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RESEARCH ARTICLE

OPTIMIZATION OF THE AIR GAP THICKNESS FOR THE INSULATION OF DOUBLE-WALLED WALLS OF A BUILDING

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ABSTRACT

This paper presents a study on the determination of wall surface transmission coefficients, the properties of the air gap used in building insulation and temperature profiles in walls. The property values show that the air gap is a good insulator if its thickness does not exceed 4 cm. When the faces of the walls are doubled, we observe a decrease in the values of the surface transmission coefficients of the walls. This reduction in these coefficients is considerable when the double faces of the walls are insulated from an air gap. The lowest coefficient value (1.45 W.m-2.K-1) is obtained with the clay-paper-cement (TPC) and clay-paper (TP) wall. The study of temperature profiles in the different wall types was made with COMSOL software. The temperatures of the inner faces of the various walls are about 27 °C for outside temperatures of 40 °C or 35 °C, a decrease from 22.86 % to 32.50 % of the values.

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INTRODUCTION

Global energy consumption in buildings represents about 40 % of total energy consumption and is responsible for about 25 % of total CO_2 emissions (N. Fezzioui and M. Benyamine, 2008). Audits carried out in air-conditioned buildings in tropical Africa show that the share of electricity consumption due to air-conditioning is within a range of 40 to 80 % (A. Kemajou, 2002) of the total electricity consumption of the building, which places this item at the centre of energy saving actions. Improving comfort conditions and reducing air-conditioning costs by environmentally friendly means at low energy cost are now considered an absolute priority by both energy users and distributors. Thermal comfort is an important parameter in air-conditioned and non-air-conditioned homes because of its impact on the quality of indoor environments, the health and productivity of the occupant. The acquisition of air conditioners to cool the air in homes has the effect of heating the outside air and for a city like Athens, there is a temperature gradient of up to 14°C in summer between the city and its periphery (N. Fezzioui *et al.*, 2012). This entropic clearance leads to a constant over-sizing of the systems. These considerations are at the root of over-consumption of energy and problems of occupant discomfort. Increased requirements for the energy performance of buildings in Sub-Saharan Africa must be reflected in the implementation of thermal regulations. In particular, the determination of heat transfer coefficients (U-value) for the various components of the building envelope. With the tightening of standards, research into the thermal properties of the building has intensified, in particular the thermal insulation of the envelope, which plays an important role in controlling energy consumption. Indeed, a large part of the increase in thermal loads is related to heat gains through walls, roof and floor.

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To this end, research is mainly focused on improving the thermal performance of existing insulation and the design of new building and insulation materials. For example, we have paper-stabilized compressed earth blocks (E. Ouedraogo *et al.,* 2014; E. Ouedraogo *et al.,* 2015), high inertia insulation, vacuum insulation panels and reflective insulation. This study focuses on determining the performance of building walls according to their composition. These different walls are composed of either single or double walls with or without air gap. The air gap must be airtight to avoid degradation of the thermal resistance in the event of air infiltration and the formation of natural convection loops.

MATERIALS AND METHODS

Overall transmission coefficient: The thermal transmission coefficient of a homogeneous multilayer wall U is the quantity of heat that passes through this wall in steady state, per unit of time, surface area and temperature difference between the environments located on either side of the wall, it is expressed in $W.m^{-2}.K^{-1}$. The thermal transmission coefficient is the inverse of the total thermal resistance (R_T) of the wall ($U = 1/R_T$). The U coefficient defines the level of overall thermal insulation of a building. The lower it is, the less heat is brought into a building through the exterior walls, roofs, floors and windows.

Coefficient of surface heat transmission of a wall

The thermal transmittance (Up) of a building wall is determined by the expression of equation 1:

$$U_P = \frac{\sum U_{Pi} \cdot A_i}{\sum A_i} \qquad \text{……………………………………….. (1)}$$

With the are A_i (m^2) a of the wall element, the U_{pi} surface heat transfer coefficient of a wall element, determined using the expression of equation 2:

$$U_{Pi} = \frac{1}{\frac{1}{h_{ex}} + \sum \frac{e_i}{\lambda_i} + \frac{1}{h_{in}}} \qquad \text{……………………..………………. (2)}$$

Where: $R_{s,ex}$, $R_{s,in}$, R_i $(m^2.K.W^{-1})$ are respectively the thermal resistances of the external surface, the internal surface and the wall component; R_{pi} $(m^2.K.W^{-1})$ is the thermal resistance of the wall element; h_{ex} *et* h_{in} $(W.m^{-2}.K^{-1})$ are respectively the external and internal surface heat exchange coefficients. Since not all building walls are homogeneous on their surfaces, it is important to determine an average thermal conductivity of the non-homogeneous layer of the masonry wall (composed of bricks and mortar joints). This average conductivity is calculated by the relationship of equation 3 (E. Ouedraogo, 2015):

$$\lambda_{mur} = \lambda_{brique} \cdot \frac{l \cdot h}{(l+h)\cdot(h+d)} + \lambda_{joint} \cdot \left(1 - \frac{l \cdot h}{(l+h)\cdot(h+d)}\right) \qquad \text{………………………………………. (3)}$$

Where λ_{brique}, $\lambda_{joint}$$(W.m^{-1}.K^{-1})$ are respectively the thermal conductivity coefficients of the brick and the joint, *l (mm)* and *h (mm)* are respectively the length and height of the brick, is *d (mm)* the thickness of the joint.

The values of the thermo-physical properties of building materials (E. Ouedraogo *et al.,* 2015) and those of walls determined using equation 03 are given in Table 1.

Table 1. Thermal conductivity of material and wall (E. Ouedraogo *et al.,* 2015)

Materials	Thermal conductivity of the material ($W.m^{-1}.K^{-1}$)	Thermal diffusion (10^{-7} $m^2.s^{-1}$)	Thermal conductivity of the wall ($W.m^{-1}.K^{-1}$)
Hollow blocks (O. Coulibaly, 2011)	1.2		1.193
BTC (Clay "T')	0.556 ± 0.006	1.767 ± 0.016	0.644 ± 0.005
BTC (Clay-Paper "TP")	0.490 ± 0.004	2.360 ± 0.034	0.588 ± 0.006
BTC (Clay –Cement "TC")	0.671 ± 0.009	2.180 ± 0.023	0.742 ± 0.011
BTC (Clay-Paper-Cement "TPC")	0.588 ± 0.006	2.140 ± 0.023	0.671 ± 0.008
Joint (Cement mortar)	1.15		

Table 2 gives the global convection coefficients (he, hi) on the walls, the absorption coefficients of the building walls.

Table 2. Surface heat exchange coefficients and absorption coefficients (O. Coulibaly, 2011)

Convection coefficients ($W/m^{-2}.K^{-1}$)	Outside (he)	16.7
	Indoor (hi)	9.0
Absorption coefficients	Outside	0.6
	Indoor	0.4

The thicknesses of the different walls (envelope and partition walls) are 14 cm, those of the double face walls of the envelope are 28 cm and those of the double face walls of the envelope with insulation are 28 cm plus the thickness of the insulation.

Thermal resistance of an air gap

The insulation of the building walls can be provided by air, therefore it is essential to determine the properties of this air gap. Figures 1 and 2 show respectively an insulation diagram of a vertical wall and a rectangular and vertical air cavity heated differentially. The temperatures T_1 and T_2 of the two lateral faces are different.

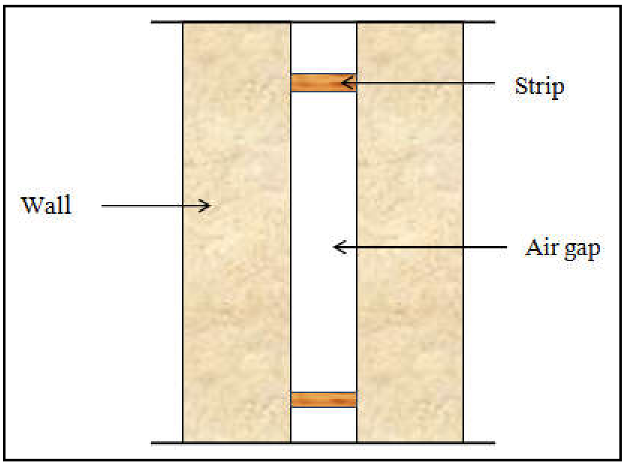

Figure 1. Insulation diagram with an air gap from a vertical wall

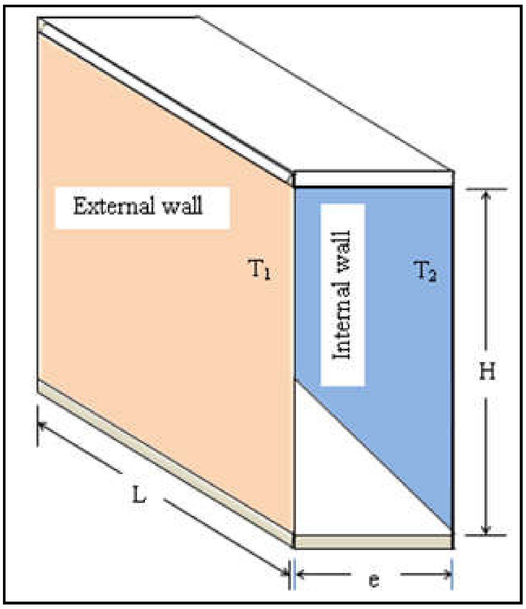

Figure 2. Differentially heated 3D cavity

For walls with unventilated (i. e. closed) or very poorly ventilated air slats, the thermal resistance of the air (R_{air}), depends on the convection movements inside the slats and the thermal radiation between the surfaces delimiting these slats.

For a thin air gap, whose width or length is greater than 10 times the thickness e (m) ,the thermal resistance is given by the equation of equation 4 (N. Morel and E. Gnansounou, 2009):

$$R_{air} = \frac{1}{h_r + h_c} \quad \text{..... (4)}$$

With: $h_r\,(W.m^{-2}.K^{-1})$ the radiation heat transfer coefficient defined by equation (5):

$$h_r = 4 \cdot \varepsilon' \cdot \sigma \cdot T^3 \quad \text{..... (5)}$$

Where: T (K) is the average of the two absolute temperatures of the two walls; σ is the Stefan-Bolzmann constant ($\sigma = 5.6696*10^{-8}$ $W.m^{-2}.K^{-4}$); ε' is a combined effective emissivity, ε' is equal to 0 if one of the two emissivities is zero, and is only one (1) if both surfaces are "black". For flat and parallel surfaces, we have equation 6:

$$\varepsilon' = \frac{1}{\frac{1}{\varepsilon_1} + \frac{1}{\varepsilon_2} - 1} \quad \text{.......} (6)$$

ε_1 and ε_2 are the emissivities of plane surfaces 1 and 2.

The convection heat transfer coefficient (h_c) is determined from the Nusselt number, given by equation 7:

$$Nu = \frac{h_c \cdot e}{\lambda} \qquad \Rightarrow h_c = \frac{\lambda \cdot Nu}{e} \quad \text{.......} (7)$$

Where: e (m) is the characteristic length or thickness between the two walls; λ $(W.m^{-1}.K^{-1})$ is the thermal conductivity of the air; Nu is the Nusselt number.

For natural convection, the Nusselt number is given by the dependence function of equation 8:

$$Nu_e = Nu_e(Ra_e, \Pr, A) \quad \text{.......} (8)$$

Where: Ra_e is the Rayleigh number; Pr is the Prandtl number, its expression is given by equation 9; $A = H/e$ is the elongation.

$$\Pr = \frac{C_p \cdot \mu}{\lambda} \quad \text{.......} (9)$$

Where: C_p $(J.K^{-1}.kg^{-1})$ is the specific heat at constant pressure, μ (Pa.s) is the dynamic viscosity.

In our study, the fluid present in the closed cavities is air. The Prandtl number can then be considered as a constant equal to 0.71. Thereafter the Nusselt number is a function only of the Rayleigh number and the elongation A, equation 10.

$$Nu_e = Nu_e(Ra_e, A) \quad \text{.......} (10)$$

Many researchers who have studied natural convection in enclosed spaces have found that problem solving integrating the results of velocity and temperature profiles within the cavity can be expressed in terms of Rayleigh number Ra, Prandtl number Pr and cavity elongation A (N. Chami, 2009). The Rayleigh number is defined by the expression of equation 11:

$$Ra_e = \frac{g \cdot \beta \cdot \Delta T \cdot e^3}{\nu^2} \cdot \Pr \quad \text{.......} (11)$$

Where: $\Delta T = T_1 - T_2$ (K) is the difference between temperatures T_1 and T_2, g $(m.s^{-2})$ is the acceleration of gravity;

$\beta = 1/T$ (K-1) is the thermal expansion coefficient and υ $(m^2.s^{-1})$ is kinematic viscosity.

Researcher Yin (S. H. Yin *et al.,* 1978) studied natural convection in a differentially heated vertical parallelepipedic cavity by experiment. The horizontal surfaces of the cavity were well insulated to ensure their adiabaticity. The correlation he developed brings together 94 % of his experimental results with a maximum deviation of 20 %. The Nusselt expression is valid for a given Rayleigh range from $1.5*10^3$ to $7*10^6$ and for an elongation that varies from 4.9 to 78.7; equation 12:

$$Nu = 0{,}23 \cdot A^{-0{,}131} \cdot Ra_e^{0{,}269} \quad \text{.......} (12)$$

The dimensionless Nusselt number depends on the nature of the convection and the orientation of the wall cavity.

As for Wright (J. L. Wright, 1996), he proposed a correlation to model thermal transfer in a vertical air cavity. This correlation is determined by several experimental results in the literature for elongations greater than 40 ($A \geq 40$) and for Rayleigh numbers less than 10^6. Wright deduced, from his study, that Nusselt no longer depends on elongation in these particular ranges of Ra and A, the Nusselt number expressions are given by equation 13, equation 14 and equation 15:

$$Nu = 0{,}0673838 \cdot Ra_e^{0{,}3} \quad 5.10^4 < \text{Rae} \leq 10^6 \quad \text{.......} (13)$$

$$Nu = 1 + 1{,}75967 \cdot 10^{-10} \cdot Ra_e^{2{,}2984755} \quad 10^4 < \text{Rae} \leq 5.10^4 \qquad (14)$$

$$Nu = 1 + 1{,}75967 \cdot 10^{-10} \cdot Ra_e^{2{,}2984755} \quad \text{Rae} \leq 10^4 \qquad (15)$$

The European standard EN 673 (EN 673, 1997), also proposes a convective exchange coefficient in a cavity. This exchange coefficient is a function of the Rayleigh number only and no validity interval for the Rayleigh number and elongation is indicated. The conditions at the boundaries of the horizontal walls delimiting the cavity are considered not important and do not influence the results of the calculation of the total exchange coefficient of the cavity. The correlation established in this standard is given by equation 16:

$$Nu = \max(0{,}035 \cdot Ra_e^{0{,}38}, 1) \qquad (16)$$

Determination of temperature profiles in the walls of buildings

Temperature propagation in a double-faced wall is obtained using the COMSOL software. For the modeling, the following boundary conditions were used:

- The outer surface of the wall is subjected to constant temperatures of 35°C and then 40°C; corresponding respectively to the average temperature value and the average value of maximum temperatures during the hot periods of the year (E. Ouedraogo, 2015);
- The exposure times are eight hours and ten hours, corresponding respectively to the average and maximum insulation (E. Ouedraogo, 2015);
- The inner surface of the wall is exposed to natural convection;
- Heat propagation is unidirectional;
- The lower and upper surfaces of the wall are assumed to be insulated;
- The thickness of the air gap is 3 cm.

RESULTS AND DISCUSSION

Thermal properties of air gaps: Figures 1 and 2 show the convective exchange coefficients and the thermal resistance of the air in the cavities with vertical walls, respectively. The results of thermal resistance take into account convective and radiative exchanges in the air gaps. The values obtained by the Yin and Wright models do not cover the entire thickness range, this is due to the conditions of each of the correlations on the elongation values A. Except for the values of the Yin correlation where we observe small differences with those of the correlation of the European standard (EN 673) between 4 cm and 8 cm, all the results are very close. The thickness of the blade has little influence on the different results when it is greater than 3 cm ($e \geq 3$ cm). We have retained the results of the European standard model for the rest of our work, as they cover the entire range of the air gap considered.

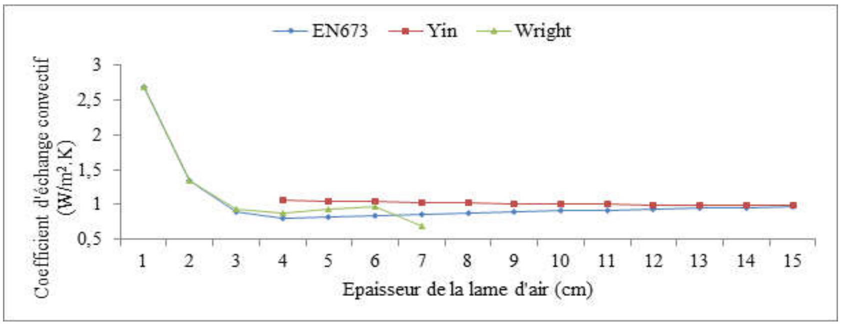

Figure 3. Convection heat exchange coefficients according to the thickness of the air gap

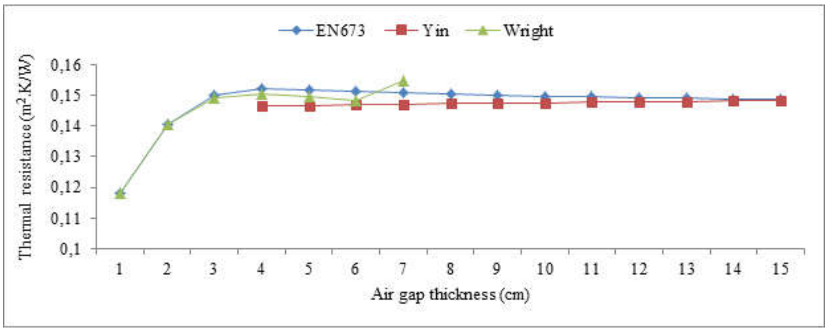

Figure 4. Thermal resistance of the air according to the thickness of the air gap

On figure 3, we notice a strong decrease in the transfer coefficients for $e \leq 4$ cm and a very slight increase beyond 4 cm for the Wright and EN 673 models. As for the coefficients of the Yin model, there is very little growth when the thickness increases. These results reflect the intensification of transfers into a cavity when the thickness of the air gap takes on increasingly smaller values (air gap thickness less than 4 cm). Indeed, the proximity of the two active walls of the cavity has an influence on the thickness of the boundary layers, which are the seats of all the transfer mechanisms. The thermal gradients are then higher and the exchanged flows are higher. We notice an increase in the values of thermal resistances for air gap thicknesses of less than 4 cm (Figure 4), and a very slight decrease beyond 4 cm. This can be explained by the fact that for thin thicknesses, conduction is the dominant thermal transfer regime, and therefore the thermal resistance and air gap thickness are inversely proportional. By increasing the thickness of the air gap beyond a certain value (in this case 4 cm), the modeling results show a decrease in thermal performance. This is due to the amplification of convection in the thicker air gap and the resulting degradation of thermal resistance.

Overall heat transfer coefficients

The surface transmission coefficients of several wall configurations and the single wall building are presented in Table 2. We have neglected the effects of thermal bridges in the calculation of coefficients. Apart from the transmission coefficients of the TC walls, which are substantially equal to those of the cement block walls, the coefficients of the other formulated materials (T, TP and TPC) are lower, so they have the best thermal performance. We can say that the temperatures inside the habitats built with these formulated materials will be lower than in a block building.

Table 3. Surface transmission coefficients of the wall and building

Wall composition	Transmission coefficients surface area of the wall (W.m^{-2}.K^{-1})
Clay (T)	22568 ± 0.038
(Clay-Paper) TP	2.448 ± 0.037
(Clay-Paper-Cement) TPC	2.623 ± 0.040
(Clay- Cement) TC	2.755 ± 0.042
Block	2.785 ± 0.042

The lowest values are obtained with clay-paper blocks (TP), however they remain high to have the required comfort inside the building. To reduce these different coefficient values, we propose to insulate the different walls with air. For this reason, we use double face walls with an air gap between the walls. We use air because it is free and available and has a very low thermal conductivity. The values of the transmission coefficients of these walls have been determined. For the double walls, we used materials with high water stability and the best mechanical resistance, namely clay-cement blocks (TC) and clay-paper-cement blocks (TPC) blocks for the external walls, and finally to solve problems due to bad weather.

Figure 5 shows the surface transmission coefficients of the double face walls according to the thickness of the air gap between the two walls (TC-TP: wall in TC and TP, TC-TP: wall in TC and T, TC-TPC: wall in TC and TPC, TC-TC: wall in TC and TPC, TPC-TP: wall in TC and TC, TPC-TP: wall in TPC and TP, TPC-TPC: wall in TPC and TPC)

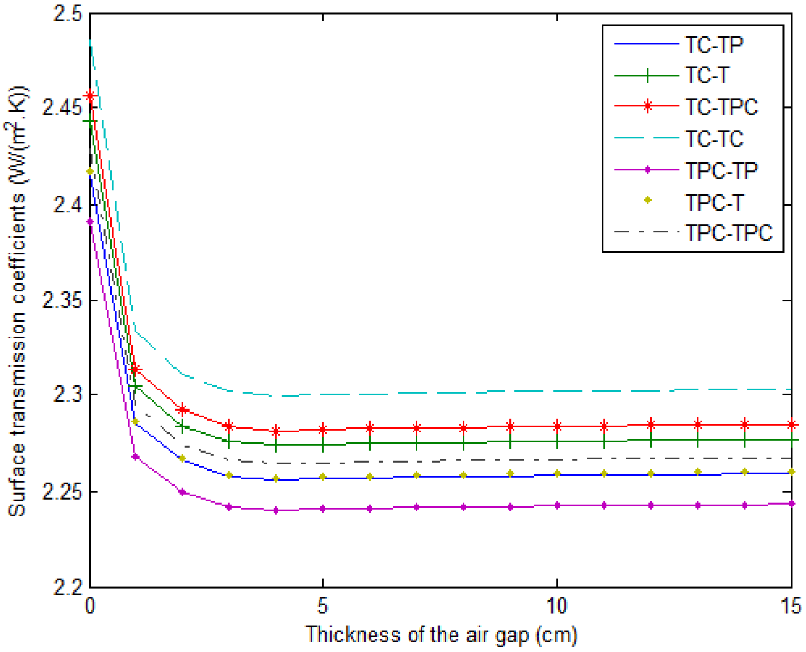

Figure 5. Surface transmission coefficients of double face walls according to the thickness of the air gap between the walls

From the different values presented in Figure 5, it can be seen that by doubling the faces of the walls, a decrease from 23.44 % to 38.75 % in the surface transfer coefficients is observed depending on the composition of the walls. The insertion between the two walls of an air gap of 1 cm thick allows a considerable reduction of the different coefficients. This decrease goes from 35.63 % to 47.48 % depending on the type of wall. These transfer coefficients decrease considerably with air gap thicknesses ranging from 0 to 4 cm and increase very slightly beyond 4 cm. This is due to the fact that the thermal resistances of the air degrade (decrease) gradually for air gap thicknesses greater than 4 cm. So for air insulation, the thickness of the air gap must not exceed 4 cm in our case. For the study of temperature profiles inside the walls, we will use a 3 cm air gap (the decrease in coefficient values varies from 38.20 % to 49.37 %).

Temperature profiles

Figure 6 shows the temperature propagation within the wall when the exterior surface is subjected to a constant temperature of 35°C for eight (08) hours

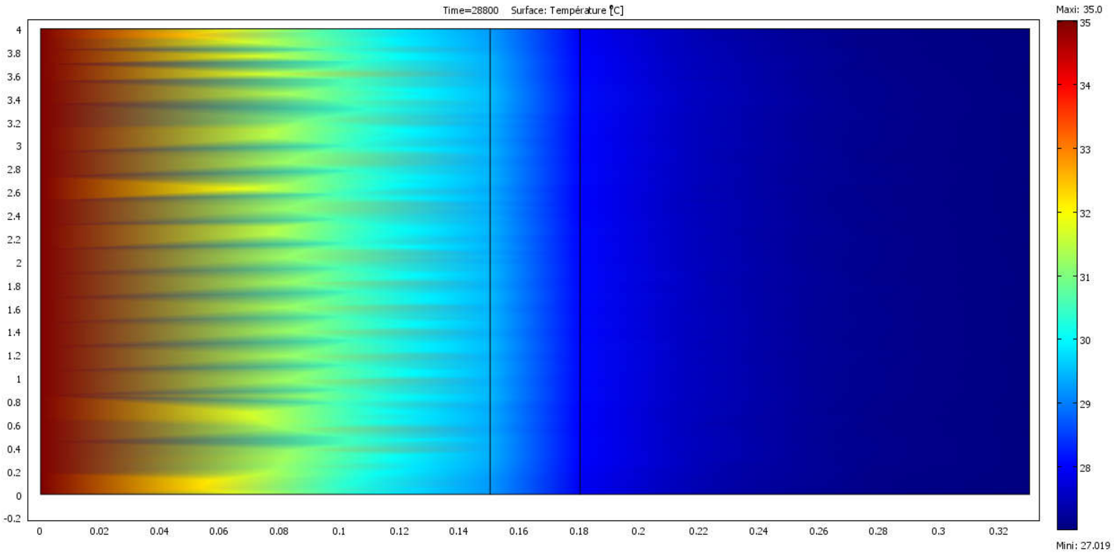

Figure 6. Temperature propagation in the exposed wall for 8 h at 35 °C

We notice that a large amount of heat is stored in the first wall (exterior wall) due to the air gap that prevents its propagation. This results in a temperature of 27 °C on the inner surface of the wall, which is a decrease of 8 °C in amplitude. This stored heat will be returned to the environment at night because the ambient temperature values are lower (below 28°C)

Figures 7 and 8 show temperature profiles in different wall types when their exterior surfaces are exposed to temperatures of 35 °C and 40 °C for eight (08) hours and ten (10) hours respectively. We considered the higher coefficient wall (TC and TC wall) and the lower coefficient wall (TPC and TP wall), all insulated walls with 3 cm air gap.

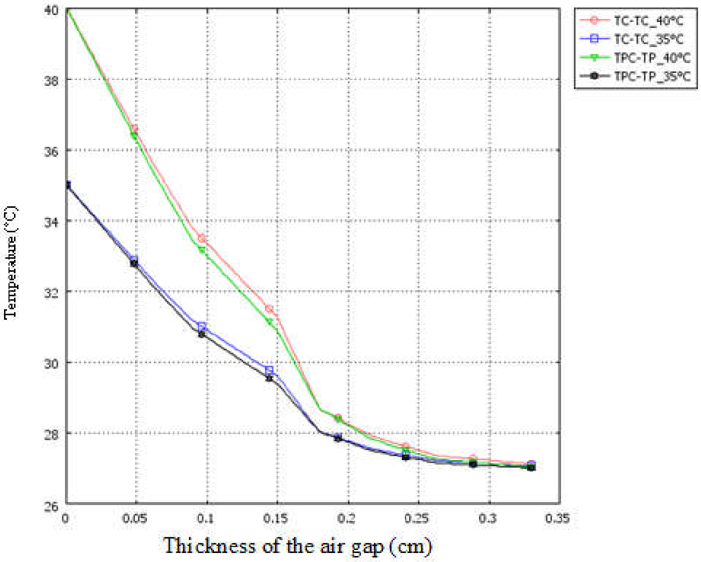

Figure 7. Temperature profiles in the exposed wall for 8 h at 35 °C and 40 °C

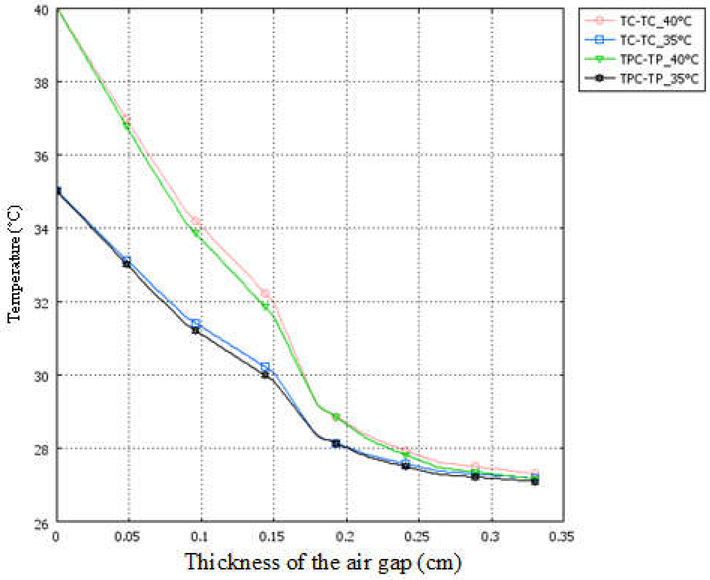

Figure 8. Temperature profiles in the exposed wall for 10 h at 35 °C and 40 °C

Figures 7 and 8 show the evolution of temperatures through the wall according to their composition and whose walls are subjected to temperatures of 35 °C and 40 °C for eight (8) and ten (10) hours respectively. We notice a decrease in the values of these temperatures and this decrease is considerable (strong) in the first wall and the air gap, with a minimum amplitude decrease of 7 °C regardless of the type of brick used (the reduction varies between 6.97 °C and 11.32 °C). However, after the air gap the reduction in temperature amplitudes varies from 0.95 °C to 1.63 °C.

This confirms the insulating nature of this air gap, which prevents heat transmission. This heat is then stored in the first wall, which will then be returned to the environment at night (night temperatures being lower); therefore, regardless of the duration (8 h or 10 h) of exposure of the outer surface of the wall and the value of the imposed temperature (40 °C or 35 °C), the temperature of the inner surface is approximately 27 °C, i.e. a decrease from 22.86 % to 32.50 %. This value is close to that of the thermal comfort setpoint temperature, which is 26 °C (O. Coulibaly *et al.,* 2015). Therefore, the air gap can be used as insulation for building walls.

Conclusion

The determination of the surface transmittance coefficients of the single-face walls shows that these values are high for achieving thermal comfort in the building. When we use double walls, we see a decrease from 23.44% to 38.75% in the values of the coefficients. To improve thermal comfort in the building by reducing their surface transfer coefficients, the double-faced walls are insulated with an air gap. The air gap is a good insulator when its thickness does not exceed 4 cm. Above 4 cm, the thermal properties of the air gap degrade. Insulating the double-faced walls with 1 cm of the air gap reduces the transfer coefficients from 35.63% to 47.48% depending on the composition of these walls (type of material). The lowest coefficient value (1.45 $W.m^{-2}.K^{-1}$) is obtained with the TPC and TP wall. The study of temperature profiles in the different wall types shows that the temperature value of the internal face is slightly below 27°C. These temperature profiles show a 22.86% to 32.50% reduction in outdoor temperature values. These walls provide thermal comfort inside the building.

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