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3D INVESTIGATION OF SEMI-UNDERGROUND ROOM COMFORT IN A DESERT CLIMATE

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ABSTRACT

In Algeria, the residential sector registries a high rate of energy consumption which requires an important action for rationalizing this charge and integrating renewable energies. Particularly, the geothermal energy with its less intermittence presents an attractive candidate to reinforce energy-saving and building thermal comfort. In this paper, geothermal energy is used to create a favorable environment for creating a better life inside a semi-buried building during the very hot period in the desert climate of southern Algeria. The cooled room is buried in rocky soil until 3 m depth, and only 0.5 m of the room high is above the ground level. The upper parts of southern and northern room walls are provided by small windows for aeration and lighting purposes. Inside room the air flow is modeled by Navier-Stocks and energy equations. The computational domain is taken as 3D design, and the prediction of temperature is calculated by ANSYS-Fluent code. For the base case, at 2 m height, the indoor temperature fluctuates between 30 and 33°C which is in good concordance with experimental data. For reducing the indoor temperature, some simple design modifications are introduced and a small ventilation system is installed. The new results show that the indoor temperature does not exceed 25 °C at the height of 2 m, therefore the temperature for height between 2 and 3 m it fluctuates between 25 and 26 °C. This indoor thermal behavior ensures acceptable cooling with negligible electricity consumption.

Keywords: *Semi-Buried Room, Desert Climate, Passive Cooling, Experimental Investigation, 3d Simulation.*

INTRODUCTION

In arid hot climate of southern Algeria, the cooling of buildings needs a large energy amount to reach thermal comfort [1]. To ensure this comfort, mechanical air conditioners with high energy consumption are used. But, the integration of passive techniques can reduce energy consumption. In traditional houses and bioclimatic constructions, natural ventilation is a common technique for reducing the temperature. New several techniques are used such as vegetation cover, phase change materials, solar chimney ventilation, earth-air-exchange tube, and underground construction. The latter two methods are very attractive, especially for cooling single-floor buildings which are highly dependent on external thermal fluxes from direct solar radiation. In particular, for isolated residences where power supply by a fuel-driven generator is very expensive and photovoltaic panels require good rationalization and control of energy management. Underground building types are used in the ancient civilization such as in Cappadocia and Jordan, where man has left us some testimonials of dug cities. Also, in the south of Algeria, some traditional buildings are drug in Ground bumps and plateaus during past centuries. Their architectures respond more adequately to the climatic problems and energy saving. Noting, that [2] indicated that the southern Algeria underground soil is characterized by a moderate stable temperature during the whole year. In literature, some works analyzed these kinds of building characteristics according to geographic location, climate, and human acceptability. [3] studied semi-underground building which is partially buried along the northern front using the site slop. The thermal radiation strikes the greenhouse and transforms into heat by ventilation ducts. The outside glass is inclined at 10 ° to protect from the summer sun but allows the winter sun to penetrate. Vents at the bottom and the top of the glass are opened to the ventilation system. The buildings' roofs function as "roof gardens". [4] investigated the coupling of solar chimneys with buried cooling ducts as design for cooling in hot climates. The thermal mass of the ground is estimated for buildings cooling potential. The results indicate that if irrigation is applied to the soil surface in summer, the ground offers a good source of cooling for buildings. A decrease in temperature to 18° C is noted between the soil temperature at a depth of 1m and the ambient outside temperature.

[5] explained the cost/benefit relationship between underground and energy use by underground space utilization could help to raise the quality of energy services. In such a new Underground Urbanism approach, the need for long-term Integrated Master Plans that propose suitable Guidelines is highlighted. [6] attempted to analyze the thermal performance of a naturally-ventilated underground shelter in a hot and humid country such as Malaysia. An optimal design is proposed, the room temperature of the shelter was significantly lower than the outdoor temperature during the hottest month. The optimal design showed about a 3.4% increase in ventilation rate and about 2.8% decrease in room temperature as compared to the previous design. [7] studied the Yang Emperor Mausoleum of the Han Dynasty, and China's first wholly underground protection and exhibition hall of relics. They discuss the preservation of historical relics, the harmonious relationship between architecture and nature. The energy-

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saving ratios of underground versus ground architecture are as follows: service architecture, 60%; warehouse, 70%; and semi-earthed underground structures, 69%. [8] investigated the potential in reducing the heating and cooling energy demand for underground buildings compared to aboveground buildings. Energy reduction is achievable for all climates and functions when underground and aboveground buildings, but the magnitude is related to different design elements. They noted that 11% of cases analyzed can be considered near zero-energy buildings (energy demand less than 10 kWh/m2 year). [9] analyzed the relationship between air-conditioning effectiveness and the corresponding energy efficiency. Energy and CFD simulations are conducted to the underground air-conditioning data centers in the tropics. The analyze concerns the energy consumption and energy efficiency of the whole air-conditioning system and the corresponding airflow pattern. The optimization of air management shows that fan energy can be saved by 20% to 25%.

[10] realized comparative thermal comfort surveys including field measurements and questionnaires have been carried out in a different underground air-defense basement. Based on the psychometric chart, the recommended temperature ranges for different cities compared with the original temperature ranges, it shows that the recommended temperature ranges varying with the ground temperature could save lots of energy consumption. [11] investigated the critical risks in the constructions of underground residential building projects. Results of the questionnaire survey showed that "space-saving" was the most significant advantage, followed by "improved indoor thermal comfort," "more resistant to external noises". Also, results revealed that "limited access to natural light" was the most severe disadvantage, followed by "high construction cost," and "psychological resistance from residents". [12] deducted a graphical model of earth-sheltered buildings visualizing their major aspects such as design, thermal performance, and sustainable development. The building is dug in the mountain slope, the roof and the three sides are covered by rocks, and only the south side is exposed to the sun. The additional design cost can be offset by omitting the cost of air conditioning installation, external wall painting, and expected lower foundation. [13] dimensioned underground spaces in terms of heat transfer and thermal comfort and developed a dynamic physical and mathematical model. The obtained simulation results are presented in diagrams in favor of the quick sizing of the required heating and cooling performance. The presented diagrams can be used in an effective manner also for the calculation of thermal comfort. [14] studied a cooling system using phase change materials, to absorb external heat gain of solar radiation across building walls in Ouargla city (Algeria). But the indoor temperature reduction can reach a maximal average of 8 °C compared to the outside temperature. [15] presented a passive cooling system incorporating solar chimney and earth-air heat exchanger system for cooling telecommunication shelter in a desert climate. They show that this cooling system requires a low cost and it is eco-friendly. The temperature in the middle of the shelter does not exceed 29 °C.

[16] investigated the thermal comfort of low-income group houses by passive cooling techniques as the green envelope, shaded wall and ventilation. During the early summer day hour, the outside temperature is lower which can reduces the indoor temperature, but it remains insufficient to reach thermal comfortable. [17] conducted a review study on the earth air pipe heat exchanger (EAPHE) system. They show that, the pipe depth less than 4 meters and the increase of air speed reduce the system thermal performance. Also, to achieve EAPHE operating optimization, the system must be coupled with other systems, such as photovoltaic panels, wind turbine and solar basket. [18] simulated a heated room to evaluate the thermal comfort under air natural convection. The results show that indoor temperature changes between 20 °C and 22 °C which presents a comfortable temperature for winter days.

[19] described and analyzed the principal of architectural designs of an underground and semi-underground building used to overcome the hard climate in different dry and hot sites in Iran. The chosen three cases (Shabestan, Shavadan and sunken garden) are analyzed to show the environmentally sustainable architecture, but the study is limited to the descriptive aspect and measurement of temperature. This study doesn't contain any simulation of air flow to show clearly the interaction and influence of building design and thermal comfort.

Many recent works are carried out, but they mostly treat the totally buried building or analyze indoor environment quality basing on experimental measurement without studding the airflow in the 3D model. [20] investigated an underground house 2D model with the uncovered entrance door, access tunnel and roof chimney. For maximal outdoor temperature, they observed appreciable thermal stability without any energy consumption. The tunnel plays an important role in the natural ventilation of airflow which escapes by the chimney with lower velocities. [21] conducted a comprehensive review of underground building studies concerning energy, thermal comfort and air quality. They found that numerical simulation is widely used to analyze energy performance while the experimentation is employed to examine indoor air quality performance. The issues of heat transfer need more improvement to reflect the prediction accuracy with calculation cost, and more researches are required for air quality performance. [22] investigated the thermal effects of building envelopes on the energy consumption of underground offices for different China climatic zones. The results show that during the year the energy consumptions vary significantly, and it depends on the U-value of the global heat transfer coefficient of the envelopes. [23] conducted a study to identify the environmental causes of health issues in the office space. The office is associated with an under-floor air distribution (UFAD) system in the office building. The results show that the diffusers are less effective in ensuring air mixing at the living space. The RH exceeds the limit of 70%. The CO_2 concentration exceeds 1000 ppm, and the formaldehyde exceeds 0.1 ppm. Therefore, there is a poor design and maintenance of the construction that create the degradation of the environmental quality inside the office. [24] evaluated the qualitative and quantitative thermal performance of an ancient cave dwelling. The qualitative performance concerns building orientation, underground courtyard, and biomass building envelope, but, the quantitative performance concerns the record of thermal parameters inside the selected building. The EnergyPlus software is used for the numerical simulation of the mathematical model. The obtained results confirm that the strategies adopted in the underground cave are highly effective to provide a comfortable environment inside rural residences. [25] realized an interesting review paper to analyze histories and design factors of underground buildings, mainly, the concept of a ventilation system, indoor environment quality (IEQ), passive design and building optimization. They noted that using both passive design and optimization approach into simulation is an interesting technique to improve the IEQ level. Also, the natural ventilation and soil adoptions can significantly decrease building energy consumption. [26] discussed the urbanization of underground building and the possibility to construct house’s projects in the deserts of Egypt. They used a questionnaire survey to evaluate the study, and applied the chi-square test for analyzing the results. They recommend a possible construction of new housing projects in the western deserts of Egypt, like "Toshka", also, in the touristic resorts, especially, in the projects of small and middle-sized.

Few works of a 3D model for simulating airflow inside underground building are found in the literature. [27] conducted a computational fluid-dynamic model that estimates the temperature and airflow in the building in real-time. They have arrived at real energy savings that can be achieved based on the 3D monitoring by applying indoor climate control and the optimal design of air-conditioner. [28] proposed a new method using computer vision for automated 3D energy modeling. This model uses thermal and digital imagery with a single thermal camera. Their results indicate that the application of this method for existing buildings is a robust tool for rapid building diagnostics.

In the present work, new building design is studied; it consists of a traditional residence in Metlili (Algeria). Generally, in this region, each residence contains a semi-buried room passively cooled by geothermal energy. The room thermal behavior is investigated numerically by a 3D mathematical model using CFD fluent code, then, the results are validated by the experimental measurements data. This base case doesn't achieve acceptable thermal comfort; therefore, some simple modifications are introduced in the room design to reduce the indoor temperature. Several tests are carried out until finding the best room design ensuring appreciable cooling level. For the maximal ambient temperature of the hottest day (48°C), the indoor temperature prediction of the new room design shows that the living space provides a comfortable indoor temperature (25 °C). So, for all days of the hot period, good air conditioning can be insured with negligible energy consumption.

TRADITIONAL SEMI-UNDERGROUND ROOM

GENERAL DESCRIPTION

The rocky region in the south of Algeria such as Ghardaia region, it is famous for its traditional residences in “Metlili” municipality which contain semi-underground rooms (see Figure 1a). Generally, these rooms are constructed with 2.7 m height, 4.8 m long, and 3.4 m as large. Most of the room height is buried in the earth, only 0.5 m is above ground level which permits to install small windows. The windows with 0.2 m height ensure the light and aeration with various rates according to the day and night (see figure 1b), the external view of air outlet windows are opened to air ambient in the garage, besides these small windows, au second entrance door links between the garage and the house via a corridor of 150 cm as the width (see figure 1c). The underground space of this corridor will be later (in the propositions) used to extend the semi-buried room and modify the stairs. The room access is ensured by a set of stairs constructed inside a separate hall (Figure 1a). At the end of the stairs, a wide opening presents the room entrance.

In summer, depending on social traditions, this room is principally reserved for living and sleeping in a hot day period (from 11h to 17h). It is characterized by a moderate temperature which not exceeds 33 °C during the day compared to 48 °C as the maximal outdoor temperature. So, generally, the air-conditioner is not needed and the only a fan is sufficient for ventilation. In Metlili, generally, traditional houses are composed of three floors; the semi-underground, the first floor and the free second floor without a roof.

a) b) c)

Figure 1. Design of traditional residence in Metlili (Algeria)

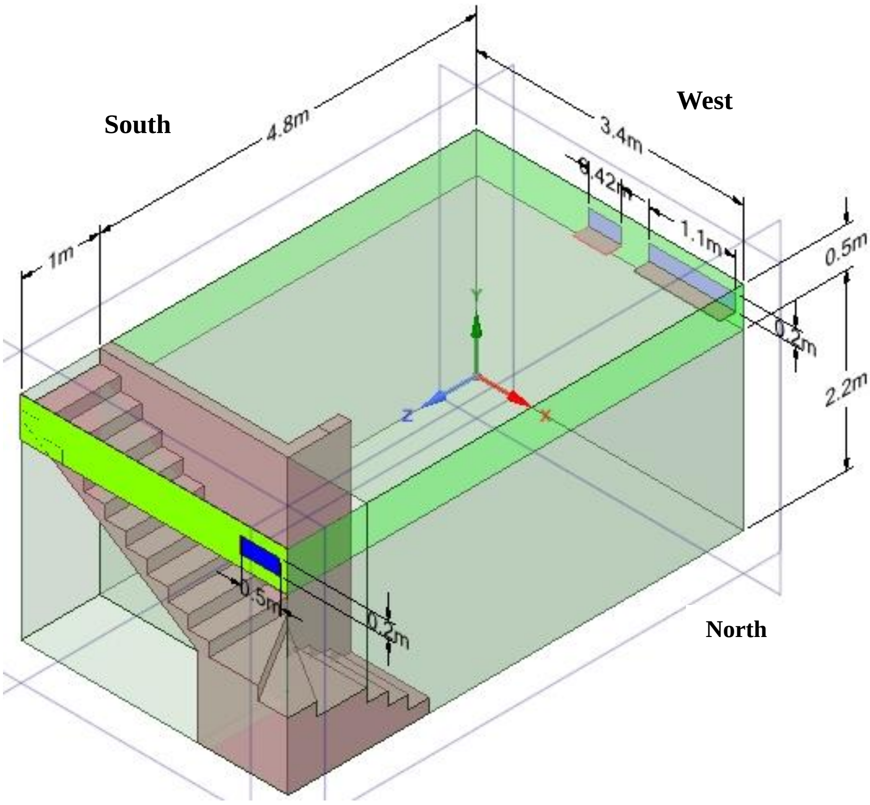

Figure 2. Dimensions of traditional room

GOVERNING EQUATIONS

Inside the room, the airflow is governed by the mathematical model composed of three differential equations presenting respectively the continuity, motion, and energy. These equations can be presented in concise form as follows:

$$\frac{\partial \rho}{\partial t} + div(\rho.V) = 0 \quad (1)$$

$$\frac{D}{Dt}(\rho.V) = \rho F - grad(p) + \mu\Delta \quad (2)$$

$$\frac{D}{Dt}\left(\rho C_p T\right) = \Delta(\lambda\, T) + q \quad (3)$$

Where: q is heat source term; C_P and λ are respectively the calorific capacity and thermal conductivity of the fluid. ρ is the air density and V is fluid velocity vector, F is the force by volume unity and μ is the dynamic viscosity.
Since, the phenomenon manifests as natural convection generated by heat transfers in the vicinity of the heated surfaces, the relation of Boussinesq approximation is introduced [29] . The density state equation becomes:

$$\rho \;=\; \rho_0\,[1-\beta(T-T_0)] \tag{4}$$

Where: ρ_0 and T_0 are density and temperature of reference thermodynamic state.
β is the isobaric extension coefficient of the fluid: $\beta = -\frac{1}{\rho} + (\frac{\partial\rho}{\partial T})_{P=cst}$

COMPUTATIONAL DOMAIN AND HYPOTHESIS

Figure 3 shows the computational domain of the room, in the north side it contains a cavity under the stairs. Near the wall and the openings of air inlet and outlet, the meshes are refined.
The temperatures of internal wall surfaces are taken as boundary conditions which are measured by a set of thermocouples. The vertical surface of the end of the stairs end is considered as an air inlet. In the base case, the critical situation of maximal ambient temperature is July 5th, 2018 at 14 h, where the ambient temperature reaches T=43 °C.
Since in the air flow the variation of the pressure is small, the density varies according to the gradient of pressure is negligible; so, the air flow is considered as incompressible. Despite the hypothesis of incompressibility, in natural convection, the Boussinesq approximation is introduced because the density is not completely constant. This lets negligible changes in density, except where the gravity effect appears (z component). The air flow is assumed as a permanent regime that is taken in limited duration (about 1h) of maximal ambient temperature which presents the critical situation.
For the forced convection, thought the opening of the air outlet and air inlet, the velocity of air is very small (< 0.07), so, the Reynolds number is small (< 2000), consequently, the air flow is taken as laminar.
Since, the presence of the natural convection, the verification of Rayleigh number is required. The calculation of Rayleigh number (Ra) indicates that $Ra = 5.57\times10^3$, ($Ra < 10^9$), so, the regime of the flow is laminar.

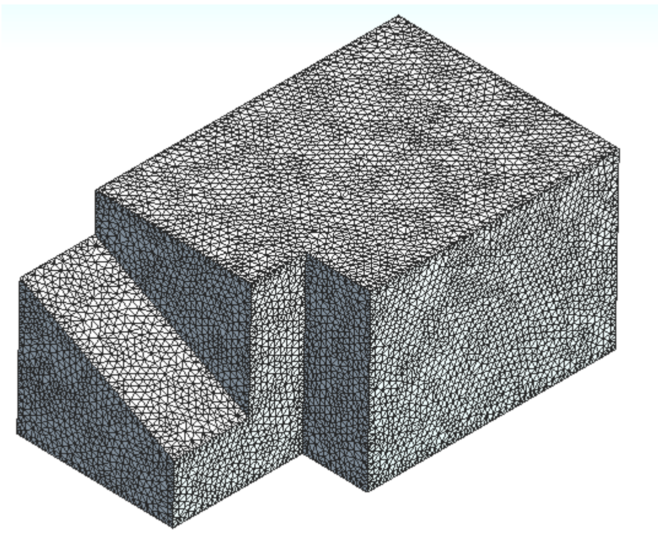

Figure 3. Computational domain of traditional room

NUMERICAL SIMULATION

The partial derivative equations of the mathematical model are coupled, where the resolution requires the use of numerical tools such as ANSYS-Fluent software which is commonly used in CFD problems. For treating the coupling between pressure and velocity, the SIMPLE algorithm is applied. A second-order upwind scheme is adopted for the discretization of the governing equations. In order to accelerate the iterations, a coefficient of under-relaxation is integrated; the indoor temperature level of airflow is examined until reaching the convergence with a residual error of 10^{-6} for various variables.
For meshes independence, the optimization is carried out to minimize the number of meshes while keeping an acceptable precision of the results. A preliminary study is launched aiming to determine the largest possible mesh size while preserving the convergence of the simulation. The determination of the best mesh is based on the variation of the temperature value as a function of the number of meshes. the point chosen for the temperature test is at the proximity of the air inlet. Several tests are carried out until the variation of temperature value is very small where the mesh reaches the optimized state. The results obtained

show that the temperature variation is very small, and the absolute relative error is less than10^{-3} at the meshes number reaches 137316. Figure 4 shows the curve of different tests of meshes independence.

In the room, the most frequented areas by the occupants are around the middle of the room (z=2.4 m and x=1.7 m), for this purpose the vertical axis is chosen as a representative reference of thermal comfort. At this axis, figure 5 shows the simulation data of temperature. The temperature increases progressively from the floor to the roof. In the bottom, the temperature is low due to the direct effect of the geothermal cooling, but in the temperature is high due to the effect of ambient air inlet and outlet through the small windows.

For the validation of the model, a collect campaign of temperature is carried out inside the semi-underground room at its median vertical axis. A set of thermocouples with digital display are used in temperature measurement, they are K type for an interval of -1000 to 1250 °, and an accuracy of 0.5%. Table 1 shows the good concordance between simulation and experimental data, where the absolute relative error doesn't exceed 0.50 %.

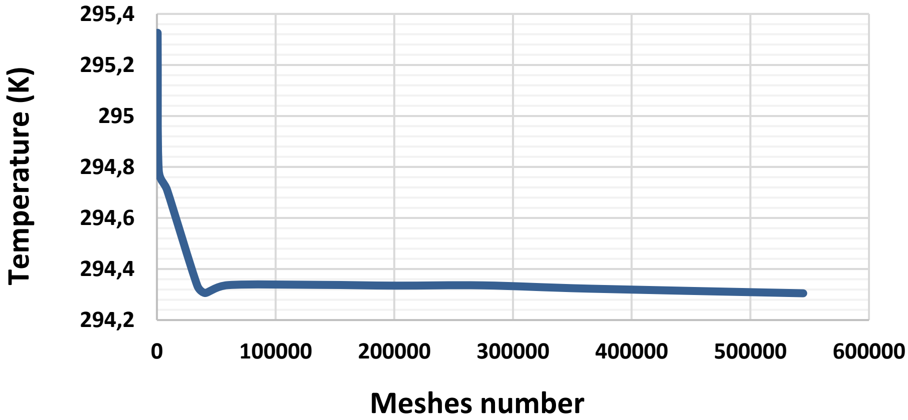

Figure 4. Tests of mesh independence

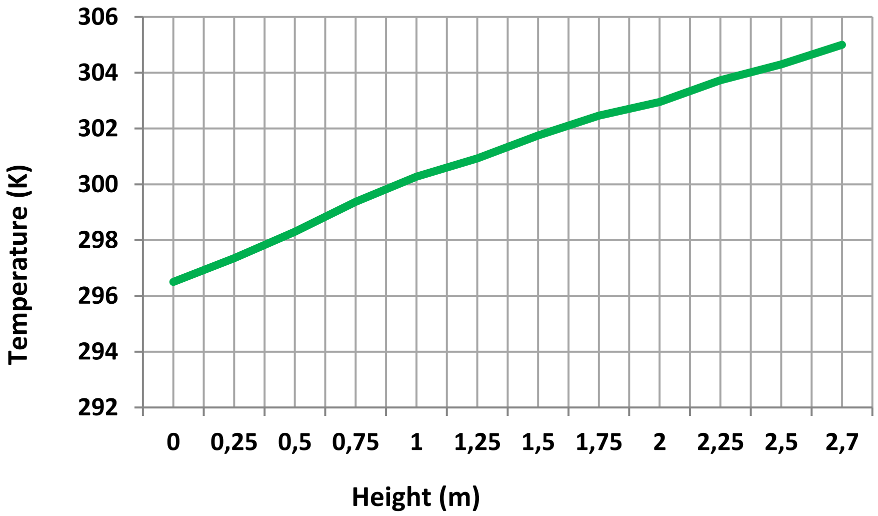

Figure 5. Indoor temperature at z=2.4 m and x=1.7 m.

Table 1: Results of model validation against the experimental data.

Height(m)	0,00	0.25	0.5	0.75	1,00	1.25	1.5	1.75	2,00	2.25	2. 5	2.7
T_{exp} (K)	296,50	298,00	299,10	300,20	301,77	301,80	302,56	303,08	303,67	304,21	304,57	305,00
T_{sim} (K)	296,50	297,35	298,17	299,37	300,27	300,93	301,75	302,46	302,95	303,73	304,11	305,00
Relative Error (%)	0,00	0,22	0,31	0,28	0,50	0,29	0,27	0,20	0,24	0,16	0,15	0,00

THERMAL FIELD

Figure 6 shows the temperature contours; they indicate that the comfortable level of temperature is situated only at the bottom of the room. On the upper room part, the temperature is high due to the influence of ambient air. The Western upper corner is more heated than the Eastern one due to the incident solar rays in the afternoon. In the front left side, the increase of temperature is extended until the room floor that is due to room entrance which ensures air inlet (relatively hot air). Figure 7 shows the temperature contours on the vertical median plan at x=1.7 m, the temperature level is comfortable only in a limited level of the room living area.

Figure 8 shows the temperature on the horizontal plan at the room height of 2 m, the temperature is about 31 °C. This level of temperature is significantly lower than the external ambient temperature (43°C). But it doesn't reach good thermal comfort. The main cause of this insufficiency is the wide entrance opening which hasn't any separation between the room entrance and the end of the stairs. So, the room requires a new design which should contain a separating door to reduce the effect of inlet hot air.

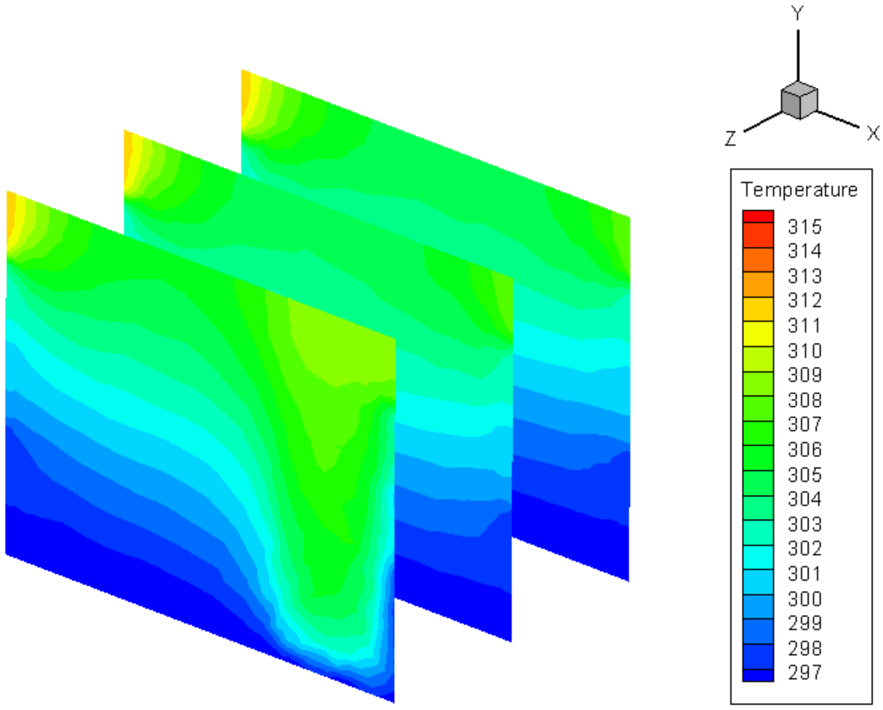

Figure 6. Temperature contours in 3D design of traditional room

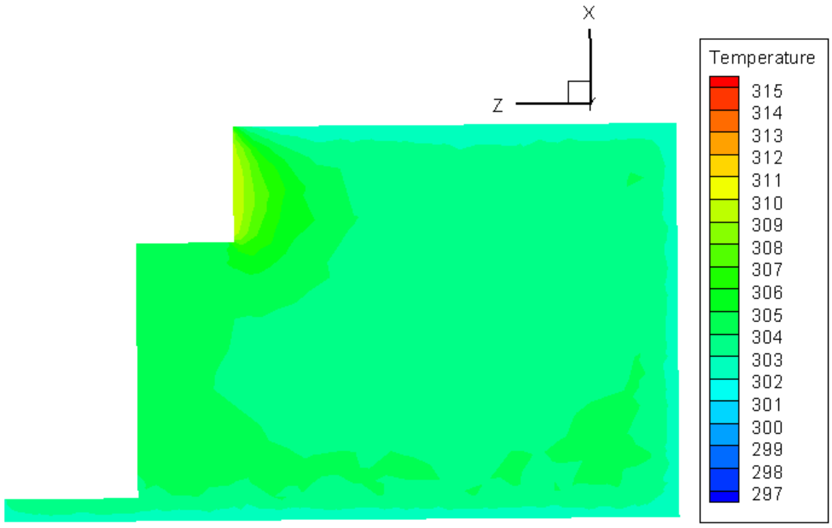

Figure 7. Temperature contours on horizontal plan at y=2 m high of traditional room

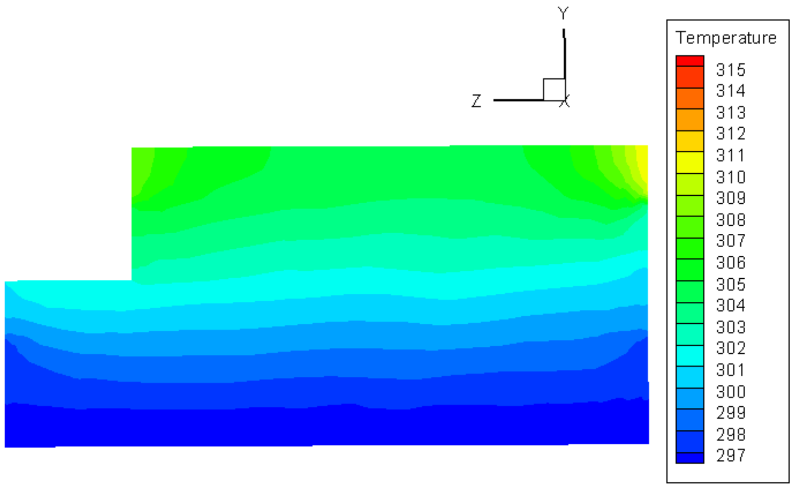

Figure 8. Temperature contours on vertical median plan at x=1.7 m of traditional room

PROPOSED SEMI-BURIED ROOM DESIGN SHAPE

To improve the cooling performance, our choice is to make some simple modifications in the traditional room design without affecting the general structure of the house. The original width of the room (3.4 m) is extended by a distance of 170 cm. This distance will be digging below the corridor which is the second entrance to the house via the garage. This extension allows the construction of new strength stairs for extended room depth. The floor level of the corridor will be increased by 0.5 m in order to get the same level of room roof. The original room depth (2.2 m) will be extended into the soil by 0.8 m.

Also, the proposed room is designed with a separate cavity containing the stairs, where, at downstairs, a wood door is added as the room entrance. The most appropriate place for the opening of the air inlet is chosen at the bottom of the door (see Figure 9). The hot air exhaust through an outlet opening situated at the room roof near the West-South corner. This air outlet is opened to the house first floor where the temperature is relatively lower than the ambient temperature. Like the traditional room, the room upper part (0.5 m) is above the ground level, which permits to the window at the West side to contribute in room lighting. These windows will be reinforced by external doors as double glass to reduce heat infiltration. The windows can be opened in the night to permit free room aeration.

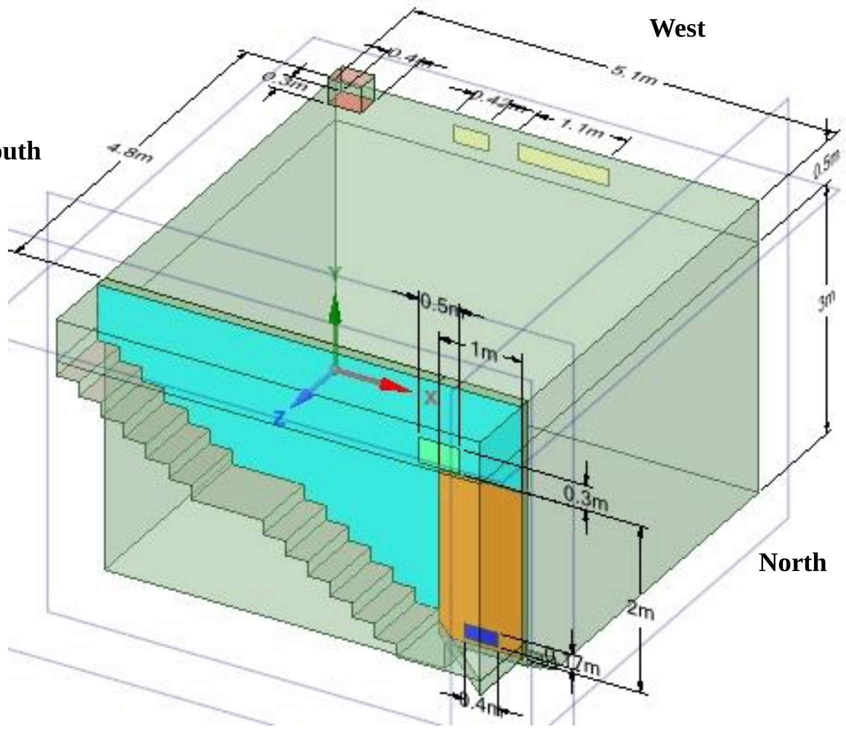

Figure 9. the proposed room with natural convection

BOUNDARY CONDITIONS

Since the roof is covered by the first floor and has good insulation, it is considered as an adiabatic boundary. The temperature of the roof outlet opening is measured inside the first floor which reached 307 K. The above-ground parts of the room sides are exposed to the ambient environment. The windows are placed on the West side; they contribute only to room lighting. The equivalent temperature of the western wall outer surface takes into account the effect of solar radiation on the ambient temperature; it is expressed as follows [30]:

$$T_e = T_o + \frac{\alpha I_T}{h_0} - \frac{\varepsilon \Delta R}{h_0} \tag{5}$$

Where: T_o : Ambient temperature.

$\frac{\alpha}{h_0}$: Absorption capacity rate of outer surface $0.026 \leq \frac{\alpha}{h_0} \leq 0.052$ [31]

$\frac{\varepsilon \Delta R}{h_0}$: A correction factor (4 °C for horizontal and 0 °C for vertical surfaces),

I_T: total solar radiation

The internal temperatures of the glass window and walls situated above ground level (no buried room part) are calculated by taking into account the heat conduction thought their thicknesses. The thermal resistance of the wall is determinate for wall thickness composed by an external plaster layer (2 cm), a brick (20 cm), and an internal plaster layer (2 cm).

At height less than 3 m, the temperature of the floor and the walls of buried room part are taken with the same soil temperature values for boundary conditions. For the month of July, soil temperatures of different depths (z) are obtained using the mathematical model given by [32]. The model is expressed by the flowing equation:

$$T(z,t) = T_{mean} + A\cos\left[\omega(t - t_0) - \frac{z}{d}\right] exp\left(-\frac{z}{d}\right) \tag{6}$$

T_{mean} is the mean annual soil temperature, (is taken 23.8 °C)

A is the amplitude from the soil surface temperature, (is taken 14 °C)

t is the time coordinate. (t = 0 from 1 January at 0 s).

t_0 is the phase constant (time of maximal soil surface temperature).

$\omega = 2\pi/P$, where P is the period of the sinusoid.

$d = (2\alpha/\omega)^{0.5}$

where α is the thermal diffusivity of the soil: $\alpha = \lambda_{soil}/(Cp_{soil} * \rho_{soil})$.

and λ_{soil} , ρ_{soil} and Cp_{soil} are respectively thermal conductivity , density and specific heat of the soil.

The results of the model are validated against the experimental data measured on May 2013 by [33]. Table 2 shows the obtained boundary conditions for different heights of the proposed designs.

Table 2: Boundary conditions of the room.

Height (m) \ Wall	North	East	West	South
0-1	295.8	295.8	295.8	295.8
1-2	298	298	298.5	298.5
2-3	299.4	300	301	302
3-3,8	302	303	304	305

FIRST CASE: NATURAL VENTILATION

Thanks to the two openings (at the door and the roof**),** the airflow moves by the effect of natural convection in the semi-buried room. For the permanent regime, the critical situation is taken at the highest ambient temperature. The hottest day in the summer of 2018 in Metlili city is 15th July as well as the hottest time is at 14:00 when the ambient temperature reaches 48 °C (according to the National office of Meteorology – Algeria) [34].

Figure 10 illustrates the temperature contours on parallel plans of 3D design; they show varied distribution in the upper part of the room. It is noted that the temperature in almost room living space is improved compared to the traditional room. The temperature level is less than 29° C except at very isolated areas in the roof corners.

Figure 11 shows the temperature contours in horizontal plan (y=2 m), near the entrance the temperature is relatively high, but it decreases progressively until the room middle where it stabilizes at 25 ° C, mainly in the room upper half. This insufficiency of natural ventilation is emphasized by the temperature contours illustrated in figure 12 of the median plan at x=2.55 m. These contours show that the comfortable temperature (25 ° C) is limited only in the first room quarter from the floor.
Figure 13 shows the temperature on the middle vertical axis of the room (x = 2.55 m & z=2.4 m). For height less than 2 m, the temperature doesn't exceed 27° C, it is better than the results of traditional room, but it still needs further improvement to reach a comfortable temperature.

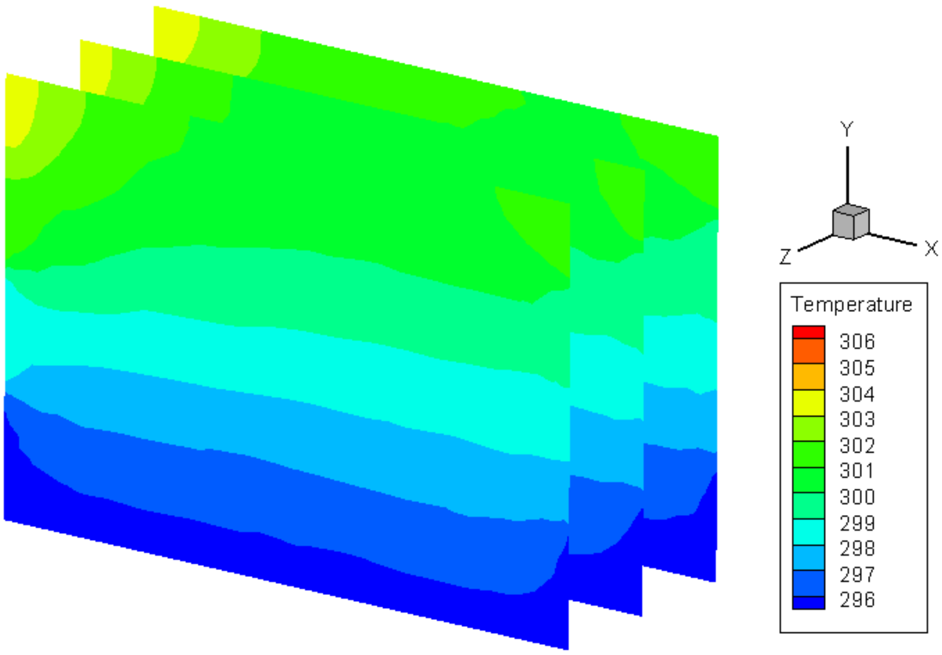

Figure 10. Temperature contours of the proposed room with natural convection

Figure 11. Temperature contours in horizontal plan of the proposed room with natural convection

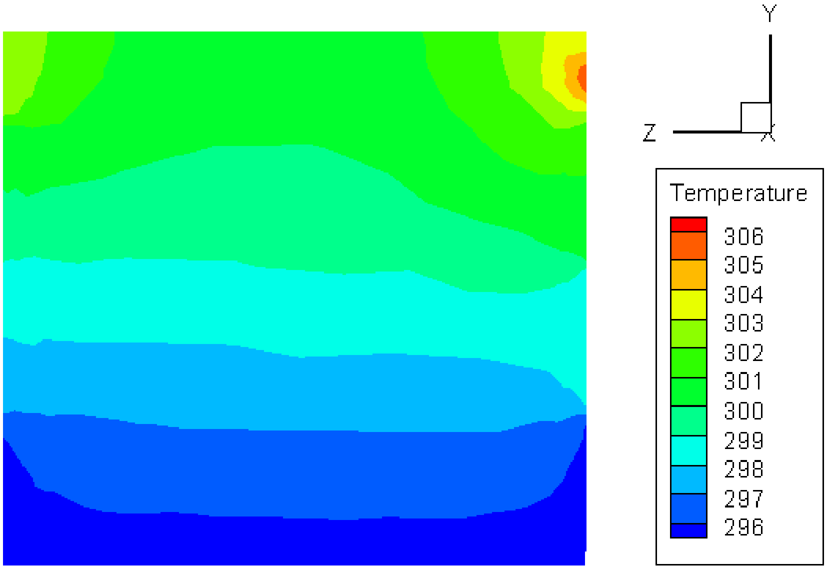

Figure 12. Temperature contours in median plan of the proposed room with natural convection

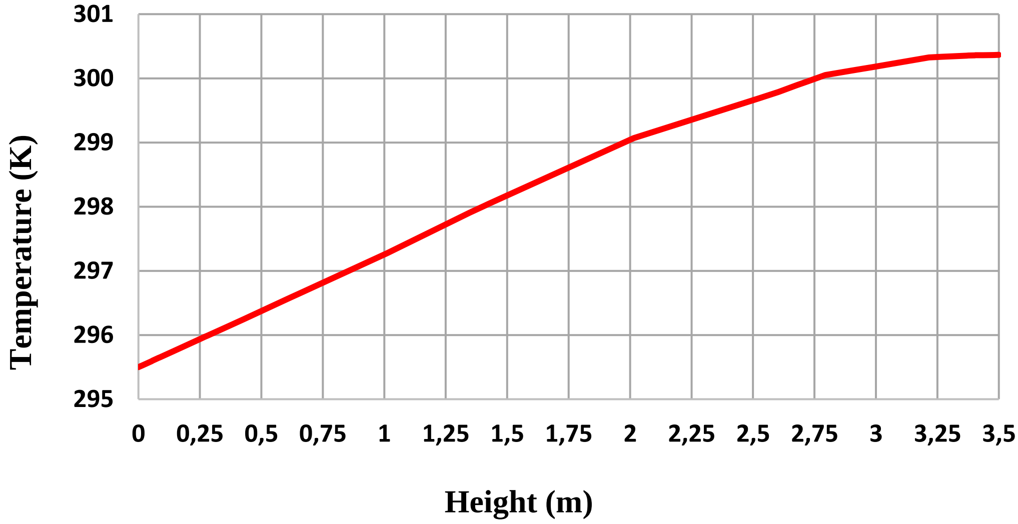

Figure 13. Temperature on room median axis (x=2.55 m, z=2.4 m) (first case

SECOND CASE: CONVECTION WITH VENTILATION FAN

For getting more improvement of the first case (with natural convection), a small fan of ventilation is added at the air inlet. The most appropriate place for installing the fan is the air inlet opening at the door bottom (See figure 14). The cavity under stairs is rearranged as a big closed cupboard to avoid the flow stagnation under the stairs.

In this case, the fan reinforces the air flow movement to sweep easily inside the room. The temperature contours show a uniform distribution in about all parts of the room (see Figure 14). The almost room living space for daily activity is at a temperature level of 25 °C.

Figure 15 shows the temperature contours in horizontal plan (y=2 m), decreases progressively until the room middle where it stabilizes at 25 ° C. This insufficiency of natural ventilation is emphasized by the temperature contours illustrated in figure 16 of the median plan at x=2.55 m. These contours show that the comfortable temperature (25 ° C) is limited only in the first room quarter from the floor. Also, figure 16 shows the temperature on the median vertical plan of the room (x = 2.55m). For different room distance from the entrance to the backroom, the temperature doesn't exceed 25° C. The same remark is noted for figure 17 where the temperature in the middle vertical axis of the room (x = 2.5r m & z=2.4 m) remains less than 25 °C. These results present a supplementary improvement and the room reaches a comfortable temperature.

Generally, the maximum size of an occupant doesn't exceed 1.9 m, therefore, the horizontal centerline located at a height of 1.9 m is chosen as a test reference for Air velocity. On this centerline, figure 18 shows the velocity magnitude which is extended between 0.02 and 0.07 m/s. This level of air ventilation remains not annoying and ensures good aeration for the room occupants. This last case shows a good improvement in air ventilation and temperature drop inside the room. Indeed, the room reaches an appreciable comfort for the occupants in the summer.

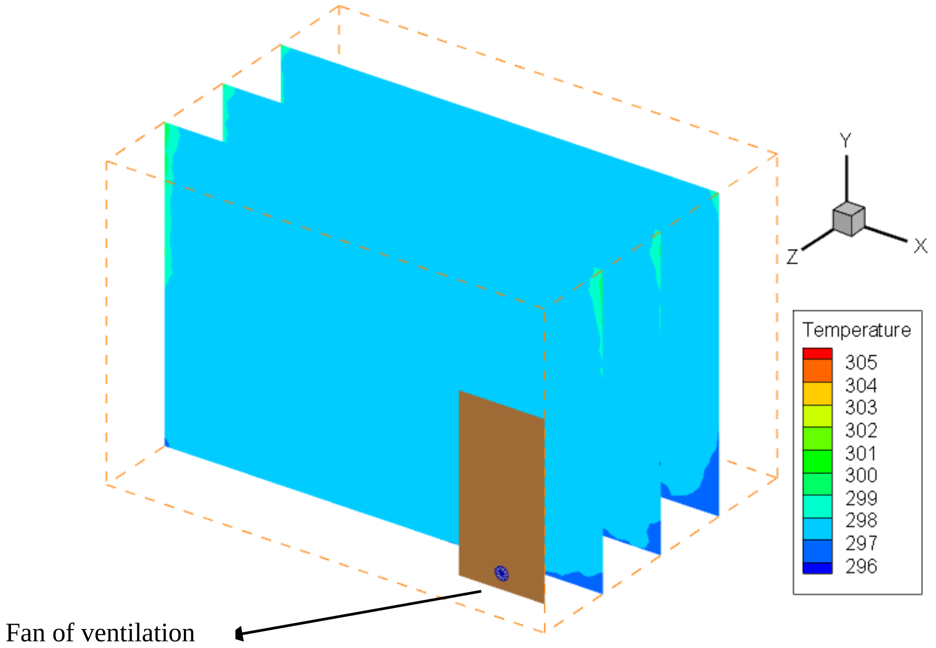

Figure 14. Temperature contours of the proposed room with ventilation fan

Figure 15. Temperature contours in horizontal plan of the proposed room with ventilation fan

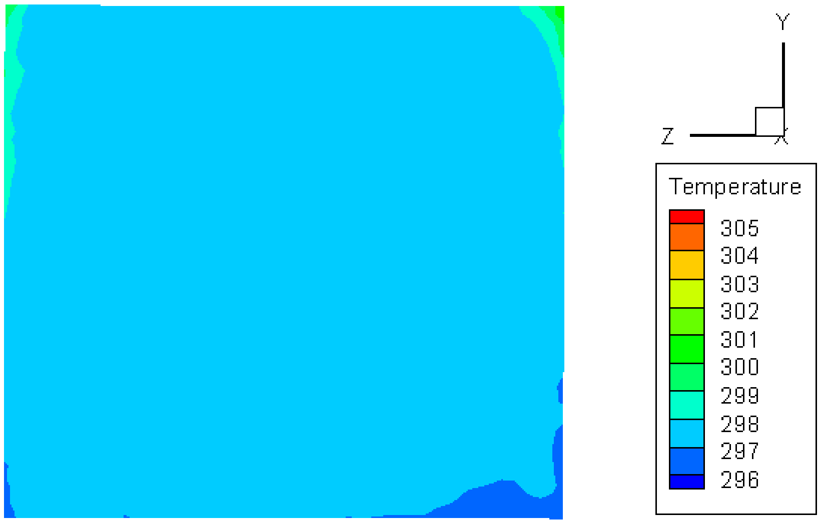

Figure 16. Temperature contours in median plan of the proposed room with ventilation fan

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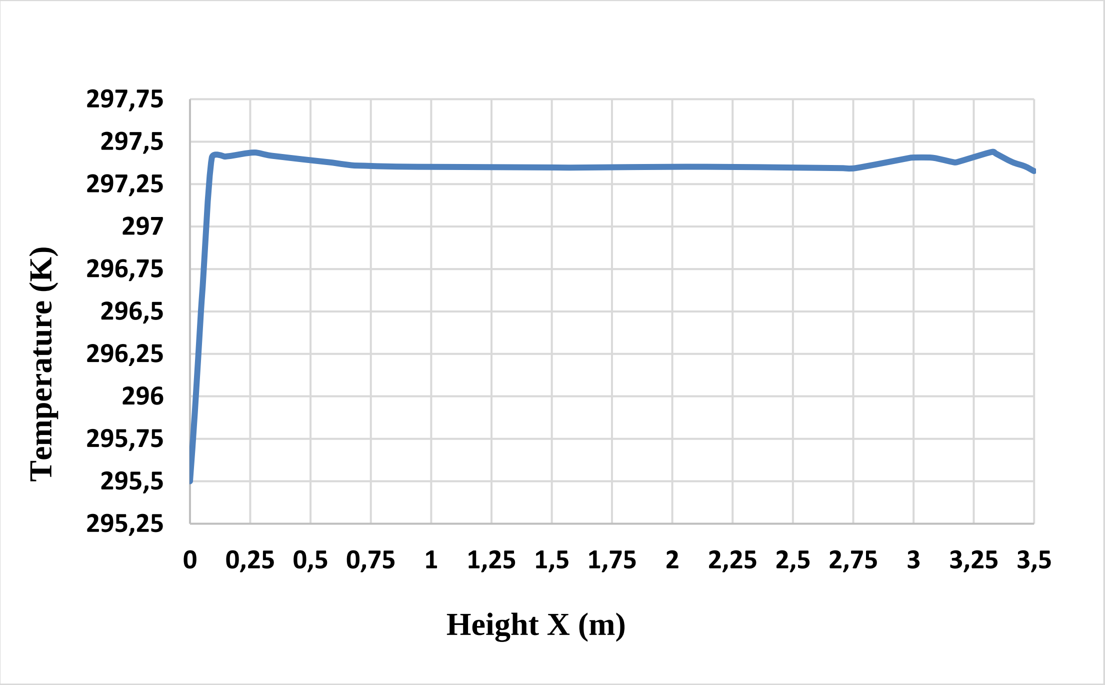

Figure 17. Temperature on room median axis (x=2.55 m, z=2.4 m) (second case)

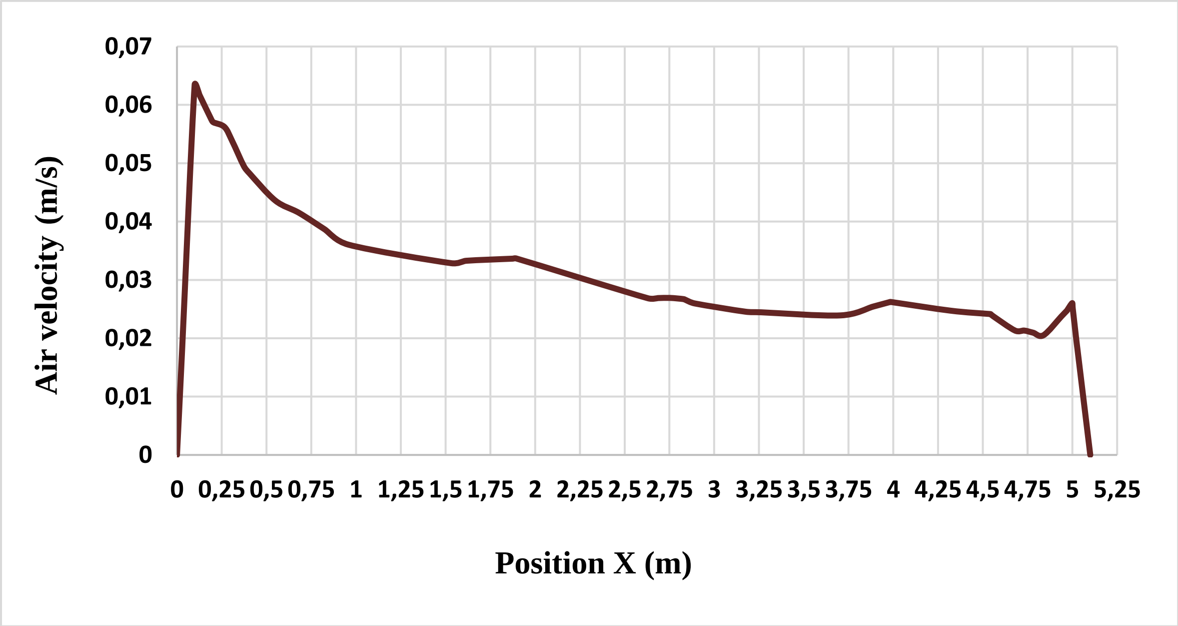

Figure 18. Velocity magnitude on the axis of y= 1.9 m, z= 2.4 m. (second case)

COMPARISON BETWEEN THE TRADITIONAL ROOM AND THE PROPOSED SOLUTIONS

Some simple modifications are introduced in the traditional house construction without any harming of the general building structure. These modifications lead to an interesting build design which performs a good passive cooling in the hard desert climate. The effect of the new design is clarified by the comparison of the indoor temperature at room middle axis between the traditional residence and the two proposed solutions (see figure 19). It is noted that the temperature levels of the two proposed solutions are significantly lower than the existing room. For the traditional room, the temperature drop at 2 m room height on the vertical middle axis of the room is 3 °C compared to the first case, but it reaches 5 °C for the second case to reach 25 °C. Also, for the forced ventilation case, the indoor temperature is stabilized at about 25 °C from 0.25 m room height, but for the two other cases, the temperature has a continuous rise. In addition to improving the thermal aspect, the ventilation fan makes a net amelioration of room aeration which gives more comfort for the occupants. For this forced air ventilation, an appropriate fan is chosen from the catalogue of SIKU-Silenta manufacturer (2018) [35]. The nominal power of the chosen fan is 24 W with an airflow rate of 292 m^3/h. So, the small size fan has low energy consumption which is considered as a negligible electrical load.

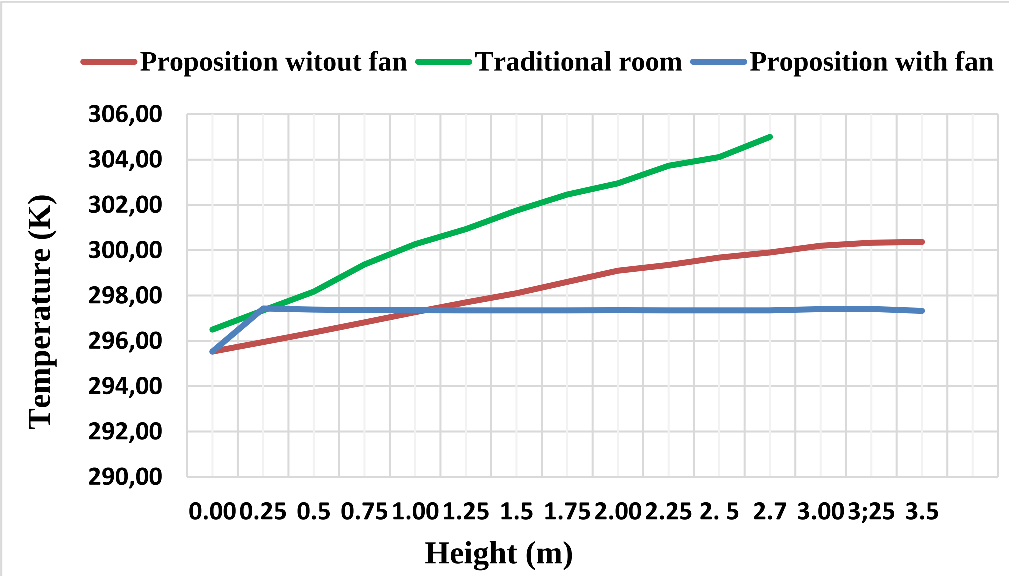

Figure 19. Comparison between the traditional room and the proposed designs

CONCLUSION

In this paper, the thermal behavior of semi-underground room in a hot climate is examined by three-dimensional airflow simulation and experimental measurements of indoor temperature.

- The simulation results of the airflow in the base case of the semi-underground room are validated by the experimental data.
- The results of the base case room show an insufficient performance of the passive cooling in a hot period of summer.
- The validated mathematical model of indoor airflow gives an appreciable opportunity to ameliorate the thermal behavior. This amelioration is based on the design adjustment and operating parameters improvement.
- Two proposed designs are examined under the critical situation of ambient temperature. The first design examined under natural ventilation; it shows an appreciable improvement of thermal comfort. But, the second design reinforced by a small fan, it shows better passive cooling where the temperature is very acceptable in all living space of the room.
- During the period of high heat (48 °C), the two configurations show that the design of semi-underground rooms presents a very interesting solution for the building's design. The temperature in the middle of the room does not exceed 25 °C at the height of 2 m, while the temperature for height between 2 m and 3 m, the temperature fluctuates between 25 °C and 27.5 °C.

For forced ventilation case, the level of ventilation remains not annoying and ensures good room aeration. The room reaches a very appreciable cooling; it is considered as an acceptable thermal comfort with small spending of energy consumption.

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