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Modeling and Simulation of Heat Exchanges in a Habitat F1 Built With Concrete Blocks in the City of Koudougou

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ABSTRACT

In Burkina Faso, the increase in energy consumption in habitat can be expected to become even more marked, not only because of the expansion of air conditioning and the number of electrical appliances. In this work, we proceeded to a modeling and a simulation of the thermal behavior of the envelope of the habitat F1 (studio apartment) built in concrete block from the software COMSOL Multiphysics Simulation 5.3a. We have noted that the concrete block habitat has a high internal temperature (temperature above 35°C) with a low thermal phase shift of 02 hours during the hot months (March and April) of the year. Block constructions would require a very large daytime air conditioning load to keep the interior at a comfortable temperature. We can therefore say that for sustainable or bioclimatic design, the concrete block is not a material adapted to the climatic context of the city of Koudougou.

1. Introduction

The building sector ranks today among the three major consumers of energy in the world with the transport sector and that of industry [1, 2]. The share of energy consumption in the building sector amounts to 40% of world energy [2, 3]. While two out of ten people lived in cities only a century ago, it is estimated since 2008 and for the first time in the history of humanity, that the urban world population has become greater than the rural population [4]. In Africa alone, about two billion urban dwellers are expected in 2050 [4]. This situation makes it possible to predict a strong increase in urban buildings and the supply of energy, water and other services. UN-Habitat estimates that 75% to 80% of the buildings of 2050 are yet to be built. It will therefore be necessary to at least triple the capacity of the current fleet in a relatively short time frame [4]. Anticipating all these new infrastructure needs and meeting the demand for resources that will inevitably be associated with them is a major challenge for countries that are already facing major difficulties, whether in terms of access to energy, or to essential natural resources [5][6]. All these reasons militate for a different design of new habitats, which will be sober in energy, will harmoniously make use of the renewable energies (sun, wind, earth, etc.) at their disposal, using local materials while stimulating the local economy and will be resilient enough to be able to adapt to the phenomena generated by climate change [6]. The buildings must therefore be designed differently and the effort must above all aim to reduce as much as possible the quantity of energy necessary to provide high level hygrothermal, visual and acoustic comfort thanks to a well-adapted architectural design.

Thus, with the current needs for savings, energy management and environmental impacts in the building sector, a craze is emerging on how to create and maintain pleasant indoor conditions [7]. Achieving thermal comfort in buildings in developing tropical countries can be a difficult task due to difficulties in accessing conventional energy capacity, extreme environmental conditions and often comes at exorbitant cost. In Burkina Faso, a country with a hot and dry tropical climate, global warming leads us to increase our consumption in search of comfort and systematically results in the installation of air conditioning units in often poorly insulated buildings [7]. This high demand for energy in the building sector in Burkina Faso is explained by the use of imported architecture that is unsuited to our climatic context, the lack of energy considerations in the design of the building envelope, and the non-existence of energy regulations in the field of buildings.

In this context, any improvement in the thermal design of the envelope is of significant socio-economic interest [8]. An essential condition for the success of the reduction of energy consumption in the building reside in the design and quality of its envelope, hence the interest of thermal housing. Knowledge of the energy performance of the housing envelope requires the use of digital models and simulation tools which constitute reasonable means in terms of time and cost to analyze and understand the thermal behavior of housing [8].

In this manuscript, it will be a question of deepening our knowledge on the thermal behavior of the envelope of the cinderblock habitat by modeling and simulating the heat exchanges in an F1 type habitat built in the city of Koudougou.

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2. Physical model of the habitat F1

The habitat model considered refers to a habitat F1 built in cement blocks with its main facade facing south. The floor area of the building is 19.54m^2 with a height of 3.95m. The roof is made of galvanized sheet metal with a door and a window located on the main facade. The walls are made of concrete block bricks of dimensions (40cm*20cm*20cm) with interior and exterior plaster.

3. Mathematical modeling of heat exchanges in habitat F1

3.1. Diagrams of the different heat exchanges

Figure 2 shows the different heat fluxes exchanged between the different elements of the home and the outside environment.

By considering each wall assumed to have a uniform temperature as a node independent of the others, it is possible to describe the evolution over time of the temperatures of the components of the room. The law of conservation of energy imposes that the instantaneous variation of energy within any node (i) of our model is equal to the algebraic sum of the flux densities exchanged within the node [10].

3.2. Simplifying assumptions on heat transfers

To simplify our heat transfer equations, we make the following assumptions:

- Heat transfers by conduction are unidirectional;
- Air is comparable to a perfect gas, homogeneous and transparent to radiation;
- Building materials are assimilated to gray bodies;
- The thermo-physical properties of building materials are constant;
- The walls of the habitat are maintained at a uniform temperature;
- The celestial vault behaves like a black body;
- The phenomenon of condensation is negligible for this study;
- The walls do not house phase change materials, nor are they the sites of internal reactions.

3.3. Modeling of heat exchanges in the home

3.3.1. Basic transfer equations

- In the walls of the habitat (walls and roof)

The heat transfer equation in the walls is given by:

$$\rho C_p \frac{\partial T}{\partial t} + \rho C_p V \nabla T + \nabla q = Q_{rad} \quad (1)$$

With :

$Q_{rad} = \alpha I$

$q = -\lambda \nabla T$

T is the temperature of the considered wall, ρ the density, C_p the thermal capacity, V the velocity, t the time and Q_{rad} incident solar radiation.

We also have:

- $\rho C_p \frac{\partial T}{\partial t}$: the component of the energy due to the thermal inertia of the wall.
- $\rho C_p V \nabla T$: the component of heat transfer by convection due to the displacement of matter.
- $\nabla q = -\lambda \Delta T$: the component of heat transfer by conduction in the walls.
- For our study, the wall is immobile (V=0). We obtain :

$$\rho C_p \frac{\partial T}{\partial t} + \nabla q = Q_{rad} \quad (2)$$

- At the level of the internal air

The heat transfer equation in fluids is as follows:

$$\rho C_p \frac{\partial T}{\partial t} + \rho C_p U \nabla T - div(\lambda \overrightarrow{grad} T) = T\beta \frac{\partial P}{\partial t} + Q_v + \mu\phi \quad (3)$$

- Q_v : is the power density dissipated. For our case, there is no internal volume source in the room (Qv=0).
- $T\beta \frac{\partial P}{\partial t}$: is the component of the variation in energy due to the compressibility of the air. This component is negligible for our case.
- $\mu\phi$: is the dissipation due to viscous friction. It is also negligible.
- We then obtain:

$$\rho C_p \frac{\partial T}{\partial t} + \rho C_p U \nabla T - \lambda \Delta T = 0 \quad (4)$$

During the simulation, all the openings are considered closed, so no air renewal and consequently the air velocity in the cell is zero (U=0). We then obtain:

$$\rho C_p \frac{\partial T}{\partial t} = \lambda \Delta T \quad (5)$$

3.3.2. Boundary conditions

- External walls

The outer walls of the building are subject to natural convection and radiation from the celestial vault.

We obtain :

$$Q_{cv} = h_c (T_{pe} - T_{am}) \quad (6)$$

$$Q_r = \varepsilon (I - \sigma T_{pe}^4) \quad (7)$$

- Internal walls

The internal walls of the habitat are subject only to internal natural convection. The temperature difference between the different internal walls being very small, we neglect the component of the long wavelength radiation. We then have:

$$Q_{cvi} = h_c (T_{pi} - T_{ai}) \quad (8)$$

3.3.3. Detailed habitat heat transfer equations

By taking into account the simplifying hypotheses and by applying the boundary conditions to the previous equations, we obtain:

East facing wall:

- External wall

$$\rho_e C_{pe} \frac{\partial T_{ee}}{\partial t} = \lambda_e \left(\frac{\partial^2 T_{ee}}{\partial x^2} + \frac{\partial^2 T_{ee}}{\partial y^2}\right) + h_{ce}(T_{am} - T_{ee}) + \alpha_e I_e + \varepsilon_e (I_e - \sigma T_{ee}^4) \quad (9)$$

- Internal wall

$$\rho_e C_{pe} \frac{\partial T_{ei}}{\partial t} = \lambda_e \left(\frac{\partial^2 T_{ei}}{\partial x^2} + \frac{\partial^2 T_{ei}}{\partial y^2}\right) + h_{caie}(T_{ai} - T_{ei}) \quad (10)$$

West facing wall

- External wall

$$\rho_o C_{po} \frac{\partial T_{oe}}{\partial t} = \lambda_o \left(\frac{\partial^2 T_{oe}}{\partial x^2} + \frac{\partial^2 T_{oe}}{\partial y^2}\right) + h_{co}(T_{am} - T_{oe}) + \alpha_o I_o + \varepsilon_o (I_o - \sigma T_{oe}^4) \quad (11)$$

- Internal wall

$$\rho_o C_{po} \frac{\partial T_{oi}}{\partial t} = \lambda_o \left(\frac{\partial^2 T_{oi}}{\partial x^2} + \frac{\partial^2 T_{oi}}{\partial y^2}\right) + h_{caio}(T_{ai} - T_{oi}) \quad (12)$$

Roof:

- External wall

$$\rho_t C_{pt} \frac{\partial T_{te}}{\partial t} = \lambda_t \left(\frac{\partial^2 T_{te}}{\partial x^2} + \frac{\partial^2 T_{te}}{\partial y^2}\right) + h_{ct}(T_{am} - T_{te}) + \alpha_t I_t + \varepsilon_t (I_t - \sigma T_{te}^4) \quad (13)$$

- Internal wall

$$\rho_t C_{pt} \frac{\partial T_t}{\partial t} = \lambda_t \left(\frac{\partial^2 T_t}{\partial x^2} + \frac{\partial^2 T_t}{\partial y^2}\right) + h_{cait}(T_{ai} + T_t) \quad (14)$$

Internal air

$$\rho_a C_{pa} \frac{\partial T_{ai}}{\partial t} = \lambda_a \left(\frac{\partial^2 T_{ai}}{\partial x^2} + \frac{\partial^2 T_{ai}}{\partial y^2}\right) + h_{aie}(T_e - T_{ai}) + h_{aio}(T_o - T_{ai}) + h_{ait}(T_t - T_{ai}) + h_{aip}(T_p - T_{ai}) \quad (15)$$

Table 1 gives the thermal and physical properties of the previous materials.

Table 1. Thermal and physical properties of materials of habitat [11] [12] [13] [14]

Materials	Density (kg m^{-3})	Thermal conductivity (W m^{-1} K^{-1})	Thermal capacity (J kg^{-1} K^{-1})
Air	1.250	0.023	1000
Cement block	1000	0.83	1000
Roof	7800	50	450

4. Numerical simulation of heat exchanges on COMSOL Multiphysics

4.1. Comsol Multiphysics 5.3a User Interface Overview

Figure 3 describe the COMSOL Multiphysics 5.3a user interface.

The COMSOL Multiphysics 5.3a user interface is divided into four parts (See Figure 3). On the left there is the Model builder part (1) in which the problem is defined. It is the place of definition of the parameters and variables, the geometry, the construction materials used as well as the physical laws applied to the problem. Column (2): Settings is used to enter data relating to the options selected in the Manufacturer model. At the top right, there is the Graphics display interface (3) which allows you to view the geometry, the mesh or the results. Below the graphic display window, a window (4) is used to view any error messages, the progress of the simulations as well as the numerical results obtained.

4.2. Model mesh and computational convergence

The COMSOL Multiphysics 5.3a software offers different types of meshes (ranging from "extremely coarse" to "extremely fine"). Our model is made under the sequence: Mesh controlled by physics. During the simulation we varied the mesh going from normal to extremely fine, but the influence on the results obtained is negligible, only the resolution time increases. We therefore chose the extremely fine mesh (figure 4). It consists of 20 point elements, 1102 border elements and 6418 volume elements.

The computational convergence is of the order of 2.10^{-3}.

5. Results

5.1. Weather conditions

For the thermal simulation of our habitat, we used a number of climatic data such as ambient air temperature, relative humidity and solar radiation for the city of Koudougou. These data were obtained from the online software PVGIS. PVGIS is software for estimating the solar resource and the production of photovoltaic systems.

Figures 5 and 6 represent the evolution of the ambient air and internal air temperatures of our F1 type cinderblock habitat during the hot months (March and April) and Figures 7 and 8 for the cold months (January and December).

From figures 5, 6, 7 and 8, it can be seen that during the periods (0h to 6h) and (19h to 23h) the temperature of the internal air is higher than the temperature of the ambient air. The process is reversed during the day (6 a.m. to 7 p.m.) and the temperature of the ambient air again becomes higher than that of the internal air under the effect of the solar flux which heats the ambient air. The maximum ambient air values during the warm months are respectively 40.45°C (for April 15 at 2 p.m.) and 39.75°C (for March 16 at 2 p.m.). During the cold months, we obtain 34.25 (for December 10 at 2 p.m.) and 30.75°C (for January 17 at 12 p.m.). Similarly, the maximum values of the internal air temperature during the warm months are 36.34°C (for April 15 at 4 p.m.) and 34.91°C (for March 16 at 4 p.m.). During the cold weather, we have an internal air temperature of 26.66°C (for January 17 at 3 p.m.) and 28.75°C (for December 10 at 3 p.m.). These results are in agreement with those obtained by A. O. Fati [5] who obtained a temperature of 37°C for April 15. These values (36.34°C and 35°C) are very high, which shows that the concrete block building is uncomfortable during the hot months of the year in the absence of a cooling system and therefore unsuitable for hot climates.

5.2. Temperature isovalues and heat flow arrows

Figure 9 represents the isovalues and the arrows of the heat fluxes of the habitat.

We observe in the figure 9 that the isovalues are tighter at the level of the walls of the envelope (wall, roof and floor) than in the middle of the building. This shows that there is more temperature variation at the habitat envelope and that in the middle the air temperature is uniform. It is also noted that the arrows indicating the propagation of heat are more visible than at the level of the walls and the roof. This explains why in the building the heat comes particularly from the walls and the roof. The share of the floor is therefore negligible.

By increasing the magnification of the display (Zoom), the following figures 10 and 11 are obtained.

Figure 10 shows that the arrows indicating the propagation of heat flows start from 15cm in the wall when counting from the outside to the inside. This shows that most of the wall has a temperature substantially equal to the external temperature.

Figure 11 shows that the roof is also a major vector of heat flow in the home. For the case of the floor, there are small arrows directed towards the interior of the habitat. These small arrows indicate that there is a heat flow between the floor and the internal air, but this flow is very weak and therefore negligible.

We also note that in figures 9 and 10 the isotherms are much more deformed in the wall at the level of the thermal bridges. This explains why the thermal flux is greater at the level of the thermal bridges than at the rest of the housing envelope. As a result, there is a large influx of heat into the habitat from these points.

The simulation results are recorded in Table 1.

The thermal phase shift observed during these two hot and cold months of the year is very low (between 1 hour and 3 hours) with a thermal wave damping factor of around 28.82% for the month April, 26.67% for the month of March, 36.94% during the month of January and 33.13% for the month of December. These results are in conformity with those obtained by A. O. Fati [7] who obtained a phase shift of 1 hour also for the cinderblock habitat during the month of April. This result shows that the thermal inertia of the cinderblock is very low, which would be the cause of the overheating effect in the block dwellers.

We also calculated the degrees of cooling for the two hot months of the year by applying the COSTIC or energy professional method. The maximum and minimum temperature values are taken inside the home. We then obtain the values of 6.26°C/day and 7.68°C/day respectively for March 16 and April 15 (see Table 1). These values correspond to those obtained by A. O. Fati [7] who obtained a value of 6.7°C/day for the month of April. These values remain high and therefore the cinder block habitat requires a very high air conditioning load during the hot months of the year.

Table 1. Summary of simulation results

Month	Tmax(°C) internal	Tmin(°C) internal	Tmax(°C) external
March	34.91	27.96	39.95
April	36.34	30.78	40.45
January	26.66	21.46	30.75
December	28.75	21.56	34.25
Month	**Phase shift (hour)**	**Damping (%)**	**DJR at base (27°C)**
March	02	26.27	6.26°C/jour
April	02	28.82	7.68°C/jour
January	03	36.94	-
December	01	33.13	-

6. Conclusion

In hot tropical countries such as Burkina Faso, the current trend of "modern" and "fashionable" construction: sheet metal as roofing material, concrete blocks and mortar for walls, all combined with the lack of thermal regulations has relayed the principles of energy efficiency in the background. This state results in an overconsumption of energy in order to satisfy the comfort of the occupants in countries where the energy question is central. The construction of new buildings with high environmental quality and high energy performance is therefore a major challenge today and in the short, medium and long term. In order to make our contribution to the search for energy efficiency and thermal comfort in buildings in Burkina Faso, we have undertaken in this work, an evaluation of the performance of cinder block habitats through simulation. It then emerges at the end of this work, that the cinderblock habitat has a high internal temperature (temperature above 35°C) with a low thermal phase shift of 02 hours during the hot months (March and April) of the year. This rise in internal temperatures during the day would explain the high temperatures observed in concrete block constructions in hot tropical environments. In addition, the calculation of cooling degree days shows that for continuous occupancy during warm months, block constructions would require a very large daytime air conditioning load to keep the interior at a comfortable temperature. From the above, we can therefore say that for sustainable or bioclimatic design, the cinder block is not a material adapted to the climatic context of the city of Koudougou.

In short, other studies oriented towards taking into account natural ventilation in freely evolving buildings, the behavior of occupants and their expectations in terms of thermal comfort appear to be interesting subjects for further research.

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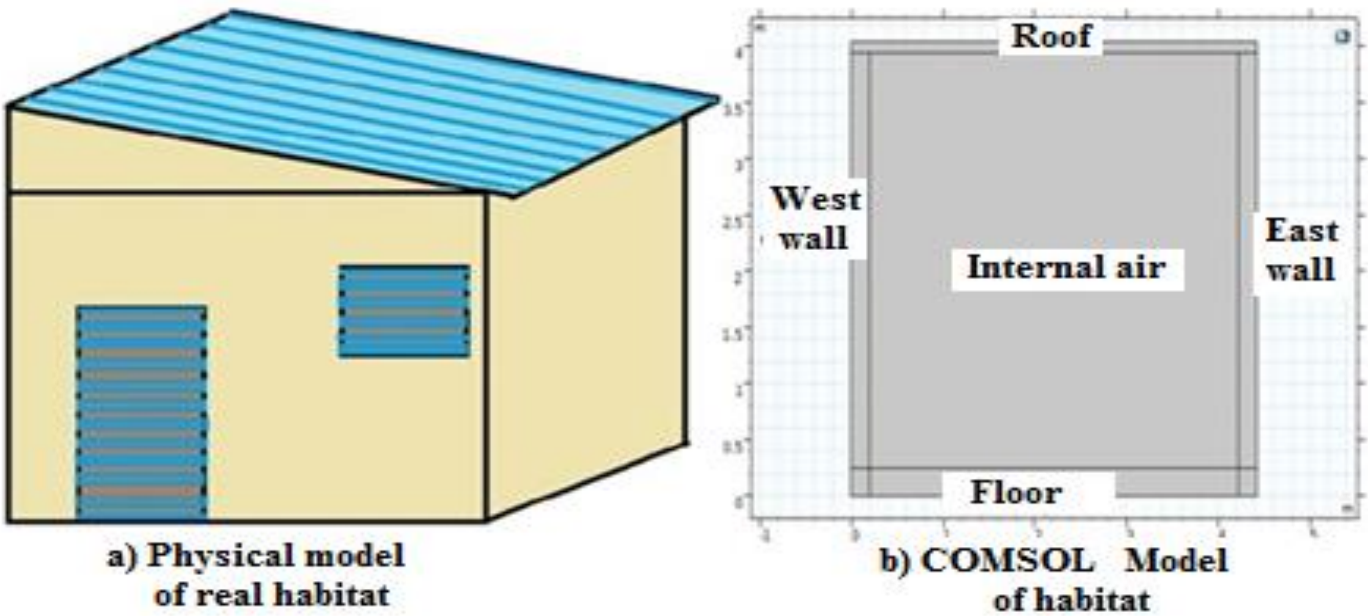

Figure 1. **Physical model of the habitat F1**

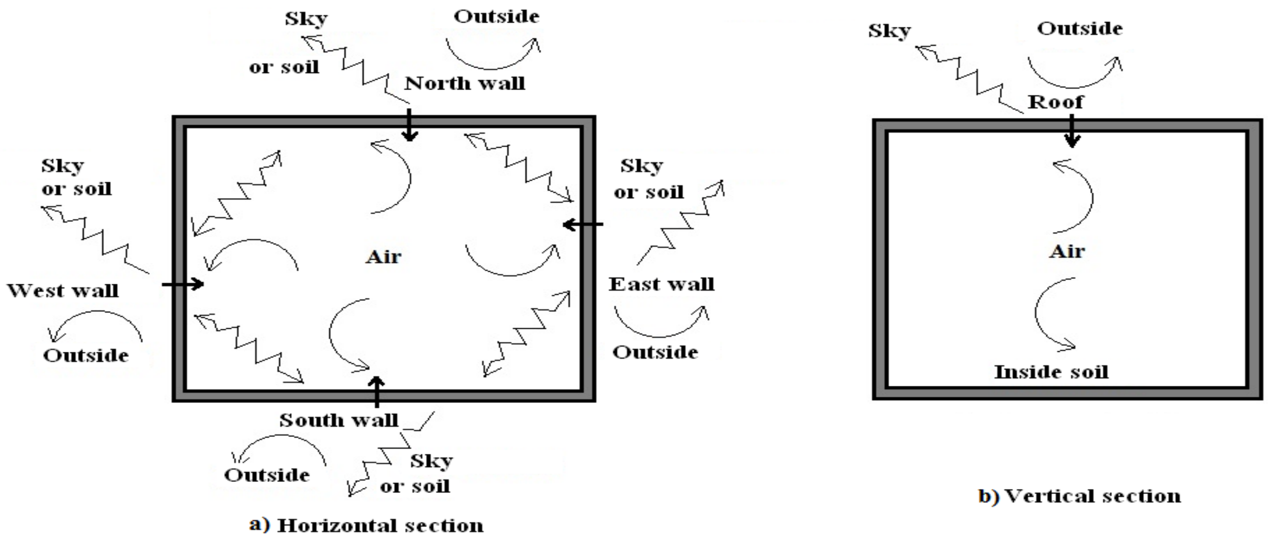

Figure 2. Diagrams of the different heat exchanges in the habitat [9]

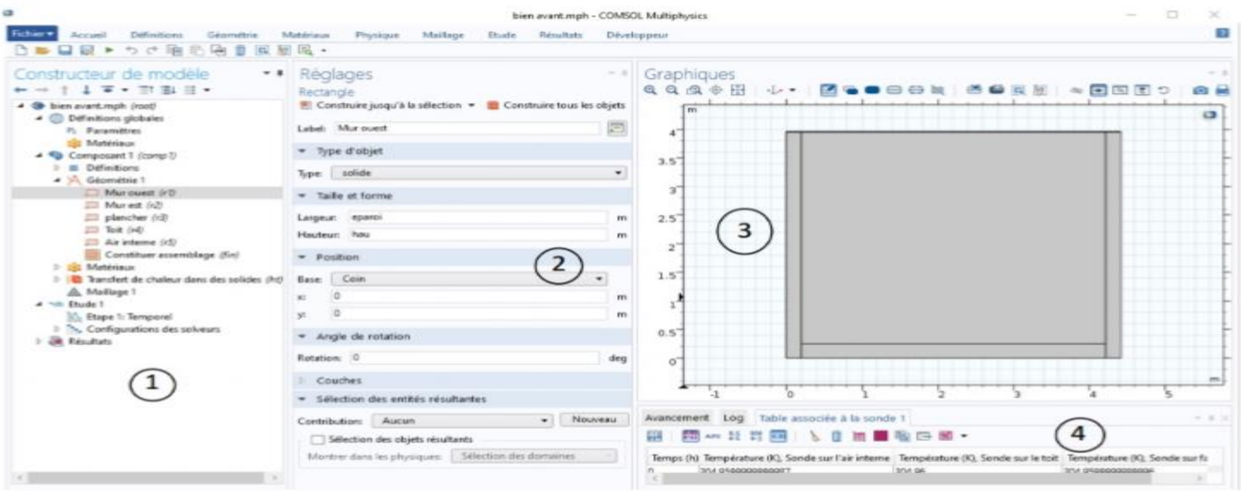

Figure 3. COMSOL Multiphysics 5.3a User Interface

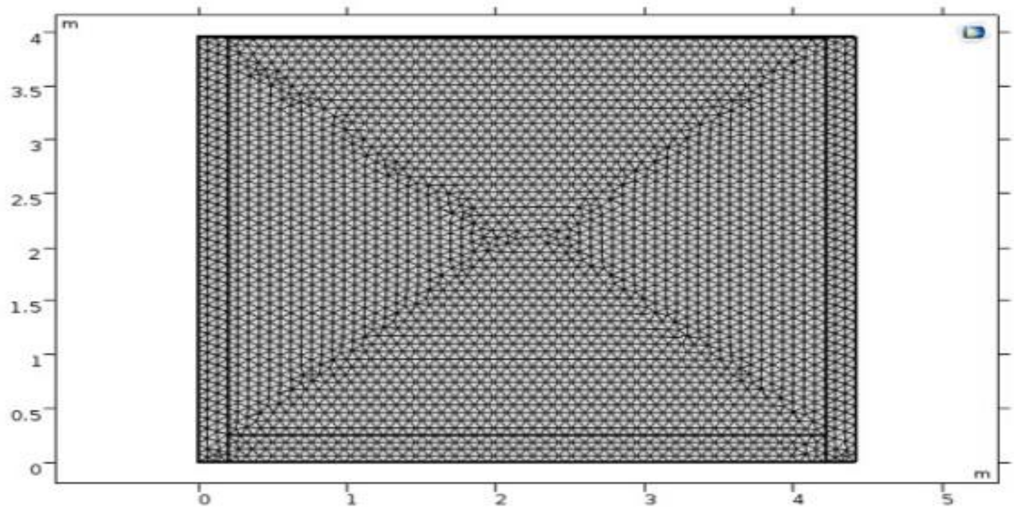

Figure 4. Meshing With COMSOL Multiphysics 5.3a

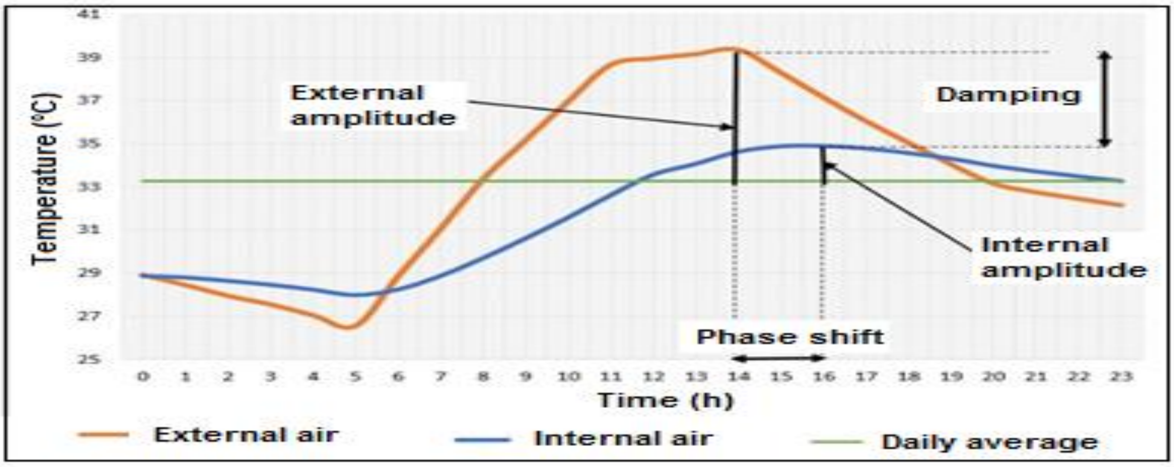

Figure 5. Evolution of temperatures for March 16, 2009

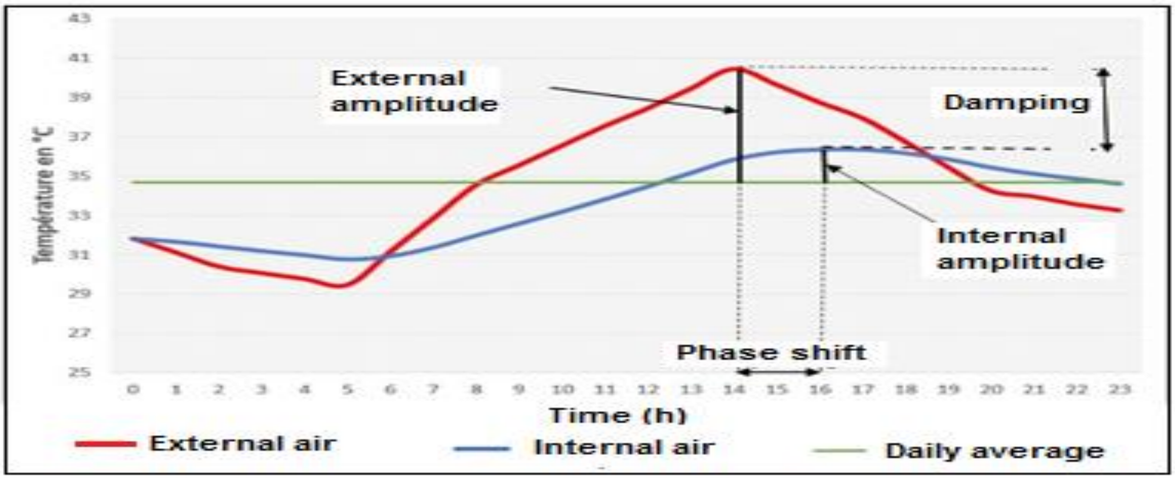

Figure 6. Evolution of temperatures for April 15, 2010

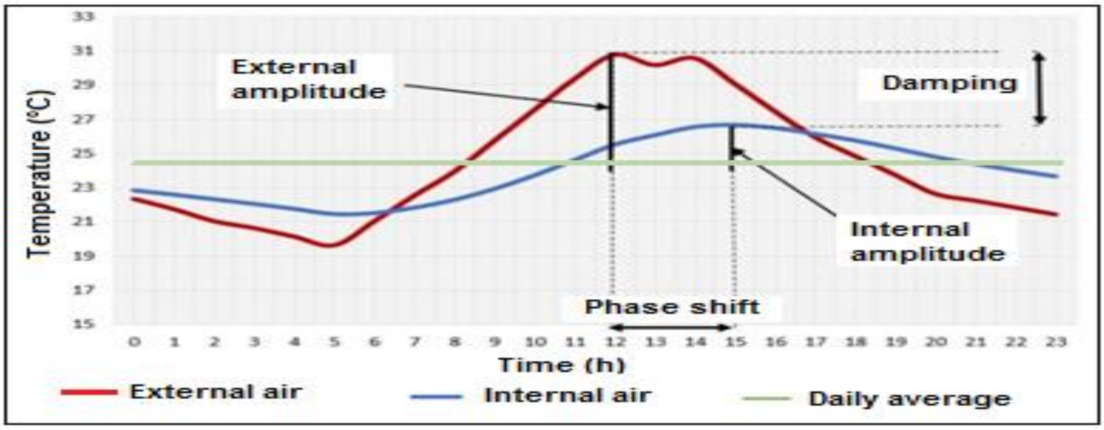

Figure 7. Evolution of temperatures for January 17, 2008

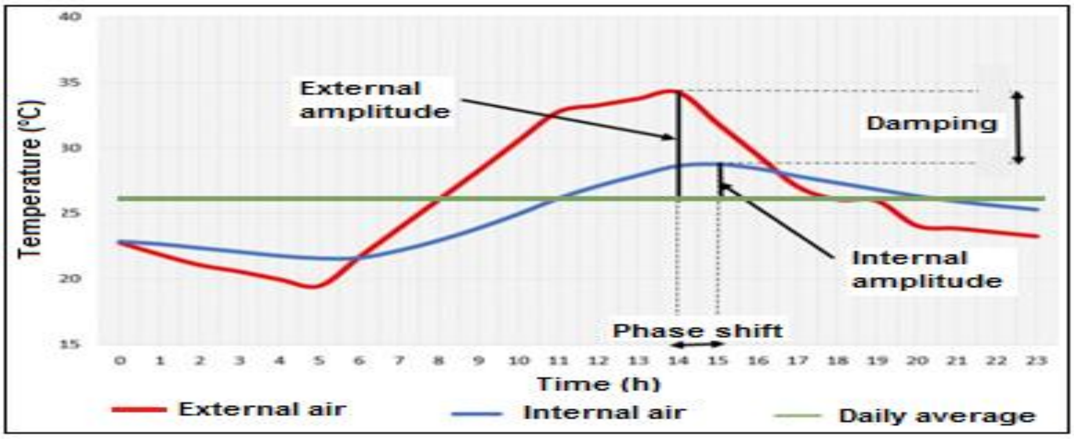

Figure 8. Evolution of temperatures for December 10, 2008

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