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Theoretical and experimental investigations on the heat transfer through an adobe wall

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Abstract **– The article presents a dynamic analysis of the heat transfer through an adobe wall of a residential detached house in Constanta, aiming to determine the temperature field in the wall, during a hot summer day. Both outdoor and indoor air temperatures are variable. It proposes a simple way for determining the conduction coefficient of a building material, by combining the finite element method of E. Smidt with in situ measurements. The adobe conductive coefficient was obtained to be λ=0.33 W/(m/K). The results regarding the limit surfaces temperature field pointed out the attenuation of the temperature amplitude from 23.4 °C at the external wall surface to 5 °C at the internal one. The presence of the glazed surfaces on the wall mitigates the good influence adobe has on the interior thermal comfort.**

Keywords – adobe, dynamic conductive heat transfer, temperature field, thermal conduction.

1. INTRODUCTION

Adobe is a widely used building material, especially within regions where other building materials are scarce. It is a cheap and sustainable material, very appreciated for its thermal inertia and hygrothermal properties. From energy consumption viewpoint, adobe has not only low embodied energy but also contributes to the reduction of heating and air conditioning needs. It complies with current low-carbon dioxide emission [1]. Being a local material, the expenses with transportation are cut, and adobe shows higher environmental performance comparing to modern building materials [2].

The energy payback time for an adobe house was found to be of 1.54 years, after the calculations of Shulka et al. (2009) cited by [3]. Furthermore, adobe is a good sound insulation material.

Due to the high heat capacity, adobe walls can store a large heat amount, keeping the indoor temperature low, during summer daytime, and release this heat during the night. So, the indoor temperature is naturally regulated in an adobe house. The indoor temperature is maintained without fluctuations in adobe buildings, where there is a reduced number of windows on walls [4]. The thermal resistance of an adobe wall depends on the thickness of the wall, as the heat conduction coefficient is rather elevated. Moreover, the heat conduction coefficient depends on the moisture content of the adobe. Therefore, the adobe buildings manifest a cyclic value of the conduction coefficient, due to the changes in atmospheric humidity. This is one of the reasons the conduction behaviour changes in time for the same composition of the adobe material.

An experimental study conducted by Ngaram [5] gives a variation of the thermal conductivity of adobe between 0.1911-0.4282 W/mK for a moisture content rising from 5% to 20%.

Nevertheless, the thermal properties depend also on the recipe the adobe is produced from, as it is a local made material. These are some reasons literature gives very different values for the thermal and physical properties of adobe, depending on the region it was made.

In [6] it is given a range between 1700-2200 kg/m^3 for the density of adobe, and a range of 0.18-0.2 W/mK for its thermal conductivity coefficient. A thorough study on physical properties of earth based building materials is made by [7]. For the thermal conductivity coefficient, he gives a range between 0.18-0.4 W/mK where the density varies between 740-1000 kg/m^3.

Investigations on the prediction of the indoor air temperature in an earth-built house were theoretically performed by [8]. The model considered that the heat transport in the wall takes place by conduction, while inside the room the predominant mechanism is the natural convection of air. The behaviour of temperature in the wall is determined from the equations of exchange temperature in a solid material. The temporal behaviour of the air temperature in the room, considered independent of the spatial position, is obtained from the energy balance between the heat accumulated by the inner volume of air due to the heat gain by convection at the inside surface of the wall. There are no other heat sources for the indoor air.

The experimental study made by [4] shows the experimental values for the air temperature obey with good accuracy the theoretical solution of the mathematical equation of [8].

Our study presents a dynamic analysis of the heat transfer through an adobe wall of a residential detached house in Constanta, aiming to determine the temperature field in the wall during summer, where not only the outdoor air temperature varies due to solar radiation, but also the indoor air temperature varies due to the heat that enters the room through the windows. There are no other heat sources for the indoor air, either.

The selected house is representative of a very large number of residential houses in Constanta and its surroundings. It is a ground floor house with attic.

A first difficulty for numerical calculation was the identification of the adobe's thermal and physical properties, as the values given in the literature vary according to the soil component properties in different regions, humidity, and the building's age.

The experimental measurements were performed on the opaque Southern wall of the house.

2. METHODOLOGY FOR DETERMINING THE ACTUAL VALUE OF THE HEAT CONDUCTION COEFFICIENT OF ADOBE

2.1. Theoretical considerations

We consider the input heat flux at the external surface of the wall is the solar radiation flux. This flux splits into two components: convection flux at the external surface of the wall and the conduction flux transmitted through the wall. The wall has no heat sources or sinks, and it is homogenous. Heat propagates by unidirectional conduction through the wall, and it is transmitted by convection to the indoor air, at the internal surface.

The heat balance equation, at the external surface of the wall gives the conduction heat flux as the difference between the radiation flux and the flux lost by convection:

$$-\lambda grad\ T = \dot{q}_r - \alpha_e(T_{so} - T_e) \quad (1)$$

where α_e $[W/m^2/K]$ is the convection coefficient at the external surface of the wall.

The wall is infinite and has plane and parallel boundary faces. It is discretised into layers of Δx thickness.

Thus, each layer of the wall opposes the same thermal resistance to conduction and has a thermal capacity corresponding to the volume element associated with that layer.

Each boundary layer has a thickness of Δx⁄2 and is completed with an air layer of Δx⁄2 thickness, so we've considered a fictive plane surface into the outdoor air and, respectively another fictive surface into the indoor air, as in Figure 1.

Space and time discretization is made complying with the convergence condition imposed by Fourier Number <0.5:

$$\Delta t = \frac{\Delta x^2}{2\,a} \quad (2)$$

where a [m^2⁄s], the heat diffusivity coefficient, is:

$$a = \frac{\lambda}{\rho c}$$

λ $[W/mK]$ conduction coefficient of the material,
ρ [kg⁄m3]- density of the material,
c [J⁄(kg·K)]-specific heat of the material.
We'll consider j the index for space step and k for the time step.

The propagation direction is along the axis Ox, with the origin at the external surface of the wall, as it may be seen in Figure1. The temperature gradient at external surface is given by (1):

$$(grad\ T)_{0,k} = \left(\frac{\partial T}{\partial x}\right)_{0,k} = \left(\frac{\Delta T}{\Delta x}\right)_{0,k} \quad (3)$$

We could calculate the gradient at each moment of time, k, knowing the radiation flux and the temperature of the external surface in the previous moment, $T_{so,k-1}$, and respectively the outdoor air temperature, T_e

At the initial moment, the temperature field in the wall is uniform, the temperature being equal to the outdoor air temperature:

$$T_{e,o} = T_{j,o}$$

The gradient is given by (4):

$$\left(\frac{\Delta T}{\Delta x}\right)_{fo,1} = -\,\dot{q}_r/\lambda \quad (4)$$

This is the gradient for the conductive heat transfer during the first time step, Δt. Knowing the gradient, we can determine the external surface temperature at the time step k=1, considering the heat entered the wall and reached the surface j=1. The gradient gives the temperature's linear variation starting from the external fictive surface j=0 to the j=1 surface in the wall, as shown in (5):

$$T_{so,1} = T_{1,0} + \left(\frac{\Delta T}{\Delta x}\right)_{fo,1} \cdot \frac{\Delta x}{2} \qquad (5)$$

As both temperatures, of the outdoor air and of the external surface, vary in time, equation (6) gives the temperature gradient at the time step *k*:

$$\left(\frac{\Delta T}{\Delta x}\right)_{so,k} = -\dot{q}_r/\lambda + \alpha_e\left(T_{so,k-1} - T_{e,k}\right) \qquad (6)$$

Equations (7) and (8) give the temperatures at the external boundary surface and, respectively, the fictive external surface:

$$T_{so,k} = T_{1,k-1} + \left(\frac{\Delta T}{\Delta x}\right)_{so,k} \cdot \frac{\Delta x}{2} \qquad (7)$$

$$T_{fo,k} = T_{1,k-1} + \left(\frac{\Delta T}{\Delta x}\right)_{so,k} \cdot \Delta x \qquad (8)$$

Inside the wall, at the space step j and the time step k, the temperature is taken as the average given in (9):

$$T_{j,k} = \frac{T_{j-1,k} + T_{j+1,k-1}}{2} \qquad (9)$$

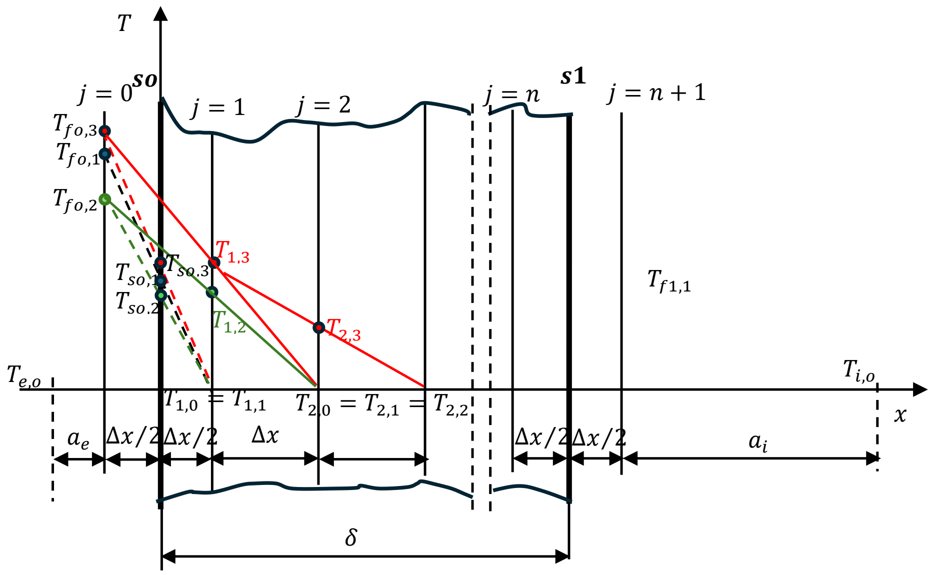


Fig. 1 Space discretization of the wall. The thermal limit layer at the external surface

At the internal boundary surface of the wall, the temperature depends on either the heat coming through the wall by conduction or the indoor air temperature. The thickness of the thermal layer is $a_i = \lambda/\alpha_i$. The temperature of the indoor air at a moment k is $T_{i,k}$

It was assumed the temperature has a linear variation between $T_{n,k}$ and $T_{i,k-1}$, Figure 2.

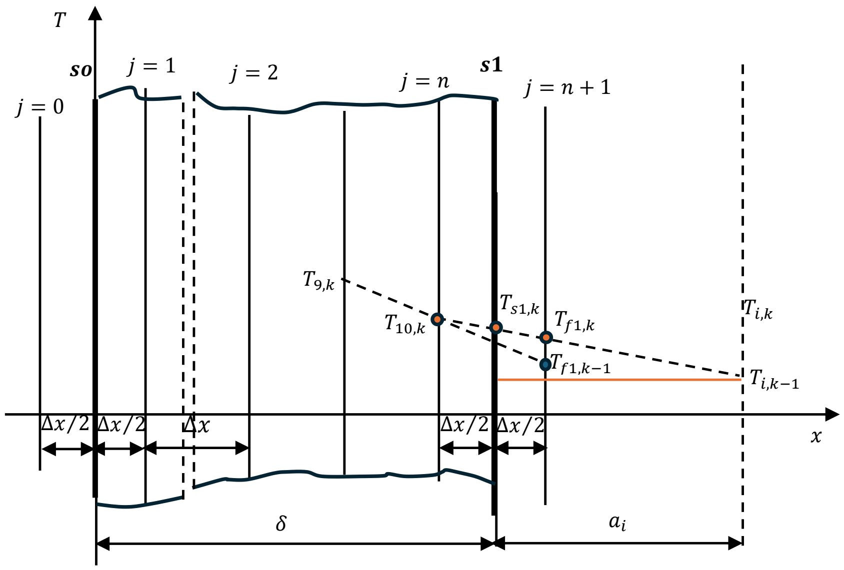


Fig.2. Space discretization of the wall. The thermal limit layer at the internal surface

Proportionally there were determined the temperatures of the interior surface of the wall, $T_{s1,k}$, and the temperature of the fictive indoor surface, $T_{f1,k}$, as given in equations (10) and, respectively, (11):

$$T_{s1,k} = T_{i,k-1} + \frac{a_i}{a_i + \frac{\Delta x}{2}} \cdot \left(T_{n,k} - T_{i,k-1}\right) \tag{10}$$

$$T_{f1,k} = T_{11,k} = T_{i,k-1} + \frac{a_i - \frac{\Delta x}{2}}{a_i} \cdot \left(T_{s1,k} - T_{i,k-1}\right) \tag{11}$$

Calculations were performed in Excel, to determine the temperature fields in the wall, during a diurnal cycle.

2.2. Experimental measurements

The experimental measurements were made on the Southern wall of the adobe made residential house. The wall is fully exposed to the sun. The house is over 65 years old, and the thermal properties of the material are no longer known. With the available laboratory equipment, the solar radiation flux on the wall and the temperature on both external and internal wall surface were experimentally measured, aiming to find out the conduction coefficient of the adobe made wall.

The solar radiation flux was measured by the help of the application Scanthesun. The experimental results, for the 10th of July are given in Figure 3.

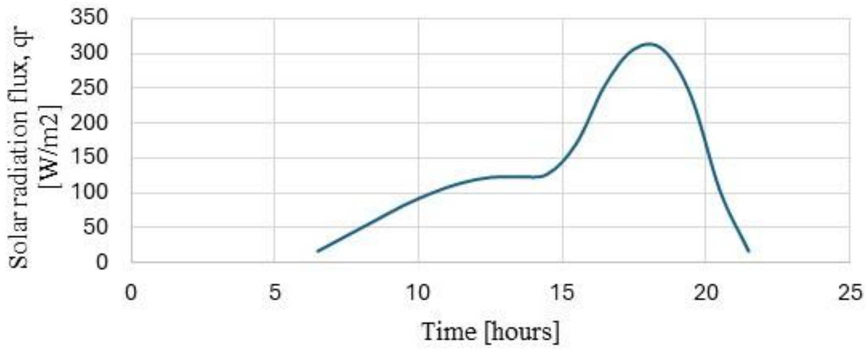


Fig. 3 Solar radiation flux, between 6 am and 9 pm

The outdoor and indoor air temperature were measured using a temperature datalogger CEM DT-172 with the temperature range: -40÷ 70°C and ±1% accuracy. The experimental results regarding external air temperature t_e and internal air temperature, t_i, are shown in Figure 4.

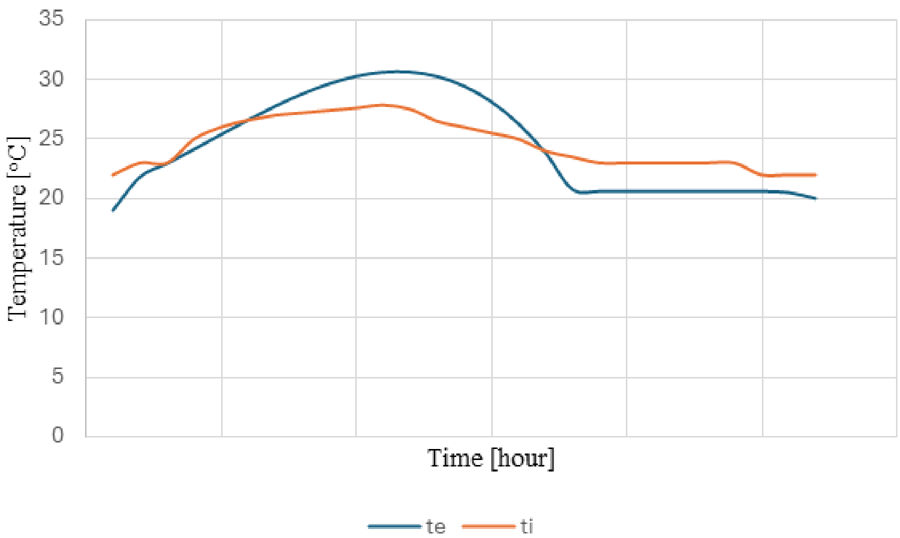
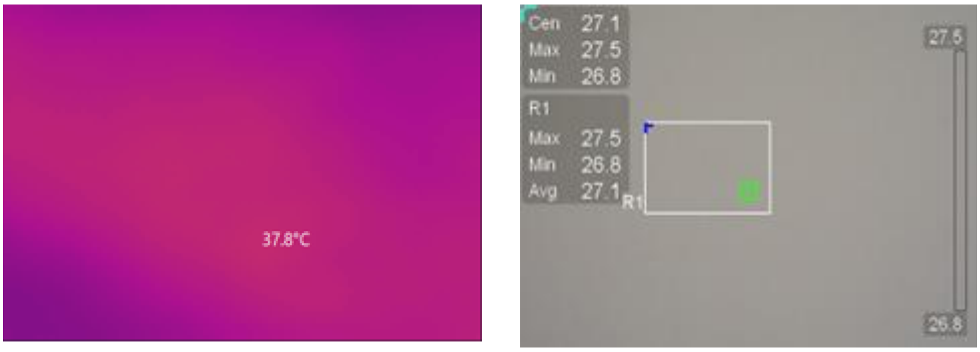


Fig. 4 The outdoor and indoor air temperature variation during July 10th 2022, between 6 am and 5:40 am the next day

The temperature on the boundary surfaces of the wall was measured with a HIKMICRO M10 Thermal imaging camera with ±2% accuracy.

All the measurements were performed during July 2022, a hot summer period considering the solely heat source is the sun. The HVAC system was turned off during the entire summer, as the owners were out of the city. We considered the indoor air temperature varied only due to the heat transferred by either the opaque or glazed surfaces of the wall.

The air temperature measurements were recorded starting with the morning of the 9th of July, when the indoor and outdoor air temperatures were equal for more than the previous 6 hours, therefore we considered a steady state temperature field along the adobe wall thickness. On the 10th of July the thermal images of the wall were taken at 4 pm, Figure 5.



(a) External surface (b) Internal surface

Fig. 5 Thermal images of the wall, in the control spot, taken at 4 pm

3. RESULTS AND DISCUSSIONS

The dynamic calculation of the surface temperatures of the wall, using the finite difference method, was performed for different values of the conduction coefficient of adobe. The wall was discretised into 10 space steps. The time step is *of* $\Delta t=0.89\ h$, and the space step is $\Delta x=0.039\ m$. The convection heat coefficients are: $\alpha_e=20\ W/m^2/K$ at the external wall surface, and $\alpha_i=11\ W/m^2/K$ at the internal wall surface.

The values of the coefficient were incremented in the range $\lambda=0.3\div0.4\ W/m/K$, by a step of $\Delta\lambda=0.01\ W/m/K$ and, for each step, there were compared the calculated temperature values of the two surfaces of the wall to the experimentally measured ones in the control spot.

The density was measured in the laboratory, on a sample taken from the same house. The experimental value is $\rho=1692\ kg/m^3$, a value in good accordance with the recommended ones in [6]. The specific heat of the adobe was considered $c=1000\ J/kg/K$, as given in [6] for the above specified density.

Table 1 Temperatures on the control spot of the wall

	External surface temperature, t_0, [°C]	Internal surface temperature, t_1, [°C]
Theoretical value	37.7	27.1
Experimental value	37.8	27

For the value $\lambda = 0.33\ W/m/K$ we have obtained the best match between the theoretical and the measured temperatures, in the control spot of the wall, as it may be seen in Table 1. The error is less than ±0.5%.

We have used this value of the conduction coefficient in all the subsequent energy analysis.

The thermal diffusivity, calculated for these properties of the material is $a = 1.94 \cdot 10^{-7}\ m^2/s$.

Once the heat properties were established, the temperature fields at any time step, and any surface of interest are also obtained.

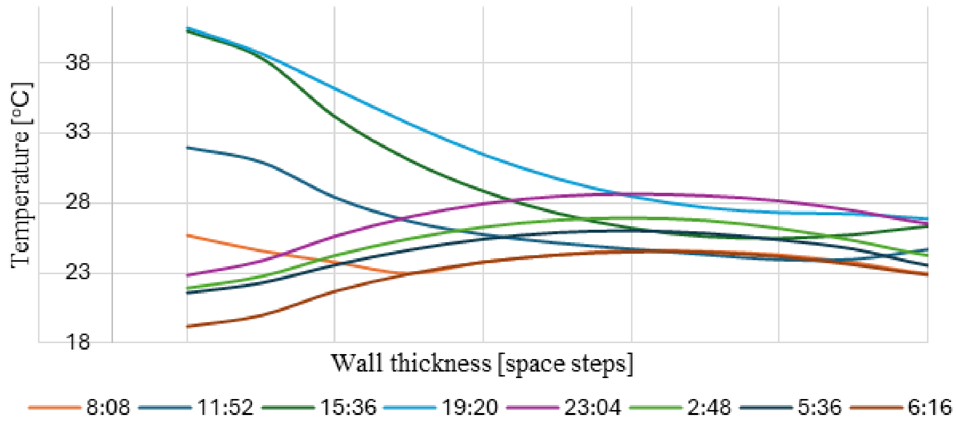


Fig. 6 The temperature field in the adobe wall, between the two limit surfaces, at different moments of time

The time delay, between the conduction heat flux enters the external surface and the moment it reaches the internal one is of 9 hours, which would have allowed a good stability of the internal air temperature during a canicular day, if the wall had no glazed surfaces. But the heat that enters the glazed surfaces, from the first hours in the morning, increase the temperature of the indoor air. So, the temperature of the internal surface of the wall starts to increase before the conduction heat flux front reaches it. Despite this influence of the glazed surface, the temperature amplitude on the external surface, of 23.4 °C, is considerably attenuated at the internal surface, where the amplitude is of no more than 5 °C. The higher temperature of the external surface is recorded between 4-7 pm, with a pick value at 5 pm. The higher temperature of the internal surface is recorded in the afternoon, between 3-8 pm, with a pick value at 5 pm. Thus, even if the highest temperatures are installed at the same time at both limit surfaces, attenuation is an important advantage.

Figure 6 points out the inflexion points of the temperature field. At 6 am the temperature field is convex, as the boundary surfaces temperatures are lower than the temperature inside the wall, because of the stored heat. At 8 am the temperature field shows an inflexion point due to the rapid increase of the external surface temperature exposed to the solar radiation. At noon, a second inflexion point is visible, the one close to the internal surface, due to the heat that enters the wall from the indoor air.

The obtained temperature fields allowed us to calculate the heat flux that enters the external wall surface, q_{se}, the heat flux that exits the internal wall surface, q_{si}, and the stored heat flux, q_w, during 24 hours, Figure 7.

Between 7:30 am and 9 am the whole heat flux that enters the external surface is stored inside the wall. During daytime, until around 6 pm, the heat flux that enters the external surface is positive, $q_{se} > 0$, and at the internal surface the heat flux is negative, $q_{si} < 0$, so the heat enters the wall at both limit surfaces, as showed in Figure7.

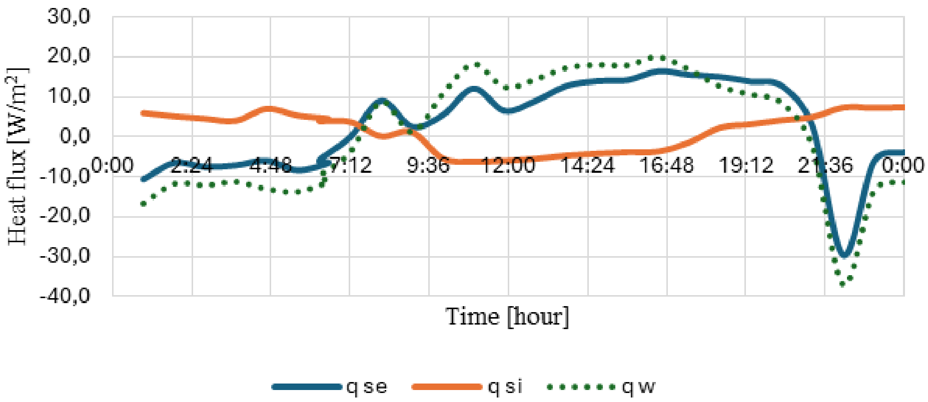


Fig. 7 The variation of the heat fluxes q_{se}, q_{si}, and q_w

Between 6 pm and 9 pm the heat flux at both boundary surfaces is positive, $q_{se} > 0$ and $q_{si} > 0$, which means the conduction heat enters the wall and is transferred to the indoor air. During the nighttime, between 9 pm and 7:30 am the conduction heat flux enters the room, while at the external surface, the conduction heat leaves the wall. Therefore, the heat is stored by the wall between 9 pm and 7:30 am, and released to the external and respectively, internal air the rest of the time.

4. CONCLUSIONS

The study proposes a new method for determining the conduction coefficient of a building material, by the help of some easy to make in-situ experimental measurements: indoor and outdoor air temperature, limit wall surfaces temperatures, and solar radiation.

This method, adapted after the E. Smidt's graphical method, allowed to determine not only the value of the conduction heat coefficient of a given type of adobe, but also the temperature field along the wall thickness at different moments of time, during 24 hours of a summer day. The method may be applied to any building material, as long as the convergence conditions are fulfilled. For the studied house, an old one, placed in Constanta city, made with local building materials, the adobe conductive coefficient was obtained to be $\lambda = 0.33\, W/m/K$. The time delay for the conductive heat to pass through the thickness of the wall is 9 hours. The temperature amplitude drops from 23.4 °C at the external wall surface to 5 °C at the internal one.

The study drops off the hypothesis of a constant temperature of the inside air, which is usually considered in literature, and considers the actual variation of this temperature along 24 hours of a day. Therefore, the temperature field across the wall leads us to a good assessment of the conductive heat flux at the limit surfaces of the wall.

Once again, the high heat capacity of the adobe is pointed out. During the daytime, between 7:30 am and 6 pm, a large part of the conductive heat is stored by the wall, and during the nighttime it is released to the air on both sides of the wall, contributing to the natural stability of the indoor air temperature. The pick conductive heat flux stored by the wall during daytime is attained at 4 pm, and the pick value of released conductive heat during nighttime is reached at 10:30 pm. So, the glazed surface of the wall, that allows a rapid heat transfer, diminishes the good influence of the adobe wall to the indoor thermal comfort.

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