THERMODYNAMIC BEHAVIOR OF A HABITABLE ENCLOSURE LOCATED ON THE ADRAR SITE

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Abstract, In this modeling context, the habitable envelope is considered as a set of parallelepiped air volumes limited by horizontal and vertical flat walls, the walls are thermally coupled by convection and radiation around each zone and are the seat of conductive flow. The walls are the only capacitive elements of the habitat. The external faces of the habitat are the seat of a convective flow with external air and irradiative exchanges with the environment (soil, neighboring buildings,). Openings (cracks, joint defects, infiltration openings, renewal openings,) allow the air to circulate inside the habitable envelope and between the inside and the outside. Thermal exchanges are studied from thermal balances established at each component of the enclosure. These equations have been discretized by an implicit finite difference method. The numerical resolution of the obtained systems is done using the nodal method in a one-dimensional case and the Gauss algorithm. We have analyzed for the climatic conditions of the ADRAR region the effect of the external ambient temperature and the geographical orientation of the habitable envelope on the distribution of the solar flow at the walls.

Keywords: Radiation, habitable envelope, nodal method, heat exchange, finite differences, ADRAR.

1. Introduction

More than a third of the energy consumed and greenhouse gas emissions into the atmosphere are caused by the building sector. The latter thus plays a big role in the fight against global warming and it is imperative to improve its energy efficiency, which requires an excellent understanding of the thermal behavior of buildings [1]. However, buildings are designed to act as a thermal filter to recreate an internal microclimate independent of external weather fluctuations. The shape, orientation, arrangement and composition of the components determine the characteristics of this filter. As the inside environment does not always meet the requirements of occupant comfort, the response of the building is corrected by air conditioning units acting as controlled sources of heat or cold and sometimes having an effect on humidity rates [2].

The standards of comfort are still relatively frustrating: an average temperature set point to be respected during the heating period, a temperature that should not be exceeded en during the warm season. These constraints are sometimes refined in detailed specifications, in too of particular in the case of buildings for individual use [3]. In addition, models describing the thermodynamic behavior of buildings provide a better understanding and design of the passive envelope which allow on one hand to obtain lower energy consumption and greater comfort, and on the other hand to predict the buildings response under extreme situations in order to size facilities and, finally, to assist in the development of new systems or control strategies [2].

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The determination of energy consumption in a building may be limited to mass and energy balances, although knowledge of the temperature field and the trend of air movement are necessary for further study [5]. Moreover, these data allow evaluating the comfort of the occupants (problems of renewal of air, strong temperature gradients, air currents, stratification)

On the other hand, the building is a complex system where many physical phenomena intervene which is usually translated by equations solved using numerical methods. This approach consists in developing models that contribute closely to the development of knowledge and the phenomena quantification. The most well-known model, particularly applied in the building field, is certainly that of Joseph Fourier [6,7]. It characterizes the transfer of heat by conduction in a solid medium. The first motion for resolution, suggested by Joseph Fourier himself, is based on the method of separation of variables. Since this first wall model, Joseph Fourier's experiments on the conduction of iron rings have been replaced by follow-ups of the thermal behavior of whole buildings [7].

The choice of Adrar region is based on the fact that Algeria in particular and the countries of North Africa in general have a great solar potential [8,9]. Solar irradiation rates by satellites of the German Space Agency show exceptional levels of sunshine of the order of 1200 kWh/m^2/year in the northern Great Sahara. On the other hand, the best solar irradiation rates in Europe are of the order of 800 kWh/m^2/year limited to the southern part of Europe [10]. Following a satellite assessment, the German Space Agency concluded that Algeria represents the largest solar potential of the entire Mediterranean basin, i.e. 169,000TWh/year for solar thermal, 13,9TWh/year for the solar photovoltaic and 35TWh/year for wind power. This renewable energy presents currently an adequate solution to the global environmental problems and greenhouse gas emissions that threaten the entire planet. Indeed, it is a sustainable solution to the current energy crisis, with the rise of oil barrel prices. This puts renewable energies (hydraulic, wind, photovoltaic, solar thermal, geothermal, biomass, biogas and fuel cells) at the center of debates on the environment and, more generally, sustainable development.

The concern for rationalizing the use of expensive energies and to design more comfortable buildings has led the various actors in the design and management of buildings to seek better knowledge and control of behavior based on energy optimization of geometric and thermal parameters [4]. In this context, this work is devoted to the development of calculation methods allowing modeling the buildings in order to analyze the evolution of its thermal behavior and to foresee the consequences resulting to the response to the excitations applied by its natural climatic environment and the thermal requirements that we must take into consideration [2].

2. Modeling Study

2.1. Climate Data

In order to assess the energy performance of the building, meteorological data corresponding to a typical year are usually used. This data was used as a reference to compare the behavior of one building to another. These data are usually measured with a one-hour step, but it is possible to have the finer meteorological data, up to the minute [11].

The city of Adrar is located in the south-east of Algeria, about 1540 km from Algiers. The region is characterized by its relatively flat topography, as well as desert geomorphology. In addition, it is characterized by low winter temperatures, high summer temperatures, high sand winds and low atmospheric humidity [12]. The station for measuring climate data (table 2) is placed at the Renewable Energy Research Unit in the Saharan Environment of ADRAR (URERMS), its geographical coordinates are 27 °, 88'N and -0.27'E, with an altitude of 263m [13].

The available measurements are hourly measurements made during the year 2014 (24 hours per day, 7 days a week). They made it possible to plot the daily variations of the internal and external mean temperatures and the incident solar flux on the walls of the habitable enclosure.

Table 1. Climatic data of Adrar region [13].

Year 2014	June	July	August
Flux_Max (W/m^2)	1052	**1051**	1040
T_{Max} (°C)	42.2	**47.8**	47.7
T_{Min} (°C)	25.6	**32.5**	39.0
Duration of day (h)	14	**14**	13
Sunrise (h)	5	**5**	6
Sunset (h)	19	**19**	19
Wind speed (m/s)	6.8	**5.8**	6.0

2.2. Description of Modeling Element

In the ADRAR region, reinforced concrete is the most widely used building material lately due to civilization and because of its rigidity and long life. Figure 1 is a schematic view of a real habitable enclosure that was built by the following elements:

- The exterior walls of the building are constructed using 15 cm thick concrete hollow blocks coated on both sides with a 2.5 cm cement layer.
- The floor is placed on a solid and flat ground with a thickness varying between 10 to 30 cm [14,15]. It is poured directly on the ground. The platform is made of sand, concrete and tiles.
- The roof is composed of hollow concrete bricks, concrete slabs, sand and mortar cement in such a way that the foundations support the loading and shocks.

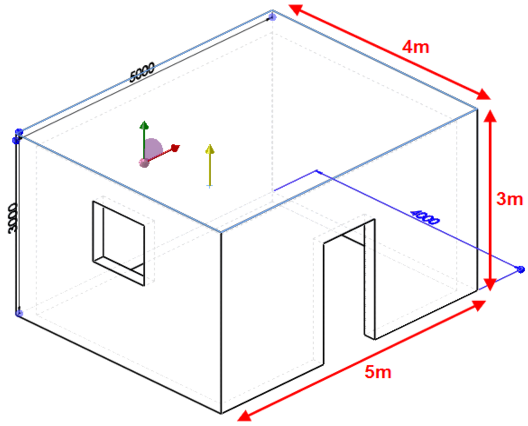


Figure. 1. Descriptive plans of the habitable enclosure constructed in Adrar region.

2.3. Modelling of Thermal Transfer Phenomena

In the domain of building energy, predictive numerical models have become, in a few years, highly used tools [16]. Thus, simulation models have been developed primarily to meet building envelope sizing needs. These models only concern the thermal exchanges between the ambient and the external facades and the internal ambient with the internal facades of the building walls. In addition, the stratification of the air in an area, the influence of wind on air infiltration, the diffusion of water in the walls, the effect of humidity variations, the changes in state and Latent heat storage are not addressed in this study. Hence, it is exclusively the envelope that is studied under isotropic conditions. The followed method aims to ensure mastery of basic assumptions and equations and to develop associated modeling aspects (radiation, convection and conduction) [16]. We used the one-dimensional nodal method for the discretization of the energy balances equations which govern these thermal exchanges in the building. The system of algebraic equations thus obtained has been solved by Gauss algorithms.
The proposed mathematical model is based on certain assumptions which can be summarized as follows:

- Thermal transfers through the walls are assumed to be unidirectional and perpendicular to these walls.
- The temperature distribution on the exterior and interior surfaces of the walls is uniform. Therefore, mathematical models will only deliver the average temperatures of the air and walls.
- Modeling is based on the concept of the typical day (Table 2).
- Convection is natural (free) and the flux is laminar.
- The door and the window are assumed to be perfectly closed.
- The heating floor temperature ranges from 18 °C to 28 °C.
- The seventeenth day of July was chosen as a typical day for 2014.
- The outside ambient temperature is equal to the soil temperature $T_{amb} = T_{sol}$.
- It is assumed that the brick is full.

It is worth noting that we have neglected obstacles such as: the cloud, neighboring buildings and trees to be in accordance with the model of Liu & Jordan [17] used in this study. Noting that Campbell & Norman [18] also considered only blue and cloudless skies when calculating the various components of solar radiation. In addition, the solar radiation measurements provided by the Renewable Energy Research Unit in the Saharan environment of ADRAR were carried out in an habitable enclosure located in a desert zone with almost the same conditions mentioned above.
Indeed, this method of calculation of solar radiation, proposed by Lui and Jordan, assumes that there is in each month of the year, a typical day or "average day" monthly [22]. In Table 2, we give the numbers of a few typical days in the year starting from January 1, in order to calculate the declination of the sun in the sky and the correction of time.

Table 2. Typical days [19, 20].

Month	''J'' of the month	Typical day	''N°'' Days in the year
June	6	12	163
July	**7**	**17**	**198**
August	8	16	228

Figure 2 shows the different modes of heat transfer at the level of each wall of the habitable enclosure assimilated to a parallelepiped cavity.

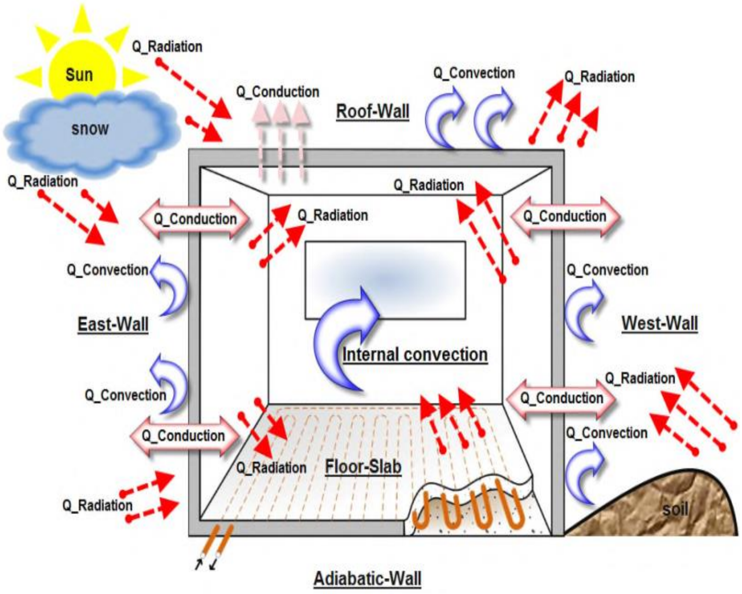


Figure 2. Descriptive of the various modes of heat exchange for the habitable enclosure studied.

The outer wall of the habitat is the seat of an irradiative exchanges with, on one hand, the celestial vault, and on the other hand, the ambient environment, in particular the soil. The coefficient for determining this transfer is deduced from the following relation [21]:

$$h_{rciel} = \frac{\sigma \times \left(T_{ciel} + T_i\right) \times \left(T_{ciel}^2 + T_i^2\right)}{\frac{1-\varepsilon_{ciel}}{\varepsilon_{ciel}} + \frac{1}{F_{iciel}}} \quad et \quad T_{ciel} = 0.0552 \times T_{amb}^{1.5} \tag{1}$$

Heat exchange between the outer face of the wall and the ambient air is mainly due to wind and it is characterized by the heat transfer coefficient [22, 23]:

$$h_{cv\_ext} = 5.67 + 3.86 \times V_{wind} \tag{2}$$

By considering each wall as an entity independent of the others, it is possible to describe the evolution over time of the thermal transfers in each wall.
In general, the instantaneous variation of the energy within a wall (i) of the model studied is equal to the algebraic sum of the flux densities exchanged with this wall.
The energy balance of the walls of the habitable enclosure is determined by the following government equation [21, 24]:

$$\frac{m_i \times Cp_i}{S} \times \frac{\partial T_i}{\partial t} = DFSA_i + \sum_{i=1}^{n} \times \sum_{x} \varphi_{x_{ij}} \tag{3}$$

where:
$\varphi_{x_{ij}}$ [W.m^{-2}]: Density of heat flux exchanged by the transfer mode x (conduction, convection or radiation) between the media (i) and (j).
$DFSA_i$ [W.m^{-2}]: Density of solar flux absorbed by material (i)

$$DFSA_i = \alpha_i \times \varphi_i \tag{4}$$

φ_i [W.m^{-2}]: Density of solar flux captured by the medium surface (i).
By introducing an exchange coefficient $h_{x_{ij}}$ and by linearizing the transfers, we can write:

$$\varphi_{x_{ij}} = h_{x_{ij}} \times \left(T_j - T_i\right) \tag{5}$$

Thus equation (3) can be written as:

$$\frac{m_i \times Cp_i}{S} \times \frac{\partial T_i}{\partial t} = DFSA_i + \sum_{i=1}^{n} \times \sum_{x} h_{x_{ij}} \times \left(T_j - T_i\right) \tag{6}$$

with :
$DFSA_i$: Density of solar flux absorbed $\sum \phi_{abso}$.
$\sum^{n} \times \sum h_{x_{ij}} \times \left(T_j - T_i\right)$: Density of solar flux emitted $\sum \phi_{emit}$.
So we can write:

$$m_i \times Cp_i \times \frac{dT_i}{dt} = \sum Q_{abso_{(i)}} - \sum Q_{emit_{(i)}} \tag{7}$$

We will then apply equation (7) to the various environments of our system. Consequently,, the establishment of a thermal balance at each node of the network associated with the habitat model leads to the following transfer equations [25]:

- **Thermal transfer balance at the external south facade**

$$m_{SW} \times Cp_{SW} \times \frac{dT_{ESW}}{dt} = \sum Q_{absorbed(ESW)} - \sum Q_{issued(ESW)} \tag{8}$$

$$\frac{m_{SW} \times C_{Pc}}{S_{SW}} \times \frac{T_{ESW}^{t+\Delta t} - T_{ESW}^{t}}{\Delta t} = h_{Conv} \times \left(T_{A1}^{t} - T_{ESW}^{t+\Delta t}\right) + \frac{\lambda_c}{e_{SW}} \times \left(T_{ISW}^{t+\Delta t} - T_{ESW}^{t+\Delta t}\right) + h_{r-HV.ESW} \times \left(T_{HV}^{t} - T_{ESW}^{t+\Delta t}\right) + h_{r-ground.ESW} \times \left(T_{ground}^{t} - T_{ESW}^{t+\Delta t}\right) + \alpha_c \times DTFS \tag{9}$$

- **Thermal transfer balance at the external west facade**

$$m_{WW} \times Cp_{WW} \times \frac{dT_{EWW}}{dt} = \sum Q_{absorbed(EWW)} - \sum Q_{issued(EWW)} \tag{12}$$

$$\frac{m_{WW} \times C_{PC}}{S_{WW}} \times \frac{T_{EWW}^{t+\Delta t} - T_{EWW}^{t}}{\Delta t} = h_{Conv} \times \left(T_{A1}^{t} - T_{EWW}^{t+\Delta t}\right) + \frac{\lambda_C}{e_{WW}} \times \left(T_{IWW}^{t+\Delta t} - T_{EWW}^{t+\Delta t}\right) + h_{r-HV.EWW} \times \left(T_{HV}^{t} - T_{EWW}^{t+\Delta t}\right) + h_{r-ground.EWW} \times \left(T_{ground}^{t} - T_{EWW}^{t+\Delta t}\right) + \alpha_C \times DTFW \tag{13}$$

- **Equation of inertia**

The inertia capacity of a material measures its ability to store heat and postpone its restitution [23]. It is given by the following relation:

$$C_{inertia(i)} = \rho_i \times e_i \times S_i \times Cp_i \tag{16}$$

3. Results and discussions

3.1. Modeling the ambient temperature and global solar flux

The model of Liu and Jordan (1960) [26] is a model which assumes that the sky is isotropic and the diffuse radiation intensity of the sky is supposed to be uniform throughout the celestial vault. This method assumes that each month of the year is represented by a typical day of the month. This means that every day of this month is identical to this day. Indeed, the model is a statistical study of real weather data in order to estimate the hourly component of the global diffuse sky radiation on an inclined plane. For this model, it is sufficient to know the value, on an average monthly, of the global daily radiation collected by a horizontal plane [27-28].

The equations of Liu and Jordan's model were numerically encoded using a FORTRAN program to facilitate calculations. Figure 3 shows the direct and the diffuse component of the global solar flux density (FSG) in a true solar time in order to derive the maximum energy received at any point of the typical day (July 17, 2014). Indeed, for a perfectly sunny day in the absence of any reflective surface and mask, we note that the values which shown in Figure 3 therefore have no meaning only in instantaneous power density of the hourly solar flux. It can also be seen that, for any value of global solar flux density (FSG) for a given month, there must be a direct solar flux component (RDIRH). In addition, the range of hourly values of the direct flux component is a little smaller than the range of hourly values of the global flux component (FSG). We also note that the diffuse solar flux density (RDIFH) has values even smaller than those of the direct solar flux (FSG).

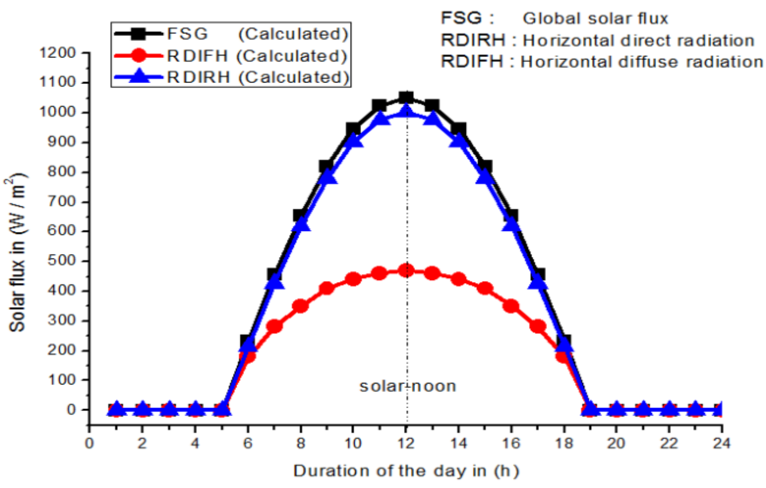


Figure. 3. Hourly evolution of the global solar flux densities, direct and diffuse on the horizontal plane of the typical day.

The hourly variations of the global solar flux and the outside air temperature of the region considered are expressed by means of two periodic functions written in a sinusoidal form as follows:

$$q(t) = q_{\max} \times \sin\left[\frac{\pi}{\Lambda} \times (t - t_s)\right] \tag{17}$$

$$T_0(t) = \frac{T_{0\max} + T_{0\min}}{2} - \frac{T_{0\max} - T_{0\min}}{2} \times \sin\left(\frac{2.\pi.t}{\Lambda} - \delta\right) \tag{18}$$

Where $q_{\max}$ is the maximum intensity of global solar radiation, t_s the sunrise time and t is the time in hours. T_{0max} and T_{0min} are, respectively, the maximum and minimum temperatures recorded during the day. Λ is the duration of the sunshine and δ is the phase shift between the maximum of the ambient temperature and the global solar radiation.

3.2. Evolution of internal and external ambient temperatures

Figure 4 shows the evolution of daily temperatures of the external facades of the habitable enclosure during the selected typical day. It can be seen that there is a noticeable phase shift between the external ambient temperature and the other temperatures of the outer facades. This phase shift can be attributed to the thermal inertia and its cruel effects on the thermal behavior of the habitable enclosure walls. In addition, these effects are more pronounced especially during the daytime period when the temperature of the horizontal face is greater with respect to the others. Indeed, it makes a phase shift of one hour thirty minutes in comparison with the external ambient temperature.

Figure 5 shows the variation of the internal faces temperature of the habitable enclosure during the selected typical day. It can be seen that the thermal inertia of the concrete plays an important role in the conductive thermal transfer of the walls. Indeed, the temperature of the bottom ceiling is greater than the temperatures of the other internal faces (i.e., South, West, North and East faces). This is due to two essential factors that are combined to generate this temperature increase. Firstly, the thickness of the habitat walls, which involves the increase of thermal inertia, and secondly, the incidence angle of the sun's rays which is equal to 0 °.

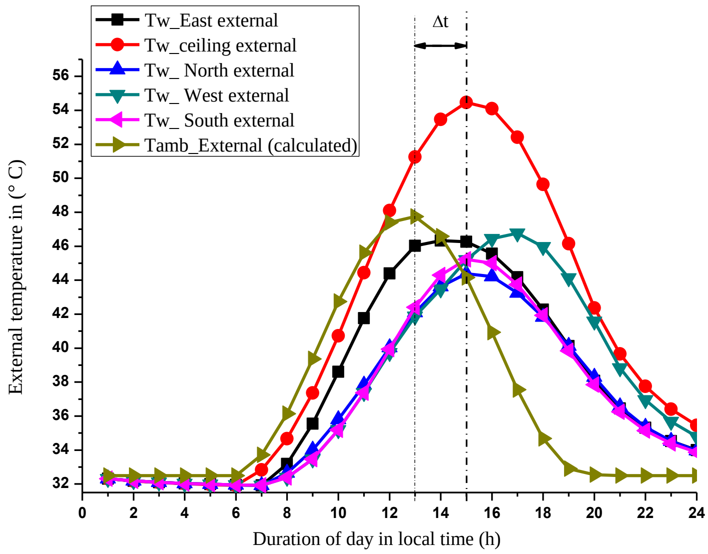


Figure. 4. Variation of the temperature of the enclosure external walls as a function of local time.

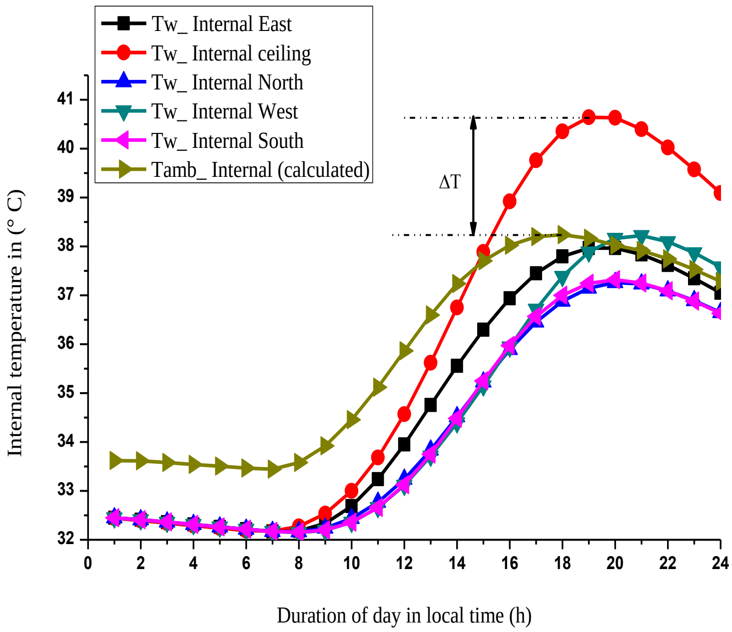


Figure. 5. Variation of the temperature of the enclosure internal walls as a function of local time.

3.2.1. Evolution of the internal temperature of the enclosure

The evolution of the internal ambient temperature of the habitable enclosure as a function of the local time for different temperatures of the heating slab is shown in figure 6. It may be noted that as the temperature of the heating slab increases, the internal temperature of the enclosure increases in a systematic manner during the diurnal period. From a physical point of view, there is a 5-hour phase shift between the external and internal ambient temperatures.

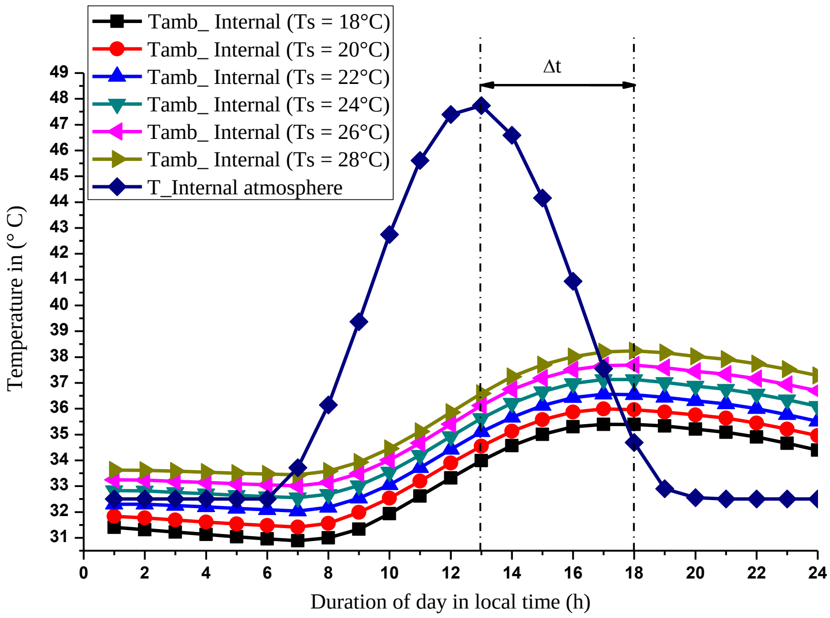


Figure. 6. Evolution of the internal ambient temperature as a function of the local time for different temperatures of the heating slab.

Figure 7 illustrates the evolution of the internal ambient temperature as a function of the local time for different walls thicknesses of the habitable enclosure. It can be seen that if the thickness of the concrete increases, the internal temperature of the enclosure decreases, and vise versa. Indeed, this variation in the internal temperature is due to the fact that the thermal inertia of the concrete plays a significant role in the thermal exchanges which take place within the habitable enclosure.

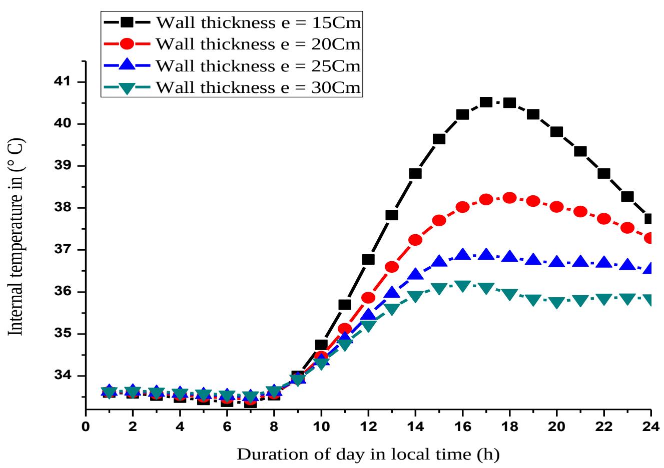
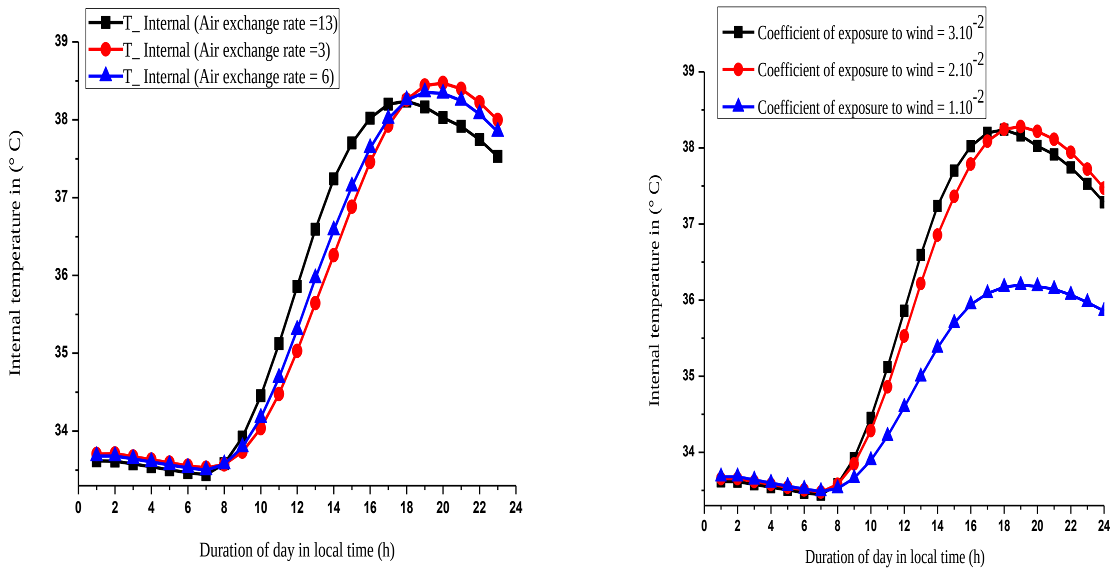


Figure. 7. Evolution of the internal ambient temperature as a function of the local time for different thicknesses of the walls.

It is interesting to note that the wind contributes to the renewal of air in the housing by natural ventilation, which is reflected in the degree of leakage of the enclosure envelope (quality of the windows and doors joints). In figure (8.a) which shows the degree of sealing effect of the windows and doors, it can be seen that before 18 hours, namely in the diurnal period, the habitable enclosure with normal quality and even in the case where there are no joints, the ambient temperature reaches a maximum value of 38°C. However, for the same enclosure with high-quality joints, the maximum internal ambient temperature is 37 °C. This slight difference is due to both the permeability of the windows and the doors and the external ambient temperature which is very high in July. Whereas, in the case of the night period (after 18 pm), we found the reverse.
It should be noted that the wind pressure on the building constitutes the predominant boundary conditions in the evaluation of air flows. In order to study its effect on the thermal comfort, it is important to adapt the available data (wind speed and orientation measured at a meteorological station) to the characteristics of the site (presence of obstacles such as trees, neighboring buildings, etc.). Figure (8.b) shows the wind coefficient effect on the habitable enclosure for different possibilities, such as a building without facade exposed to the wind, a building with one facade exposed to the wind and a building with multiple facades exposed to the wind. It can be noted that by increasing the coefficient of exposure to wind the temperature of the heated space increases significantly between the interval of 0.01 to 0.02, however between 0.02 and 0.03 a slight difference has been observed. This explains that the higher the coefficient of wind exposure (between 0.02 and 0.03), the closer the temperature of the heated space is to the external ambient temperature.



(a) (b)

Fiureg.8. Variation of the internal temperature according to: (a) the quality of the sealing and (b) the coefficient of exposure to the wind for the habitable enclosure.

Conclusion

The study presented in this paper show that the developed model can be used for the prediction of the thermal behavior inside and outside of a habitable enclosure located in a desert region. The results show that in the diurnal period the interior temperature of the habitable enclosure with several facades exposed to the wind and with a high quality sealing is moderately lower than that of an enclosure with a simple facade exposed to the wind and a low degree of sealing. Therefore, to improve the comfort level inside the living area, the joints must be of high-quality and the wind exposure coefficient must be reduced to the maximum possible as the external ambient temperature in this region is very high during the month of July.

It is noticed that the high thermal inertia of the building material used for the habitable enclosure has a considerable effect on the stabilization of the thermal comfort. Thus, it is advised to use other materials with low thermal inertia in the construction, such as, clay-based materials.

Moreover, the increase in the temperature of the heating slab leads to an increase of the internal temperature and, consequently, to an undesirable overheating of the envelope. For this reason, it is necessary to respect the ISO standards that govern the permissible limits of the heating slab temperature.

Nomenclature

α_c	Absorption coefficient of concrete	-	$Q_{absorbed}$	Quantities of heat absorbed	W
ε_{sky}	Coefficient of the sky emissivity	-	$Q_{solar\ flux}$	Density of solar flux	$W.m^{-2}$
λ_c	Concrete thermal conductivity	$W.m^{-1}.K^{-1}$	Q_{cvam}	Amount of heat exchanged by convection with atmosphere	W
η_{50}	Hourly rate of renewal of air	h^{-1}	Q_{issued}	Amount of heat emitted by a surface	W
μ_{air}	Dynamic air viscosity	$Kg.m^{-1}.S^{-1}$	$DTFS$	Density of the total solar flux incident on the south wall	$W.m^{-2}$
ζ	Coefficient of exposure to the wind of the heated room	-	$DTFW$	Density of the total solar flux incident on the west wall	$W.m^{-2}$
ρ_i	Density of the substance (i)	$Kg.m^{-3}$	S_i	Surface of plan (i)	m^2
Δt	Time difference	S	S_{WFS}	Surface of the wall floor	m^2
Cp_{air}	Specific heat of air	$J.Kg^{-1}.K^{-1}$	S_{small}	Surface of the small opening for introducing air into the heated space	m^2
$C_{inertia(i)}$	Inertia capacity of a material (i)	$J.K^{-1}$	T_{A1}	Outdoor air temperature of the habitat	°C
e_{WS}	Thickness of concrete wall	M	$Tamb(\text{int.})$	Temperature of the internal environment of the building	°C
h_{conv}	Convective exchange coefficient	$W.m^{-2}.k^{-1}$	T_i	Temperature of a surface (i)	°C
h_{cv-ext}	Convective coefficient of exchange with the external air of the habitat	$W.m^{-2}.k^{-1}$	T-int	Internal room temperature for a heating slab temperature of 18°C	°C
h_{cviam}	Convective exchange coefficient of ambient	$W.m^{-2}.k^{-1}$	T_{Max}	Maximum ambient temperature	°C
$h_{r-INW.IOW}$	Coefficient of radiation exchange between the north inner wall and the west inner wall	$W.m^{-2}.k^{-1}$	$TW_{(East-\text{int})}$	Temperature of the inner wall of the east wall	°C
$h_{r-INW.ISW}$	Coefficient of radiation exchange between the north inner wall and the south inner wall	$W.m^{-2}.k^{-1}$	$Tw_{(South-\text{int})}$	Temperature of the inner wall of the south wall	°C
h_{rsky}	Coefficient of exchange by sky radiation	$W.m^{-2}.k^{-1}$	$Tw_{west\ external}$	Temperature of the external wall of the west wall	°C

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