Computational study of transient conjugate conductive heat transfer in light porous building walls

Estudio computacional transiente de conducción conjugada en paredes de materiales porosos ligeros

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ABSTRACT

The present work was originally carried out as a project by HVAC-R engineering students of a heat transfer undergraduate course. The main goal was to introduce to the students to the implementation of a commercial simulation tool, ANSYS/Transient thermal, to analyze a transient heat transfer process of their professional interest. Behind this goal there were a set of activities that lead students to learn very important lessons that deal with computational simulation: physical and mathematical modeling, validation, measurement of thermal properties and grid size analysis. Specifically, a computational simulation of the transient cooling process of two composed building walls initially at 20 ºC was performed. Boundary conditions of third kind were imposed at the outer surfaces of the walls. The composed walls are made of light materials: oriented strand board and plasterboard, which are porous building materials and whose thermal properties can be improved by imbibe them with phase change materials (PCM). The convective heat transfer coefficients were taken from the Chilean normative (Nch853-Of91) and some of the thermophysical properties were experimentally obtained.

Keywords: Conjugate transient heat conduction, heating, oriented strand board, plasterboard.

RESUMEN

El presente trabajo surgió originalmente como un proyecto de un curso de transferencia de calor para estudiantes de ingeniería en climatización. El objetivo del proyecto era introducir a los estudiantes al uso de una herramienta computacional comercial, ANSYS / Transient thermal, para analizar el proceso de transferencia de calor transiente en aplicaciones de su interés profesional. Detrás de este objetivo principal, hay una serie de atividades que condujeron a los estudiantes al aprendizaje de lecciones importantes relacionadas con simulación computacional: modelamiento matemático y físico, validación, medición de propiedades termofísicas y análisis de tamaño de malla. Específicamente, el trabajo trata de la simulación computacional del proceso transiente de enfriamiento de dos compuestos ligeros de construcción inicialmente a 20 ºC. El proceso de enfriamiento comienza al imponer condiciones de borde de tercera clase en las superfícies de las paredes compuestas. Las paredes compuestas están hechas de materiales ligeros: madera OSB y yeso cartón, cuyas propiedades térmicas pueden ser mejoradas embebiéndolas con materiales de cambio de fase (PCM). El coeficiente convectivo de transferencia de calor fue tomado de la Normativa chilena (Nch853-Of91) y algunas propiedades termofísicas fueron determinadas experimentalmente.

Palabras clave: Conducción de calor transiente conjugado, calefacción, madera OSB, yeso cartón.

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INTRODUCTION

In the context of an undergraduate heat transfer course for HVAC-R (Heating, Ventilation and Air Conditioning - Refrigeration) engineering, the students performed a course project about several topics related to heat transfer and HVAC applications. One of them was to study the transient heat transfer problem on a building wall, made up of two oriented strand boards (OSB) or two plasterboards (PB) and a polystyrene foam layer between them. This application is considered a conjugate heat transfer process since there is a discontinuity at the material interfaces originated by the different thermophysical properties [1].

The implementation and teaching of computational tools to simulate one dimensional transient heat conduction problems have been pointed out in previous works [2-4]. Before modeling and computer simulations, it was important that students recognize the National Chilean normative who rules the procedures to calculate the thermal resistances of the constructive elements, especially in thermal envelopes, such as walls, ceilings and floors that are constructive elements whose functionality is to separate two different environments.

In the Chilean normative 853 [5] some of the needed information along with some thermophysical properties, thermal resistances and convective heat transfer coefficient values can be found. Nevertheless, in the sake of comparison and to comprehend the implementation of an experimental method, the thermophysical properties of polystyrene and plasterboard were experimentally obtained. Once the students have compiled the needed information regards to the HVAC application, they must elaborate a physical and mathematical model that describes the transient thermal process of interest.

In built environment, the transfer of moisture and the entire chemical dissolved therein plays a crucial role. Moisture transfer affects the durability and sustainability of built structures, the health and comfort of building occupants, and the thermophysical properties of building materials [6]. Water vapor resistance (μ) is a dimensionless parameter used to evaluate the vapor permeability of building materials in comparison to the unitary value assigned to air. Schiavoni and collaborators [7], present a broad compilation of μ-values of building materials, showing that the insulation materials have higher μ-values.

In the present work a conjugate thermal mathematical model with Robin boundary conditions at the outer walls is outlined. The one-dimensional transient heat conduction problem with Robin boundary conditions for a homogenous material can be solved analytically through the method of separation of variables [8]. The functions that describe the transient behavior of temperature along a distance is an infinite sum of terms, that is why only the first two terms of the infinite sum are used to validate the numerical results.

From this teaching experience, the students of HVAC-R engineering studied heat transfer processes of their professional interest, understanding the concepts of physical and mathematical modeling, validation and how important is a grid size study to test a numerical tool. Moreover, the students implemented a computational tool to understand and analyze transient heat transfer processes; a typical lack in heat transfer undergraduate courses.

THEORETICAL ANALYSIS

Physical Model

The chosen application corresponds to the study of transient heat conduction on a building wall made up of two OSB boards (case a) or plasterboards (case b) and a polystyrene foam layer between them (Figure 1). Initially, the temperature of the building wall is maintained constant at 20 ºC, then it is immersed in a constant temperature flowing media at 0ºC. The measurements of the building wall are specified in Figure 2. The thermal properties, specifically the thermal inertia, of these light porous materials can be improved by adding phase change materials [9], which store thermal energy during the hottest hours of the day and then release it during the coldest hours.

The thermal conductivity and density of OSB, plasterboard and polystyrene foam were taken from the Chilean 853 normative. Unfortunately the normative lacks of information for the heat capacity, that is why this property was taken from an undergraduate textbook [9] and experimentally measured at 25ºC by the transient line heat source method [10] using the dual needle (SH1) of a KD2

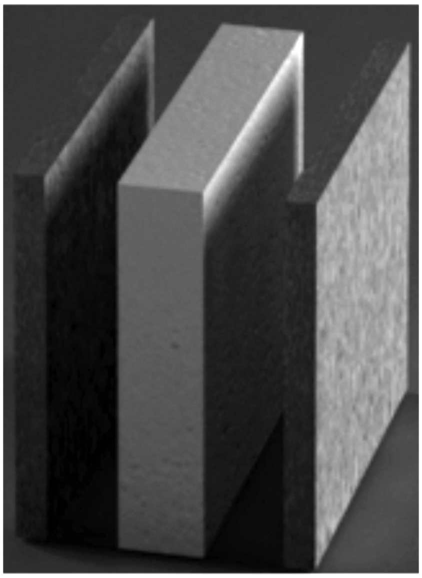

Figure 1. Building wall made up two oriented strand boards (OSB) and a polystyrene foam layer.

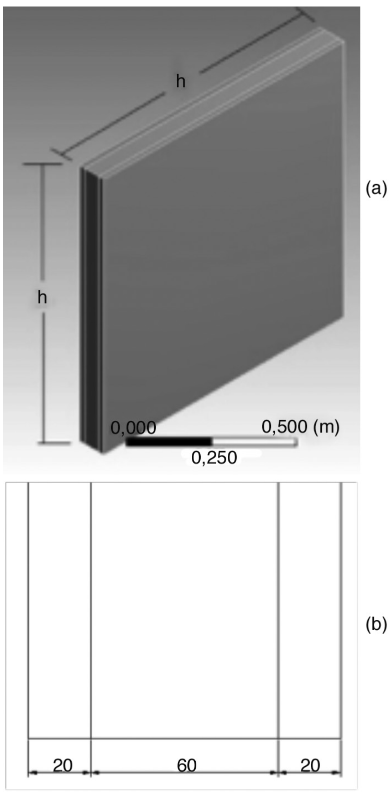

Figure 2. Isometric projection of the building wall (a) with h = 1 m and the cross section (b) with lengths in mm.

Pro thermal properties analyzer. Table 1 resumes the thermophysical data used for the computational simulations.

Table 1. Thermophysical properties of the materials of the building walls. The densities of PF and PB are given by the manufacturer (*). The property values in brackets were experimentally obtained under environmental conditions.

Material	ρ	**Cp**	**k**	α
	kg/m³	**kJ/kg K**	**W/m K**	**m²/s**
Polystyrene foam (PF)	15 10*	1.2 –	0.0413 (0.037)	2.29×10^{-6} –
Oriented normative board (OSB)	650	1.7	0.106	9.59×10^{-8}
Plasterboard (PB)	870 950*	– (0.887)	0.31 (0.140)	– (1.66×10^{-7})

The boundary conditions on both sides of the wall are of the third order or Robin boundary conditions and the other four edges are considered adiabatic. According to the geographical location, the Chilean normative Nch853-Of91 was used as well as a source of the convective heat transfer coefficient value. According to the Normative the University of Santiago is located in zone 3, where convective heat transfer coefficient is 20 W/m^{2}K for wind velocity lower than 10 km/h, higher than the average value of 4 km/h given by the meteorological authority of Chile.

Mathematical Model

The mathematical model is comprised by the transient heat conduction equation; initial boundary and conjugate heat transfer conditions. The transient heat conduction equation with constant properties is given by:

$$\rho Cp \frac{\partial T}{\partial t} = k\nabla^2 T \tag{1}$$

Where the Laplace operator is expressed in Cartesian coordinates. The boundary conditions are:

$$k\frac{\partial T}{\partial x}\Big|_{x=d} = h\left(T\left(x=0\right)-T_\infty\right) \tag{2a}$$

$$k\frac{\partial T}{\partial x}\Big|_{x=d} = h\left(T\left(x=d\right)-T_{\infty}\right) \tag{2b}$$

Where h is the convective heat transfer coefficient, d (0.1 m) is the thickness of the building wall and T_{∞} is the bulk temperature of the fluid around the wall. The conjugate boundary conditions are imposed on the interfaces (w = 0.2 m and w = 0.8 m) between the components of the building wall:

$$k_{OSB,\,PB}\frac{\partial T_{OSB,\,PB}}{\partial x}\Bigg|_{w} = k_{PF}\frac{\partial T_{PF}}{\partial x}\Bigg|_{w} \tag{3a}$$

$$T_{OSB,\,PB}\Big|_{w} = T_{PF}\Big|_{w} \tag{3b}$$

The complete set of discretized equations was solved, by using the commercial software *ANSYS/ Transient thermal (ANSYS Academic Research).*

Validation

Since the experimental validation of the process of interest was not possible in the context of the undergraduate course, the same transient process for an OSB wall was validated considering that the one-dimensional transient heat conduction problem can be solved analytically. The analytical solution of the one-dimensional equation (1) with boundary conditions (2) obtained by the method of separation of variables [8, 12] is given by:

$$\theta\left(x,t\right) = \sum_{n=1}^{\infty}\frac{1}{N}e^{-\alpha\lambda_n^2 t}\psi\left(\lambda_n,x\right)\int_0^L F\left(x'\right)\psi\left(\lambda_n,x'\right)dx' \tag{4a}$$

Where the eigenfunctions $\psi(\lambda_n, x)$ and eigenvalues λ_n are obtained through the analysis of the boundary conditions. The normalization integral N is obtained by using the orthogonality property of the eigenfunctions. Equation (4a) can be simplified considering a Fourier number greater than 0.2:

$$\theta\left(x,t\right) = \frac{T\left(x,t\right)-T_f}{T_i-T_f} = A_1\cdot e^{-\lambda_1^2\cdot FO}\cdot\cos\left(\lambda_1\cdot x/L\right) \tag{4b}$$

Where the coefficients A_1 and λ_1 are available in several undergraduate heat transfer textbooks and the Fourier number (Fo) is:

$$Fo = \frac{\alpha\cdot t}{L^2} \tag{5}$$

An important dimensionless number in conduction heat transfer problems with convective boundary conditions is the Biot number (Bi), which relates the conductive and convective thermal resistances:

$$Bi = \frac{h\cdot L}{k} \tag{6}$$

The obtained temperatures from equation (4b) at the center and the surface of the OSB wall present deviations lower than 2%, when $t > 170.9$ s, considering an OSB wall of thickness of 0.2 m. The preceding temperatures as well as the rate of heat transfer can be determined using the Heisler charts [13], Nevertheless the difference of the obtained temperature values can be 15%.

The validation of the numerical results with analytical values was performed by comparison of the transient temperature profile obtained at the center and the surface of the OSB layer. The comparison of the numerical predictions (discrete markers) with analytical results (solid lines) can be observed in Figure 3, where the maximum relative error does not exceed 2%.

Grid size study

The effect of the grid size on the numerical results was analyzed by comparing the transient temperature distribution at the center and surface positions of the building wall (Figure 4). Four grid size were

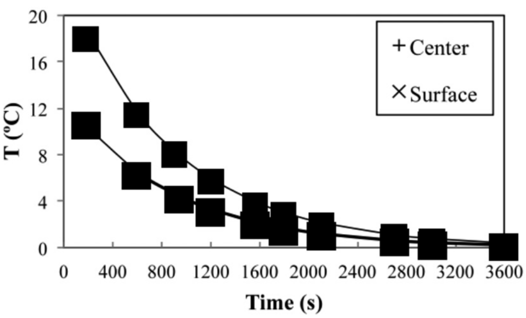

Figure 3. Validation of the transient cooling process of an OSB layer with analytical results represented by solid lines (Grid size of 0.1m and adaptive automatic time step).

analyzed, the coarser grid with elements of 20 mm (G1) and finer grids with elements of 10 (G2), 5 (G3) and 2.5 (G4) mm. According to Figures 4, the effect of the grid size is more important in the prediction of the inner temperatures, such as the effect on the temperature profile is mainly noticed during the first 200 seconds of the cooling process, i.e. at times where the error associated with the use of the Heisler charts is higher. In this time interval, the relative difference between the predicted temperature values with the two finer grids (G3 and G4) is very low (<0.005%) and it can be as high as 3% at greater times. The relative differences between the predicted temperature values with G2 and G3 are lower than 0.1%. Therefore a grid of elements of 5 mm was chosen to perform the simulations of both building blocks.

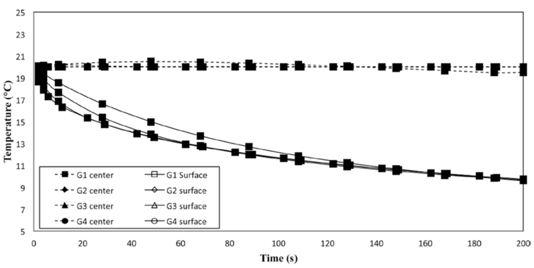

Figure 4. Grid size study for the transient cooling process of a building wall (OSB/polystyrene/OSB).

RESULTS AND ANALYSIS

The transient temperature distributions along the OSB and PB layers of the building walls during the first 300 seconds of the cooling process are shown in Figure 5. During this period the temperature of the PS layer is practically constant. After comparing Figures 5a y 5b, it can be seen how the temperature profile in the PS layer is more pronounced than in the OSB layer, which is explained by the lower thermal capacity (the product of density and heat capacity) of PS (843 kJ/m^{3}K) in comparison with OSB (1105 kJ/m^{3}K). At higher times, it can be seen at each time step how the OSB layer remains at a higher temperature (Figure 6a) than the PB layer (Figure 6b).

After comparing the temperature profiles, especially those corresponding to 900 s and 1800 s, it can be noticed that there is a greater temperature drop at the PB/PS interface than in the OSB/PS interface (L = 0.08 m). It is important to notice here than the thermal resistance associated to with interfaces or thermal contact resistances were not taken into account. In such a case, its effect would be observed as a localized temperature discontinuity at the interfaces.

In Figures 5a and 5b, it can be noticed that at the lower shown time (10 s) there is an increase of temperature near to the surface (L = 0.096 m). These hot spots during the first seconds of the cooling process can be explained because at this instant of time convection controls the heat transfer process.

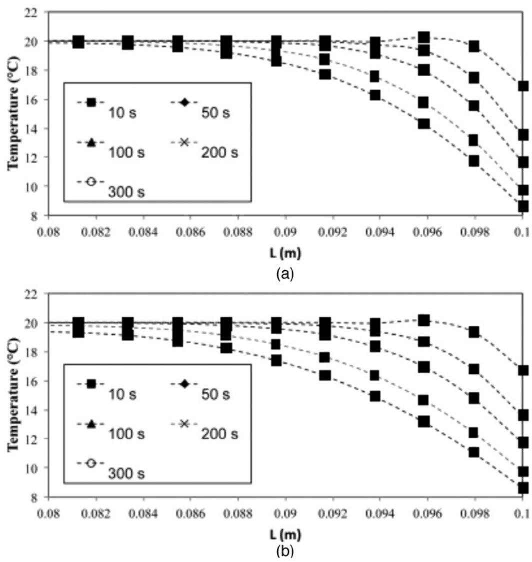

Figure 5. Transient temperature profile during the cooling process of a building wall made up of OSB/PS/OSB (a) and PB/PS/PB (b).

The thermal inertia of a material is defined as the square root of the product of the thermal conductivity and the thermal capacity. Accordingly, OSB has a thermal inertia of 342.24 J/(mK√s) and PB has a slightly higher thermal inertia of 343.47 J/(mK√s). Therefore the transient effects are important to analyze the heat transfer process in heating applications with both materials. The transient cooling process of both constructive blocks can be understood by observing temperature contours, wich represents a temperature range by using contours

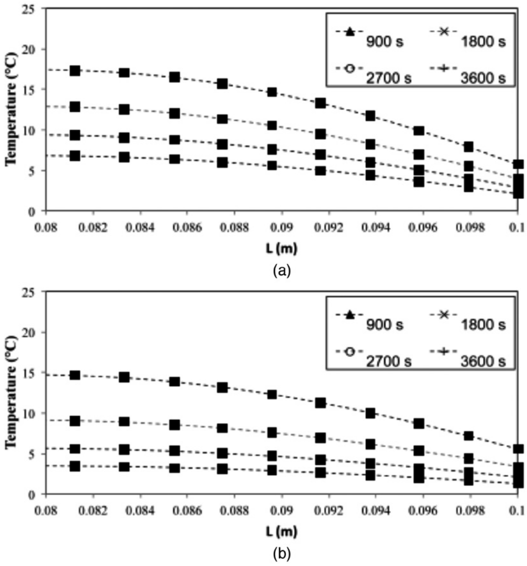

Figure 6. Transient temperature profile during the cooling process of a building wall made up of OSB/PS/OSB (a) and PB/PS/PB (b).

colors. Normally the more intense represent higher temperature regions. After observing Figures 7 and 8 it can be noticed the symmetric feature of the cooling process and how the cooling rate of the PB/PS/PB building wall is higher. The Biot number (Bi) which relates the conductive and convective heat transfer resistances is higher in the OSB than in the PS layer. In both cases Bi is higher than 1 (Bi_{OSB} = 3.77 and Bi_{PB} = 2.86) which means that conduction is an important mechanism to take into account in order to analyze and study the transient heat transfer process with thermal envelopes.

Since the transient temperature distribution is known, it is possible to calculate the heat flux along the building wall. Except for the obtained curves after 10 s, the curves have a similar shape, showing how the heat flux is greater towards the OSB and PB outer surfaces and lower along the polystyrene layer. Comparing Figures 9a and 9b, can be observed how the heat flux is higher along the OSB layer than in the PB layer, especially at greater times. This result is in agreement with the thermal capacity of OSB, which is higher and therefore it takes longer to achieve a thermal equilibrium condition. That is why the heat flux is higher during most of the cooling process since the temperatures along the OSB layer are higher than those observed in the PB layer. The particular shape of the curves of heat flux at t = 10 s, where a peak is observed near to L = 0.094 m, is explained by the higher temperature point in the temperature profile (Figure 5) at L = 0.096 m. During the first instants of the cooling process, heat transfer is governed by convection that is why a high temperature zone is observed near to the wall surface.

CONCLUSIONS

The thermophysical properties available in the National Chilean normative are not complete in the sake to perform a transient study of thermal envelopes normally used in construction of houses. That is why to experimentally determine heat capacity was necessary to carry out a complete study.

During the first second of the cooling process of the building blocks, it was observed a hot spot near to the outer surface of the wall, more pronounced in the case of the OSB/PS/OSB wall: this is explained because at this instant of time convection controls the heat transfer process.

The transient thermal conduction study of two different building walls allowed identifying advantages of OSB over PB regarding preservinge heat and therefore maintaining a comfortable indoor temperature. Based on the results shown in this study, it is more beneficial to use OSB as an inner layer and PB as an outer layer in constructive walls.

This work arose from an undergraduate project and remarked the importance to teach computer tools to HVAC-R Engineering students to understand better transient heat transfer processes. Heat transfer students performed essential steps related to computer simulation, which are outlined in this work, including mathematical and physical modeling, grid size study, validation, experimentation, analysis and post-processing. It is essential important that the students can relate computer simulation to problems of practical interest, in this case how constructive materials commonly used in housing construction in Chile responds to transient thermal disturbances.

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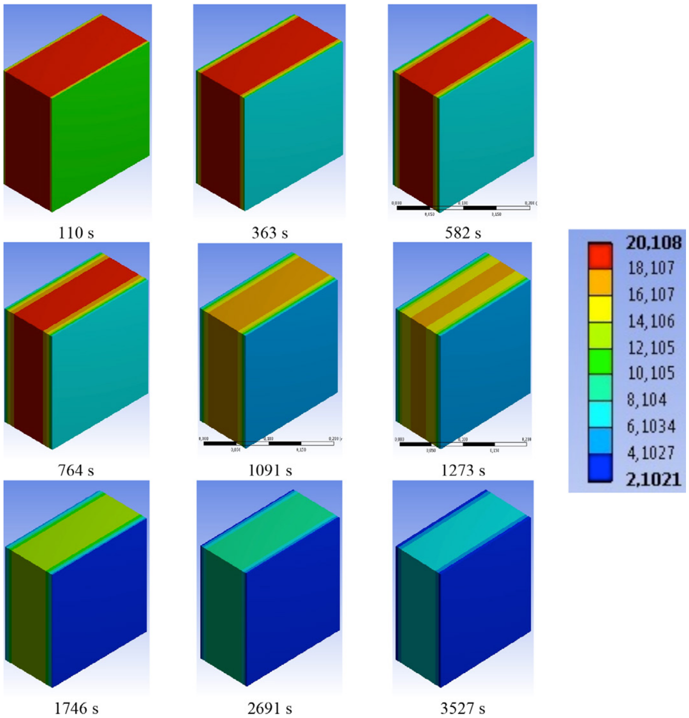


Figure 7. Transient temperature contours during the cooling process of a building wall made up of OSB/PS/OSB (case a).

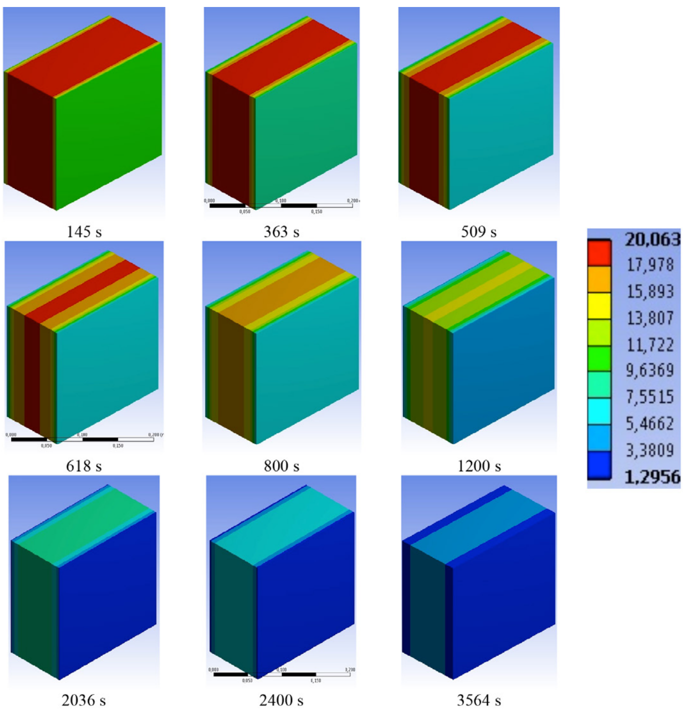
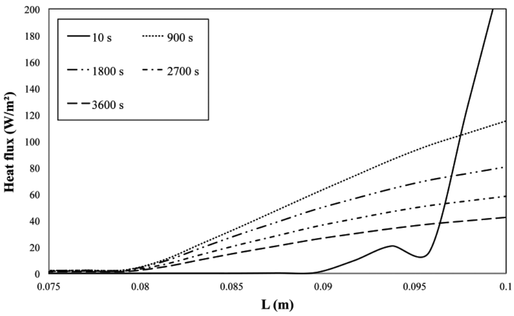


Figure 8. Transient temperature contours during the cooling process of a building wall made up of PB/PS/PB (case b).



(a)

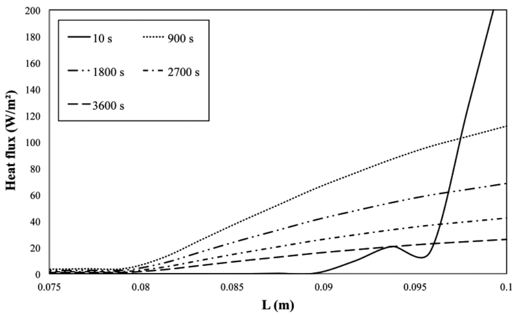


Figure 9. Transient heat flux during the cooling process of a building wall made up of OSB/PS/OSB (case a) and PB/PS/PB (case b).

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