THERMAL PERFORMANCE ASSESSMENT OF A CLAY HOLLOW-BRICK MASONRY WALL SUBJECTED TO FIRE

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

This work aims to analyse the thermal performance of a clay hollow-brick masonry wall under a fire action referring to the standard time-temperature curve (EN1991-1-2). For this fire exposure, temperature profile calculations underline the thermal response of certain wall configurations, while resulted temperatures of the non-exposed surface can illustrate the thermal resistance in terms of the insulation criterion (I). For the aims of this study, a transient thermal model is utilized to assess the fire behaviour of the assumed wall assemblies. This paper introduces a full three-dimensional finite-element analysis focused on heat transfer processes; in this regard, conductive, convective and radiative heat transfer mechanisms are assessed by adopting a finite element methodology (FEM) to cope with the geometry of the wall, the thermophysical properties of building materials and the prevailing environmental conditions. With respect to the thermal performance of the masonry wall subjected to fire, two sets of thermophysical property values of the clay material were examined. Accordingly, the influence of clay thermal conductivity and density variations were considered to deduce the thermal responsivity of masonry walls. In addition, a parametric procedure highlights the findings of a numerical study concerning the effect of low thermal emissivity coatings applied to hollow-bricks cavity surfaces. Results of this analysis indicate the fire behaviour of masonry walls under elevated temperatures. The outcomes of this investigation exhibit a suitable approach to improve the overall fire performance of building elements under severe transient conditions.

KEYWORDS

Fire action; Hollow clay-brick; Masonry wall; Thermal emissivity; Thermophysical properties.

1. INTRODUCTION

Nowadays, fire safety design of buildings has acquired a great deal of world-wide interest. In this regard, fire safety design can be attained by the integration of active and passive fire protection systems. First of all, the installation of active fire protection technologies, such as fire-smoke alarm systems, sprinkler systems and fire extinguishers, can detect whether there is smoke/heat in a building and slow/restrict the growth of the fire. On the other hand, passive fire protection solutions concern a set of measures that compartmentalize a building envelope through the use of fire-resistance rated elements.

Among the different building envelope solutions, increasing awareness about the benefits of improving the assembly and thermal properties of opaque building elements underlines a profitable way to cope with this demand. Within the basis of the aforementioned concerns, the assessment of cavities in building elements (i.e. hollow clay-bricks) also shows a significant effect. The influence of the emissivity of cavity surfaces has been analysed thoroughly under conventional environmental conditions [1-3]. Previous research 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 summarise the end-point parameters that control their fire-resistance. In the framework of another study the thermal behaviour of a reinforced concrete slab subjected to fire was examined [6]. Furthermore, upgrading of the overall thermal response of wall assemblies through a proper selection of density is emphasised in another study [7].

The above-presented literature reveals that there is a gap within the context of the fire performance of masonry walls under a variety of thermal emissivity and thermophysical properties. These issues are investigated and discussed in the following sections.

2. IMPACT OF FIRE ACTION IN TERMS OF TEMPERATURE PROGRESS

Processes that involve temperature dissimilarities through solids and fluids define a transient heat flow through time. On this account, the rate of heat flux is directly related to the interrelated temperature fluctuations.

Within this framework, analysing the exposure of building elements against fire actions (elevated temperatures) suggests an even more multifaceted procedure. Although the research theme appears to be similar, there are several additional points to be examined; for example, temperature-dependent physical properties of materials, as well as phase change processes during the melting stage, give clues to big-picture thermal behaviour at fire circumstances.

3. TRANSIENT THERMAL ANALYSIS OF MASONRY WALL

3.1 Analysed masonry wall assembly

As shown in Figure 1 (a), the analysed building assembly refers to an uninsulated masonry wall. The masonry wall consists of conventional hollow clay-bricks, which are laid in and bound together with cement mortar. In that respect, the thickness of each clay-brick unit of the masonry wall is 25 cm, while the thickness of the bond between bricks and mortar is considered to be 1 cm. In addition, both sides of the brick wall are covered with 1.5 cm thick lime mortar.

The exact layout of the cross section of a brick unit is specified in Figure 1 (b); the corresponding stratigraphy of hollow cores is illustrative of brick layers in the Southern and Eastern European countries.

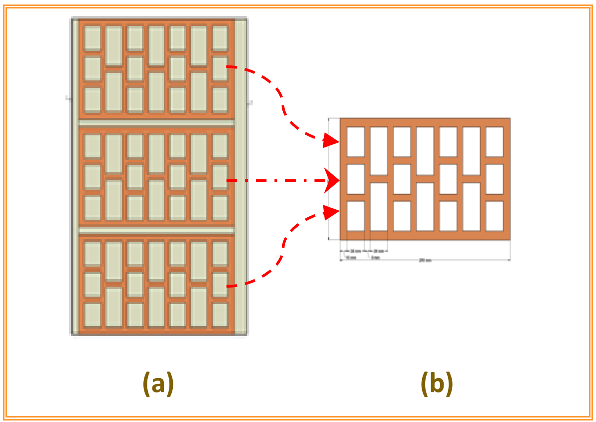

Figure 1. Layout of examined masonry wall.

It should be noted that the pattern in which the brick units are assembled, as well as the geometry of brick cavities, can vastly affect the heat transfer processes through the masonry wall.

3.2 Material properties of masonry wall

The thermophysical properties of: (a) the clay material of brick units composing the masonry wall, (b) the brick bonding – cement mortar and (c) both coatings – lime mortar, are listed in Table 1 [8]. With reference to hollow-blocks, two different types of clay material are examined (lightweight and heavyweight).

Table 1. Thermophysical properties of involved masonry materials.

Material	λ [W/(m·K)]	ρ [kg/m³]	C_p [J/(kg·K)]
Clay (Lightweight)	0.40	1000	1000
Clay (Heavyweight)	0.80	2000	1000
Cement mortar	1.40	2000	1000
Lime mortar	1.40	2000	1000

Apart from that, different values of the thermal emissivity coefficient of the clay material on hollow-brick cavity surfaces are taken into account (ε = 0.10, ε = 0.50 and ε = 0.90).

3.3 Environmental conditions - Fire action

Gas temperatures in the vicinity of the fire exposed masonry wall can be replicated by adopting nominal temperature-time curves according to EN1991-1-2 [9]. For the aims of this work the standard temperature-time curve is applied as the principal forcing function (Figure 2):

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

On the other hand, the air temperature in the margin of the unexposed surface of the masonry wall is assumed constant:

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

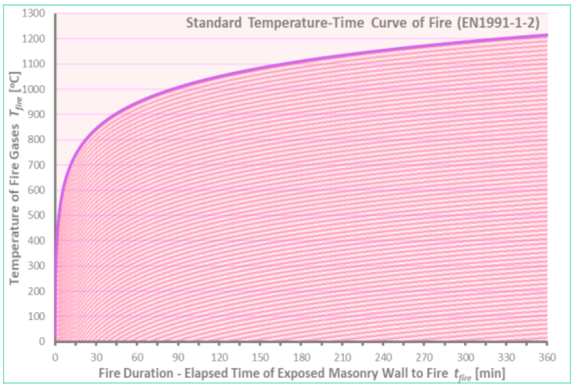

Figure 2. Gas temperatures due to fire action.

3.4 Analytical solution - Numerical analysis

To resolve heat transfer processes through a building member it is necessary to specify: (a) the geometry of its structure, (b) the thermal properties of entailed building materials and (c) the forcing functions on both boundaries.

In this study, the masonry wall as well as material properties have been already clarified. Besides, temperature variations rely on the thermal analysis of the masonry wall exposed to the fire action. Given this, a finite element methodology (FEM) and an associated simulation software (COMSOL Multiphysics [10]) are utilized to simulate heat transfer mechanisms (Figure 3). Thereby, the deriving processes of heat transfer are:

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

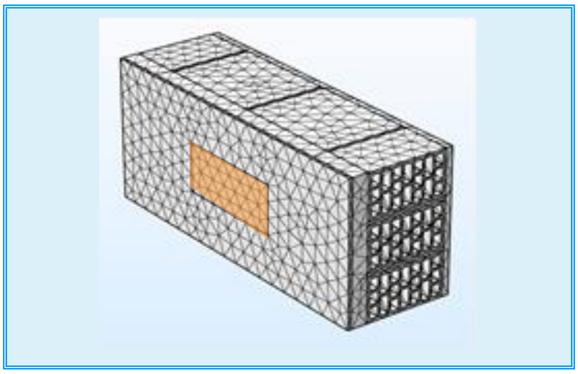

Figure 3. Three-dimensional modelling and meshing sequence of heat transfer effects via COMSOL Multiphysics.

4. RESULTS AND INTERPRETATIONS

In this study, the analysed assemblies correspond to non-insulated masonry walls with variable clay thermal conductivities λ and densities ρ of hollow-bricks. Two sets of thermophysical property values of the clay material, corresponding to lightweight hollow-bricks and heavyweight hollow-bricks, are analysed. Furthermore, in order to highlight the significance of heat transfer due to radiation the effect of the thermal emissivity ε of hollow-brick cavities is taken into account. As it is already mentioned, three values of the thermal emissivity are assessed. In overall, a total of six masonry wall configurations are thoroughly analysed (Table 2).

Simulation software output showing the impact of the above-mentioned parameters, on the development of temperatures of masonry walls subjected to fire (standard time-temperature curve, EN1991-1-2), are given in the following subsections. All numerical simulations are carried out by adopting a finite difference analysis, via COMSOL Multiphysics simulation software (the duration of the thermal simulation is 6 hours).

Table 2. Analysed masonry wall configurations with reference to the considered thermal properties of the clay material.

No.	ε [-]	λ [W/(m·K)]	ρ [kg/m³]
	1st Set of clay material properties Lightweight hollow-brick		
1	0.10	0.40	1000
2	0.50	0.40	1000
3	0.90	0.40	1000
	2nd Set of clay material properties Heavyweight hollow-brick		
4	0.10	0.80	2000
5	0.50	0.80	2000
6	0.90	0.80	2000

4.1 Effects of thermal emissivity

The graphs of Fig. 4 (a) and (b) refer to the dependence of the shown temperatures, of the non-exposed to fire surface, on the clay's thermal emissivity ε.

As shown in Fig. 4 (a), an increase of the thermal emissivity, leads to a parallel increase of the resulted temperatures of the non-exposed surface. Thus, for lightweight masonry walls subjected to fire the maximum surface temperatures are nearly T_{surf} = 185 °C, T_{surf} = 220 °C and T_{surf} = 235 °C for ε = 0.10, ε = 0.50 and ε = 0.90, respectively. It is worth noting that as the value of the thermal emissivity increases, its effect on the temperature values weakens. Moreover, the rate of temperature increase declines as asymptotically approaches a constant value.

From the graphs in Fig. 4 (b) it can be observed that variations on clay-material properties affect the thermal response of heavyweight masonry walls in a similar fashion. For this case the corresponding temperature values of the non-exposed surface are approximately T_{surf} = 180 °C, T_{surf} = 240 °C and T_{surf} = 265 °C.

It becomes apparent that the thermal behaviour of a masonry wall is strongly related to the thermal emissivity ε of the clay material of cavity surfaces of hollow-bricks. Considering the above, the thermal effectiveness of low emissivity coatings is essential with respect to moderated heat fluxes through the geometry of the masonry wall. Studying the effects of rising temperatures on the unexposed surface of the separating masonry wall revealed that brick units integrated with low-ε coatings are less prone to the engaged fire exposure; the corresponding temperature reduction values can vary from 50 °C (lightweight configurations) to 85 °C (heavyweight configurations).

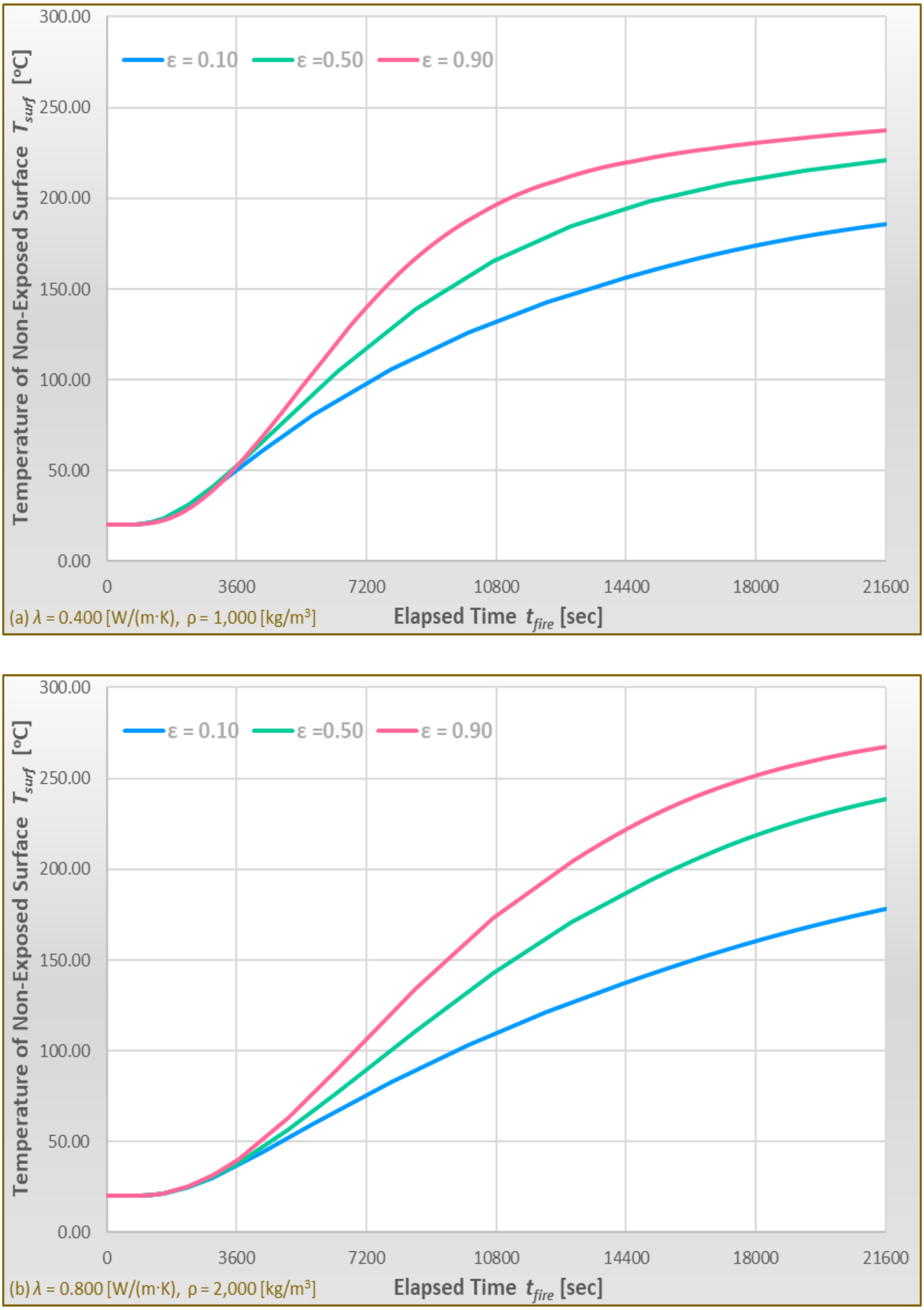

Figure 4. Temperature evolution of the unexposed masonry wall surface, in relation with the thermal emissivity of the clay material: (a) lightweight hollow-brick, (b) heavyweight hollow-brick.

4.2 Effects of thermophysical properties

Following the findings presented in the previous subsection it becomes evident that the effect of thermal emissivity ε in terms of heat wave propagation and temperature elevation is dominant; in this regard, the variation trend of temperatures with ε is straightforward. Nevertheless, a careful examination of the presented temperature variations indicates that the thermophysical properties of the clay material, such as thermal conductivity λ and density ρ, can shift the hierarchy of the optimal masonry wall configurations subjected to fire (according to the temperature peaks on the unexposed surface), at a certain time point. Thus, the objective of this research is to clarify the significance of the correlations between the thermal resistance (R) and the thermal capacity (C); in this matter, an increase in the walls' clay thermal conductivity and density lowers its thermal resistance but, at the same time, increases its thermal capacity.

The influence of the thermophysical properties variations of the clay material (for a certain value of ε of the clay material in the region of the hollow-brick cavities) is underlined in Figs. 5, 6 and 7. As seen, the temperature progression through masonry walls shows a similar pattern to the one specified before; thus, a gradual rise of surface temperatures is driving this overall trend.

In Fig. 5, the graphs illustrate the dynamic process of heat flow for both sets of the clay material, while assuming a value of its thermal emissivity equal to ε = 0.10. For the entire period of the analysis the transient thermal behaviour of the heavyweight masonry wall is superior, as compared to the lightweight assembly. In that respect, for the entire period of the analysis the demonstrated temperatures for the first choice of clay thermophysical properties (low values of λ and ρ) are higher in comparison to the second choice of clay thermophysical properties (high values of λ and ρ). As it is clear, the effect of the thermal resistance is more profound rather than the thermal capacity. In other words, a lower thermal conductivity value improves the overall thermal response of a wall subjected to fire.

Furthermore, Fig. 6 delineates the temperature growth for a thermal emissivity of the clay material equal to ε = 0.50. For the heavyweight masonry wall, initially, as time elapses from t = 0 sec to t = 16000 sec, the temperature values of the unexposed surface are lower in comparison to the lightweight masonry wall. However, this behaviour is reversed for the remaining time (from t = 16000 sec to t = 21600 sec); thus, the heavyweight wall assembly shows worse thermal performance compared to the previous trend. This implies that the thermophysical properties of the clay material of hollow-bricks should be emphasized at the very beginning, during the modelling process of building envelopes.

Similarly, Fig. 7 highlights temperature variations for a thermal emissivity of the clay material equal to ε = 0.90. At first, for the heavyweight masonry wall, as time elapses from t = 0 sec to t = 14100 sec, the temperature values of the unexposed surface are lower in comparison to the lightweight masonry wall. After this point and for the remaining time (from t = 14100 sec to t = 21600 sec), this state is altered; consequently, the temperature development for the lightweight wall assembly is better.

From the above results it becomes evident that the influence of the thermophysical properties of the clay material is strongly related to the thermal emissivity ε.

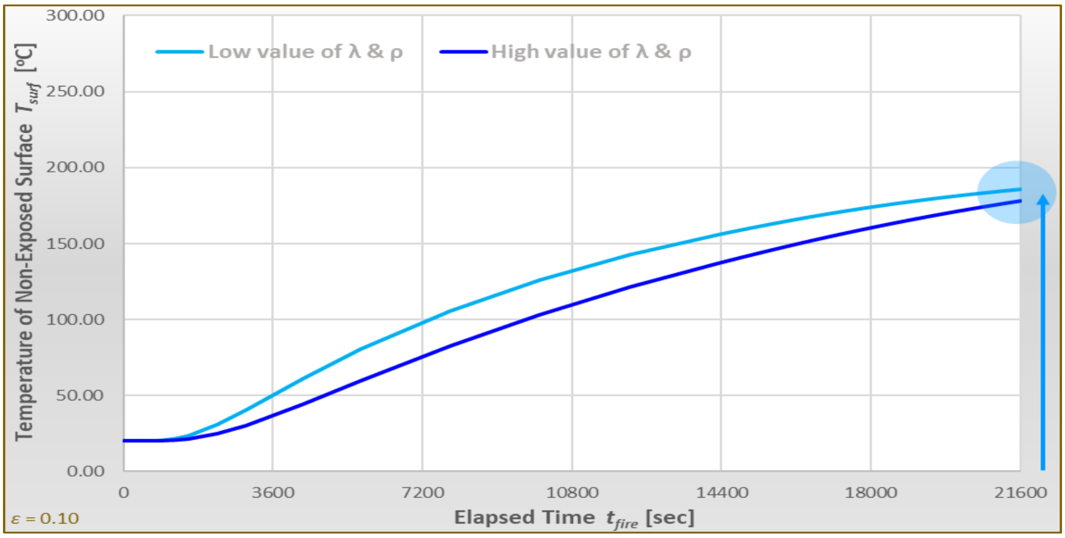

Figure 5. Temperature evolution of the unexposed masonry wall surface for ε = 0.10.

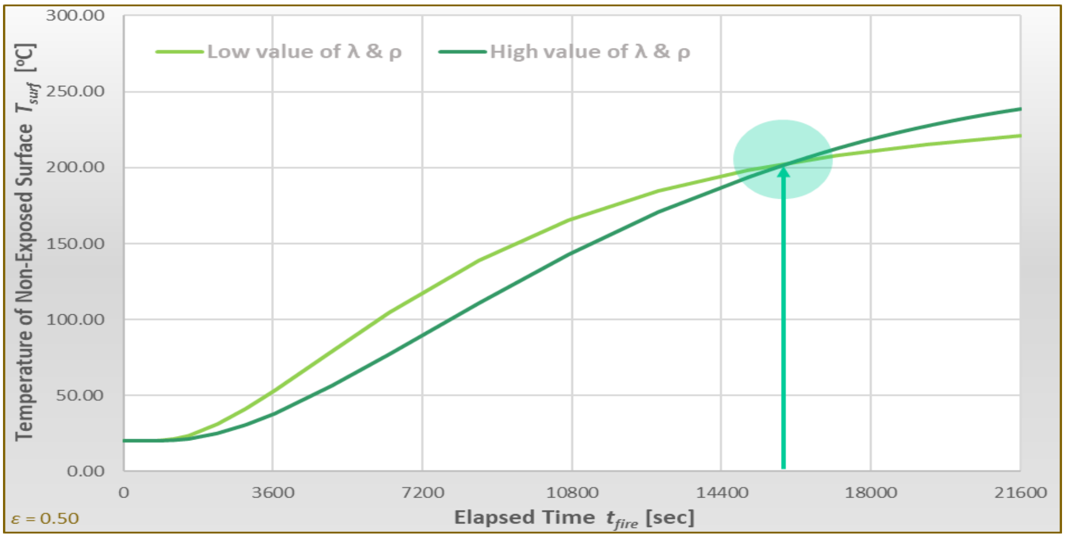

Figure 6. Temperature evolution of the unexposed masonry wall surface for ε = 0.50.

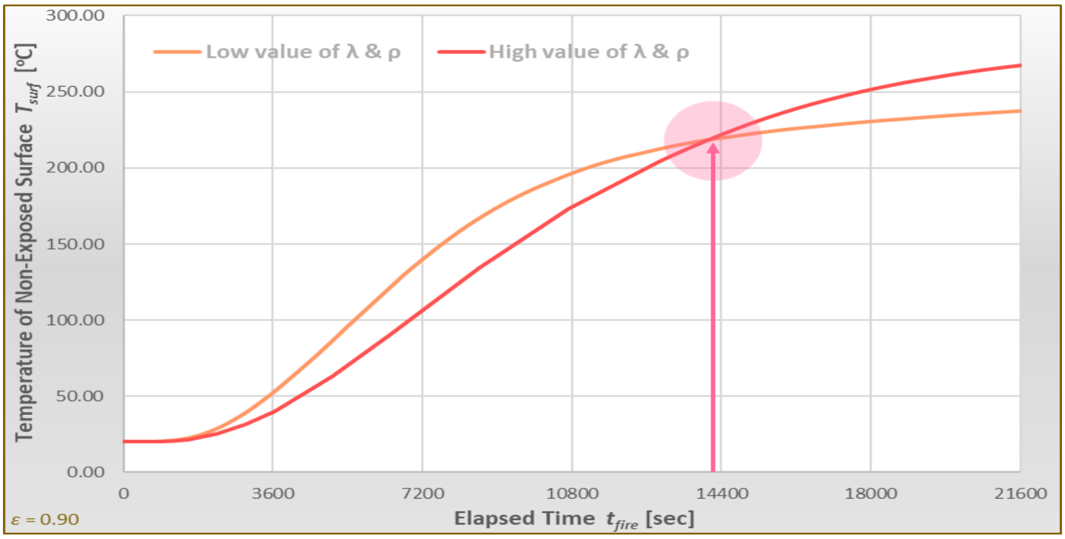

Figure 7. Temperature evolution of the unexposed masonry wall surface for ε = 0.90.

5. CONCLUSIONS

Analysing the thermal behaviour of masonry walls under fire actions is an integral part of building design. The selection of materials' thermal properties plays a significant role as regards the temperature evolution through building elements. Neglecting these aspects may cause severe consequences and repercussions in terms of fire behaviour.

The present paper has interpreted the key issues that define the propagation of heat through masonry walls, settled with clay hollow-bricks, subjected to fire. The effect of the thermal emissivity is central, and it accounts for the majority of present masonry configurations. High emissivity results in an important heat bridge that accelerates the heat transfer and the heat wave progress towards the unexposed side. Decreasing the emissivity will introduce a secondary heat resistance within the brick unit. Furthermore, another way to reduce the influence of rising gas temperatures relies on the proper selection of the density of the clay material. As seen, the impact of the density relies on the emissivity of the clay material on the hollow-brick cavity surfaces.

Results have highlighted these issues from a quantitative and qualitative point of view. In conclusion, their consideration should be given special attention to upgrade the fire response of building envelopes, as well as to tackle the necessities of current regulations.

REFERENCES

[1] Fioretti, R., & Principi, P. (2014). Thermal Performance of Hollow Clay Brick with Low Emissivity Treatment in Surface Enclosures. *Coatings*, 4(4), 715–731. doi:10.3390/coatings4040715

[2] Fantucci, S., Serra, V., & Martinelly, A. (2014). Thermal effectiveness of low emissivity coatings in hollow bricks: a numerical analysis for different cavity concentration. *9th International Masonry Conference 2014*, Guimarães, Portugal.

[3] Bouchair, A. (2008). Steady state theoretical model of fired clay hollow bricks for enhanced external wall thermal insulation. *Building and Environment*, 43(10), 1603–1618. doi:10.1016/j.buildenv.2007.10.005

[4] Nguyen, T.-D., & Meftah, F. (2012). Behavior of clay hollow-brick masonry walls during fire. Part 1: Experimental analysis. *Fire Safety Journal*, 52, 55–64. doi:10.1016/j.firesaf.2012.06.001

[5] Nguyen, T.-D., & Meftah, F. (2014). Behavior of hollow clay brick masonry walls during fire. Part 2: 3D finite element modeling and spalling assessment. *Fire Safety Journal*, 66, 35–45. doi:10.1016/j.firesaf.2013.08.017

[6] Allam, S. M., Elbakry, H. M. F., & Rabeai, A. G. (2013). Behavior of one-way reinforced concrete slabs subjected to fire. *Alexandria Engineering Journal*, 52(4), 749–761. doi:10.1016/j.aej.2013.09.004

[7] Kontoleon, K. J., Theodosiou, T. G., & Tsikaloudaki, K. G. (2013). The influence of concrete density and conductivity on walls' thermal inertia parameters under a variety of masonry and insulation placements. Applied Energy, 112, 325–337. doi:10.1016/j.apenergy.2013.06.029

[8] Greek Ministry of Environment and Energy. Greek Regulation for the Energy Efficiency of Buildings (KENAK) 2010.

[9] EN 1991-1-2, Eurocode 1: Actions on Structures – Part 1-2 "General Actions – Actions on Structures Exposed to Fire", European Standard: Brussels November2002.

[10] COMSOL Multiphysics Reference Manual, version 5.3", COMSOL, Inc. (www.comsol.com).