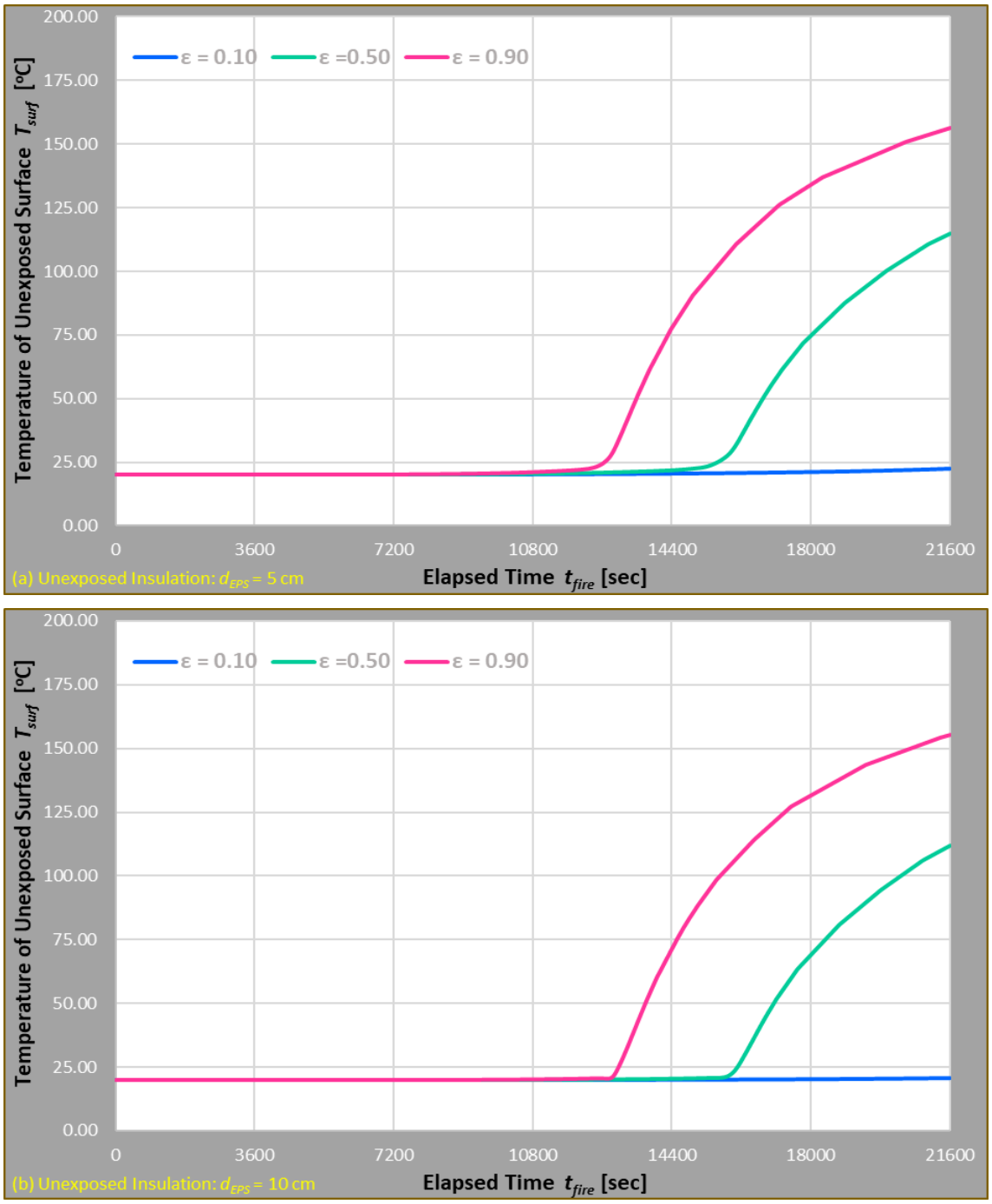

Figure 5. Temperature variations due to fire, on the non-exposed surfaces of insulated masonry walls, for an unexposed insulation layer with thickness: (a) d_{EPS} = 5 cm and (b) d_{EPS} = 10 cm.

From these facts one may conclude that the thermal behaviour of a masonry wall is fundamentally related with the thermal emissivity ε of air cavity surfaces of hollow clay-bricks. An increase of the thermal emissivity leads to a corresponding increase of the developed temperatures on the non-exposed surface. For d_{EPS} = 5 cm and d_{EPS} = 10 cm the temperature peaks (after 6 hours, final plotting of transient thermal analysis) are approximately T_{surf} = 25 ^{o}C, T_{surf} = 115 ^{o}C and T_{surf} = 155 ^{o}C for ε = 0.10, ε = 0.50 and ε = 0.90, respectively. As emissivity increases, its consequence on unexposed surface temperatures declines.

4.2 Masonry walls subjected to ISO-834 fire curve – Exposed insulation layer

The graphs in Fig. 6 (a) and (b) show the temperature variations due to fire, on the non-exposed surface, for a masonry wall with an insulation layer located on the exposed surface of its structure.

As has already pointed out, the impact of an unexposed thermal insulation layer regarding the mitigation of temperature peaks is shown to be profound. On the contrary, an insulation layer subjected to the fire action presents a dissimilar thermal behaviour. In that respect, the reduction of temperature variations is shown to be the same, regardless of the insulation layer thickness, since the melting of EPS restricts evocatively the overall thermal resistance of the masonry wall. Accordingly, both graphs (for d_{EPS} = 5 cm and d_{EPS} = 10 cm) demonstrate an almost identical pattern as regards the temperature evolution. In other words, the role of a flammable insulation layer thickness subjected to a fire action is negligible.

From a quantitative point of view, someone can notice that the temperature peaks for ε = 0.10, ε = 0.50 and ε = 0.90 are T_{surf} = 50 ^{o}C, T_{surf} = 130 ^{o}C and T_{surf} = 175 ^{o}C, respectively. Furthermore, for the previously mentioned emissivity values the temperature increase up to 25 ^{o}C is exhibited for a period of 3.0 hours, 2.0 hours and 1.5 hours, respectively.

4.3 Overall evaluation under fire action: Exposed vs. Unexposed insulation layer

In general, the appropriate placement of the thermal insulation layer is widely known as one key factor in terms of energy-efficiency strategies in buildings. However, from a fire performance point of view it is also important to assess how the arrangement of insulation affects the effectiveness of masonry walls under fire exposure. Taking into account this condition, a numerical analysis was carried out to comparatively analyse the fire performance of characteristic wall insulation forms with reference to the rapid increase of temperatures on their unexposed surface.

The graphs in Fig. 7 (a) and (b) show that the different wall insulation forms, subjected to ISO-834 fire curve, have a remarkable effect on the temperature response rate and the heat flow through the assemblies of masonry walls. Placing the insulation to the non-exposed surface of the brick layer exhibits a more suitable thermal behaviour. Thus, it decreases the rate of temperature rise, but still faces critical challenges, as the influence of the thermal emissivity is significant.

Furthermore, from the above results it becomes evident that the temperature difference between unexposed and exposed insulation scenarios range from 20 ^{o}C to 25 ^{o}C, approximately. Then again, temperature variations regarding the examined thermal emissivity margins (ε = 0.10 and ε = 0.90) lead to temperature deviations up to 125 ^{o}C (with reference to a similar thermal insulation layer placement).

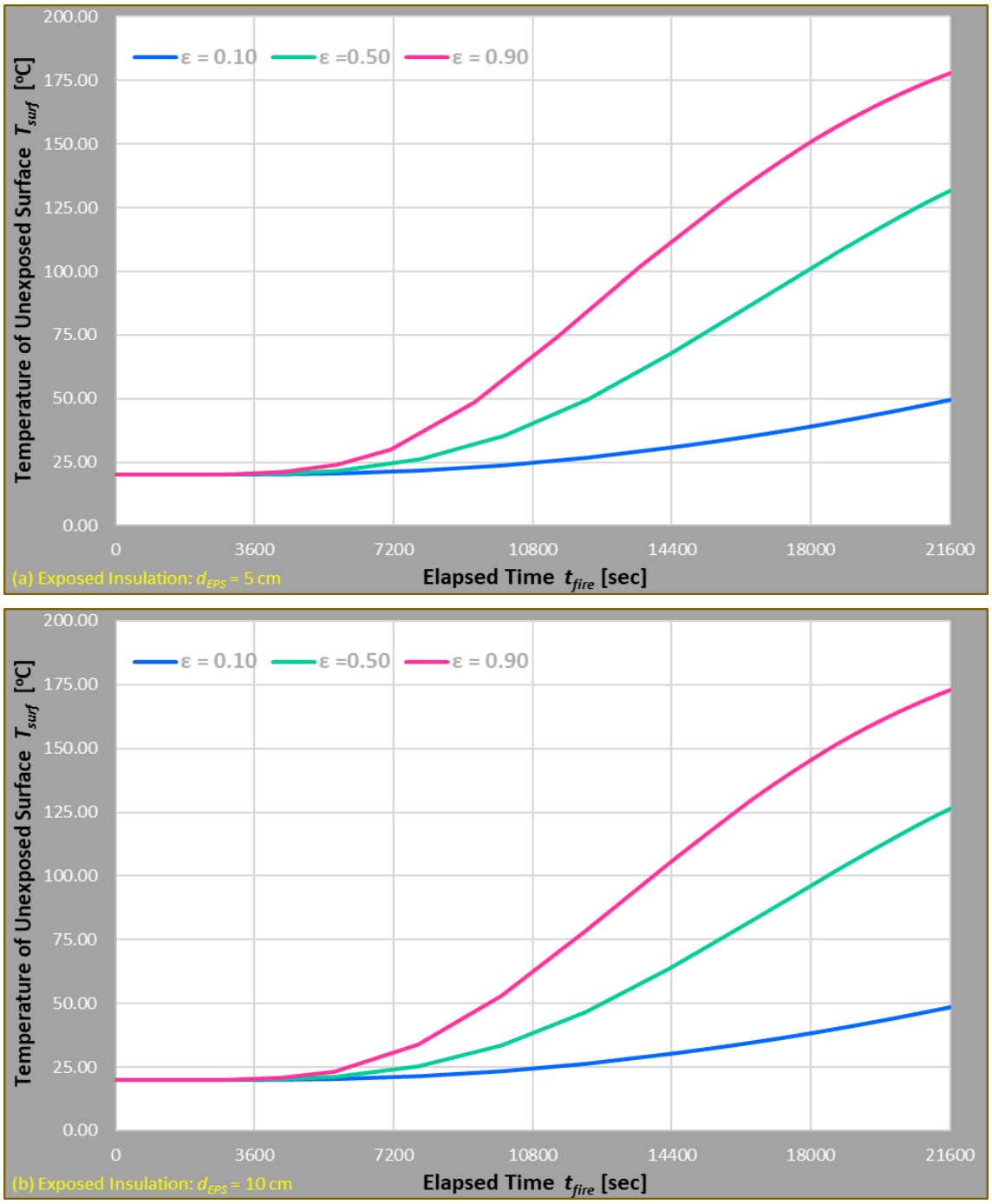

Figure 6. Temperature variations due to fire, on the non-exposed surfaces of insulated masonry walls, for an exposed insulation layer with thickness: (a) d_{EPS} = 5 cm and (b) d_{EPS} = 10 cm.

5. CONCLUSIONS

Throughout this study, the determination of the thermal behaviour of insulated masonry walls subjected to fire action was assessed. Numerical analyses were conceded with regard to the position/thickness of EPS and the emissivity of the clay material on the temperature variations of masonry walls subjected to fire.

Two settings were evaluated, one that describes the temperature variations due to fire, on the non-exposed surface, for a masonry wall with an insulation layer positioned on the unexposed side of its

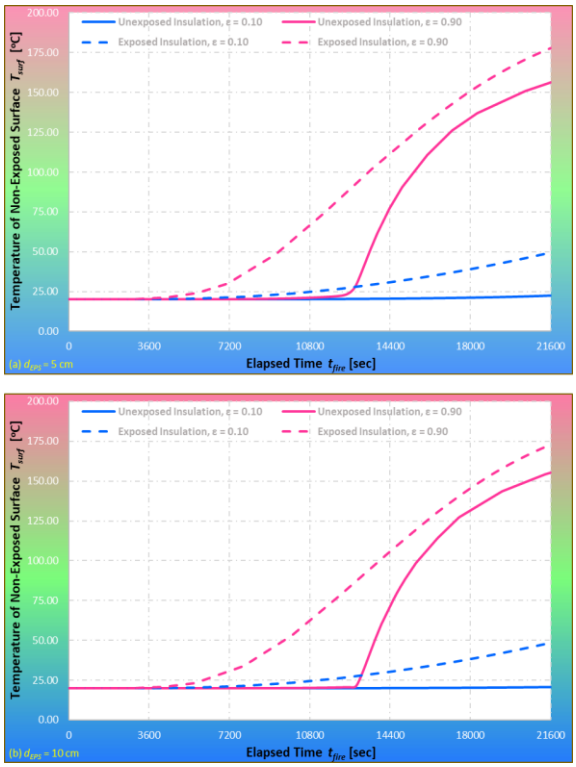

Figure 7. Temperature fluctuations due to fire for: (a) d_{EPS} = 5 cm and (b) d_{EPS} = 10 cm.

structure. And the second delineates the temperature variations due to fire, on the non-exposed surface, for a masonry wall with an insulation layer located on the exposed surface of its structure.

This study perceived that the thermal behaviour of a masonry wall is fundamentally related to the thermal emissivity of air cavity surfaces of hollow clay-bricks. The impact of the non-exposed surface regarding the mitigation of temperature peaks is shown to be profound. High emissivity leads to a central thermal bridge that facilitates the heat transfer and the heat wave progress towards the unexposed side. Decreasing the emissivity suggests a secondary thermal barrier within the brick unit.

Furthermore, different assemblies regarding the insulation layer position and thickness have addressed a dissimilar thermal behaviour. In that respect, the reduction of temperature variations is shown to be the same, regardless of the insulation layer thickness, while the position of the insulation layer affects to some extent the exposed temperature profiles.

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