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Research Article

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Numerical analysis of the thermal behavior of building integrated hybrid solar wall

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Abstract: Building designers have to think about new strategies to achieve the best sustainable building designs. Well-planned passive solar heating strategies in building design may reduce a building's energy consumption significantly. In this paper, a proposed design of the south façade of a room by integrating a hybrid solar wall and a window to passively heat a room is studied. The simulations for the three-dimensional model of BIPV Trombe wall system were carried out for December 10th, 2015. The temperature and velocity distribution of indoor air in different positions inside the room are obtained from the simulation results. The obtained results show that the temperature difference between the inlet and the outlet of the solar wall can reach 9°C. The 3D analysis of the proposed model clearly shows that the window's thermal effect on the passive heating cannot be neglected. Meanwhile, the simulation's daily electrical efficiency conversion and average indoor air temperature of this system can reach 18% and 28°C, respectively for maximum solar radiation of 470 W/m^2.

Keywords: Natural ventilation, Trombe wall, photovoltaique cells, hybrid solar wall

1 Introduction

Control of natural ventilation provides answers to multiple issues. First, it allows the building to have a sufficient quality of indoor air for the health of its occupants, replacing the stale air released by the occupants and the various sources of pollution (kitchens, bathrooms, workshops, etc.) with fresh air. Secondly, it contributes to the sustainability of buildings by removing moisture that could cause damage.

Any solution for ventilation must be adapted to the local context, climate, urban, technical and economic. Our prototype provides passive heating of a room based on the phenomenon of natural convection. The solar energy utilization in the field of the habitat to reduce its energy consumption has been the subject of several studies. A technique of heating based on the solar system, that of collecting, storage and restitution of heat was developed with the C.N.R.S. (France) by Trombe [1].

The use of solar energy in the area of habitat to reduce its energy consumption has been the subject of several studies. Bassiouny *et al.* [2] also studied the influence of certain parameters on the thermal behavior of solar chimney to optimize its design. The results obtained show that the width of the chimney has a very important influence on the ACH (air changes per hour) compared to that of the inlet section. The results show that there is an optimum intake section beyond which ACH begins to decrease. It was concluded in the study that increasing the intake size three times improves the ACH by almost 11%. However, increasing the width of the stack by a factor of three improves the ACH by nearly 25%, keeping the intake section fixed. Subsequently in 2009 [3], the same researchers studied a solar chimney placed on a sloping roof to see the influence of the inclination on the thermal behavior of the chimney. The results show that the inclination significantly affects the rate of ventilation and the airflow, which crosses the chimney. This study shows that the optimum angle of inclination of the stack is between 45° and 75° to 28.4° latitude.

Guohua *et al.* [4] numerically studied natural ventilation through a vertical solar chimney using a CFD model. The simulation is performed using two fields, the first (s) identical to that of the cavity size of the stack, and the second (L) is extended. It has shown the use of two areas for effective simulation for a variety of ventilation; however, the use of a single field identical to that of the cavity of the chimney size is favored for long chimneys where the wall strength is dominant. Photovoltaic cells are adapted to receive the electrical gain using a hybrid solar wall. Basak and Zerrin [5] studied the design parameters that influ-

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enced the thermal efficiency of a solar wall such as the south facade.

A numerical model carried out by Bourdeau and Jaffrin [6] and Bourdeau *et al.* [7] showed that the use of a wall of 3.5 cm thickness can replace a wall of concrete having 15 cm thickness. The use of pcm reduces 90% of mass of wall of storage and increases their effectiveness by a factor of 20% [8].

Zalewski *et al.* [9] concluded that the solar energy that crosses the glazing is approximately 78 kWh/m^2; the wall in PCM absorbs 37.7 kWh/m^2, which accounts for 49% of incidental energy. The wall in PCM generates 23.5 kWh/m^2 in the open cavity and this quantity accounts for 68% of absorptive energy. Thus, the effectiveness of this wall does not exceed 30%. The aim of this work is to produce a three-dimensional numerical model of the passive heating of a place with a hybrid solar wall. This prototype is designed for cooling the PV cell and providing a passive heating to our home for the cold period of the year.

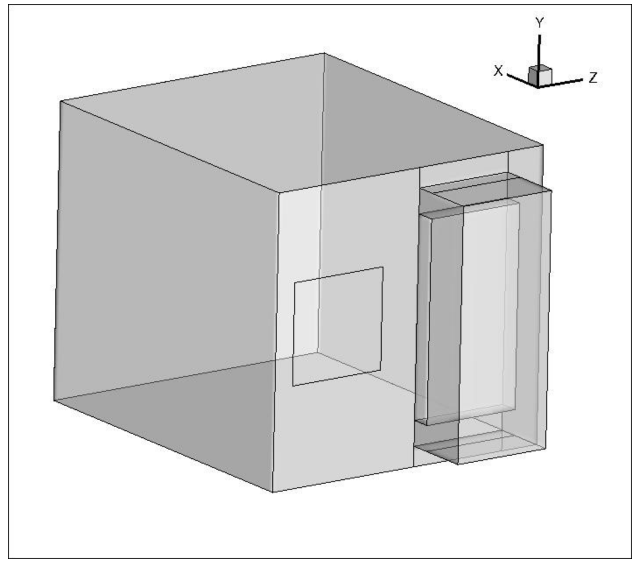


Figure 1: A general schematic of the physical domain.

2 Physical model

Figure 1 illustrates a schematic of the physical domain, with an attached hybrid solar wall of length L, and width d. The domain considers having a window (1 m × 1 m), and it is at 1 m height from the floor. The considered dimensions for this room were 3.5 × 3 × 3 m (Figure 1), and the hybrid solar wall was considered with 1.8 m length and 1.2 m width and the air gap was taken as 0.5 m.

The PV-Trombe wall system, as shown in Figure 1, is composed of a semi-transparent PV cell panel, a thermal mass wall acting as a thermal absorber and an air duct in between. There are also two air vents for winter heating. The PV-Trombe wall system works as the original Trombe wall and its detailed description can be found in [10].

3 Boundary condition

Our area to be treated is a three-dimensional room (Figure 2), having a hybrid solar wall and a window on the south façade. All the walls of the studied rooms are adiabatic, except the south wall. The convection and the radiation heat flux effect are added at the south wall and the concrete roof.

Where the solar radiation values are from real climatic data of a typical day of Tlemcen. The convection heat transfer coefficient due to wind is defined by equation (1) recommended by McAdams [11]:

$$h = 5.67 + 3.86V_{wind} \tag{1}$$

where V_{wind} is the wind velocity.

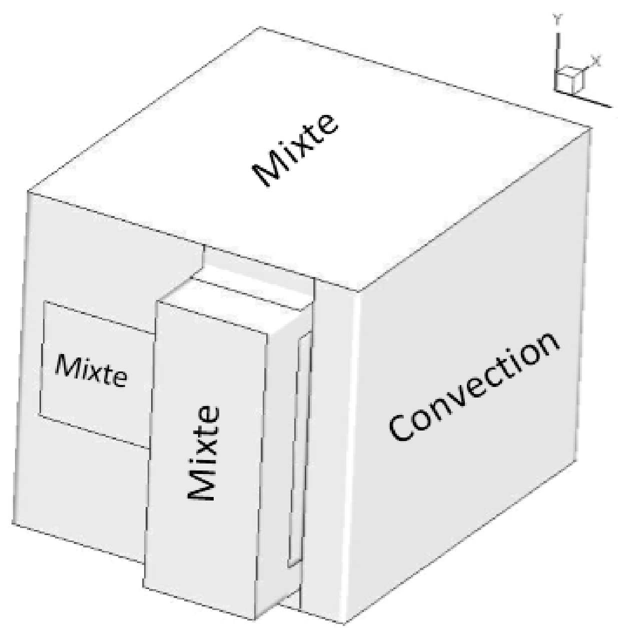


Figure 2: Boundary condition adapted in CFD model.

The air inside the hybrid solar wall is heated by the greenhouse effect. The warm air lighter as it is less dense, and hence it rises, which causes the aspiration of fresh air. The circulation of air is made naturally without mechanics; this circulation also ensures the free cooling of our photovoltaique cell. The outlet at the top of solar wall is in the opposite direction of the inlet (at the bottom of the solar wall). The size of the inlet section of the solar wall is identical to that of the exit section. Simulation is carried out under the laminar mode, and the air is initially considered stable.

4 Result and discussion

The following sections present the numerical results obtained from the three-dimensional unsteady-state turbulent simulations using the standard k-ϵ model with an enhanced wall function for the attached solar chimney model.

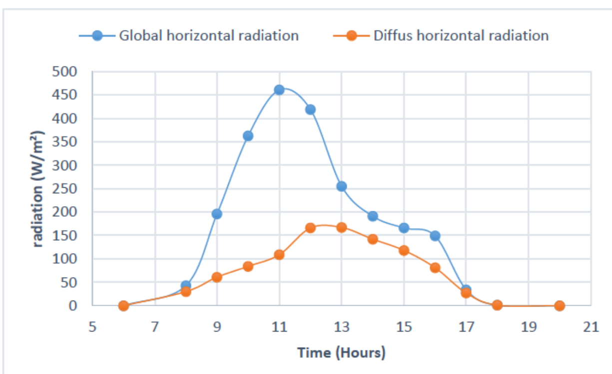


Figure 3: The hourly solar radiation in Tlemcen on December 10th.

The simulation has been carried out with the data of a day during wintertime (December 10th) in Tlemcen (altitude 750 m, latitude 35° 28'N, and longitude 17°1'). The hourly variation of global and diffuse horizontal solar radiation during the 24 hours of the selected day is shown in Figure 3.

After designing the models using Gambit software, their networking is made by organized networks. The boundary conditions of the models are defined based on Figure 2, although these conditions can be altered by "Fluent software" in the next stages of the analysis.

The commercial CFD software package, FLUENT, which is based on the finite volume approach was used for the simulation in three dimensions using the segregated solver.

In the second stage, the models are utilized in "Fluent software" (Fluent 6.3.26), the solution condition is described as follows:
Solver: Pressure based
Space: 3D
Formulation: Implicit
Time: Unsteady
Operating pressure: 101325P

The convergence criterion was set equal to 10^{-6} for all the parameters.

To verify the precision of the developed numerical model, we propose to compare the obtained results with those obtained experimentally by Basak and Zerrin [4] who studied a Trombe wall system with single glass, double glass and PV panels. Figure 4 represents the hourly change in surface temperature of the PV cell recorded for two successive days. A comparison shows that our results that appear in dotted black curve agree well with that of the literature [4]. This proves the good accuracy of the method proposed in this work.

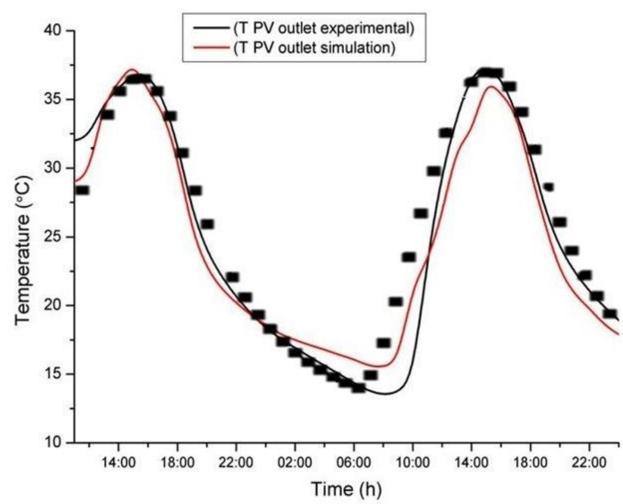


Figure 4: Validation of results.

Figure 5 and Figure 6 show the temperature contour recorded every two hours starting at 07:00. The higher values of solar radiation increase the air temperature inside the chimney and the air temperature difference between the inlet and the outlet of the hybrid solar wall also increased (Figure 5).

The air temperature rise in the proposed model is proportional to the solar radiation intensity. An increase in solar intensity increases the PV cell temperature and consequently increases the air temperature inside the hybrid solar wall. We can see clearly that the important values of temperature are recorded near the PV cell and the window. The air inside the room is warmed naturally by the solar chimney effect explained bellow.

Figure 4 shows that the window has a more significant effect in the passive heating of air inside the room. The ther-

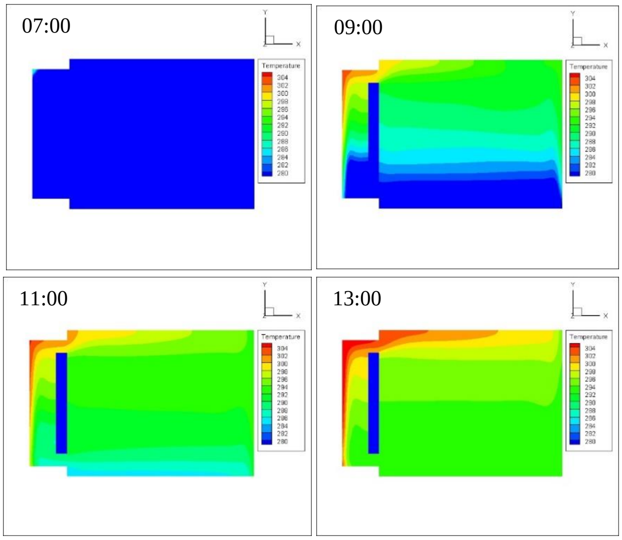


Figure 5: Temperature contour recorded every two hours (z = 2.4 m).

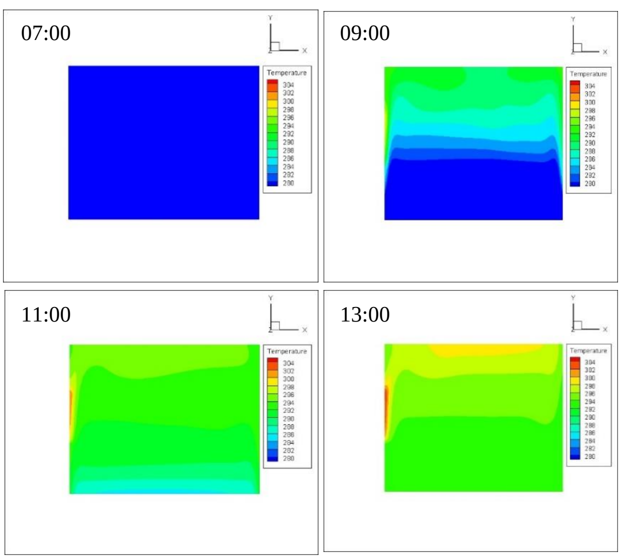
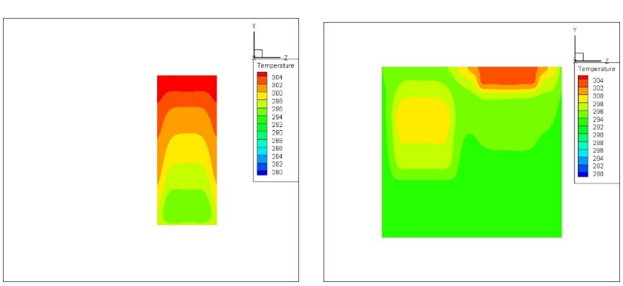


Figure 6: Temperature contour recorded every two hours (z = 1 m).



(a) **(b)**

Figure 7: Temperature contour near the PV cell (a) and the window (b).

mal effect of adapting a window in the south wall cannot be neglected, which proves that the study of a similar problem could be carried out in three dimensions.

Figure 7 shows the air temperature distribution inside the hybrid solar wall near the PV cell (a) and the air temperature distribution inside the room near the window (b). The figure indicates the significant temperature changes corresponding to solar intensity variations. Further, as the intensity increases, there is an increase in all the temperatures. During the day, we notice that the PV records the most important temperature. As seen in Figure 7, the temperature reaches 304 K near the PV and 300 K near the window.

Figure 8 shows the evolution of the temperature fields inside the test room. The heat generated in the level of the PV cell and the window has a significant impact on the temperature distribution inside the room as seen in Figure 8. The highest temperature recorded inside the room are located on the top near the ceiling (≤ 302 K).

As seen in Figure 9, the following inlet and outlet hybrid solar wall temperatures are compared. The fresh air inside the room will be changed with one warmed naturally by the greenhouse effect inside the hybrid solar wall during the day. The air temperature in the inlet and the outlet of the hybrid solar wall reach the maximum value at 1300 hours which is 302 K and 293 K, respectively. Figure 10 shows the hourly electrical efficiency change with PV cell surface temperature during the selected day December 10^{th}, where the PV cell conversion efficiency related to the cell temperature is:

$$\eta_{pv} = \eta_0(1 - 0.0045(T - 298.15)) \qquad (2)$$

η_0 is the electrical efficiency under standard conditions (1000 W/m^2, 25°C) [12].

The PV cells have the ability to produce electricity during the day as long as it is exposed to the solar radiation. As seen in Figure 10, the electrical efficiency conversion has its highest value that was recorded at 0600, which is 18.02%, while the surface temperature of the PV cells has its lowest value of 14°C. The electrical efficiency drops to its lowest value of the day at 1300 which is 16.3% when the surface temperature of the PV cells increases to its highest value of 37°C. Then, the electrical efficiency conversion increases to 17.94% at 1800 as the surface temperature of the PV cells decreases to 16°C.

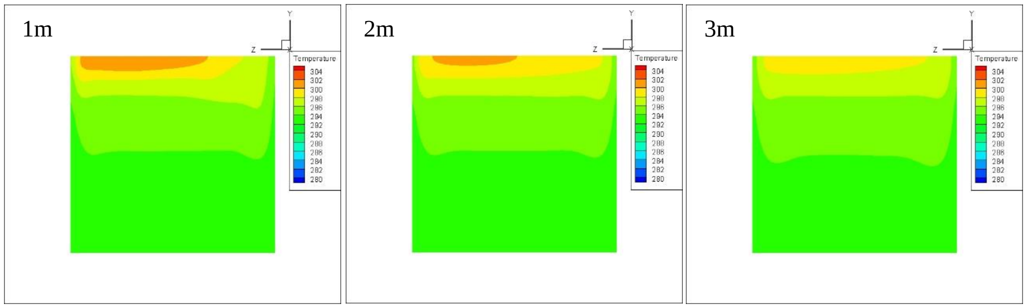


Figure 8: Temperature contour in 1, 2 and 3 m along the x-axis from the south façade, respectively.

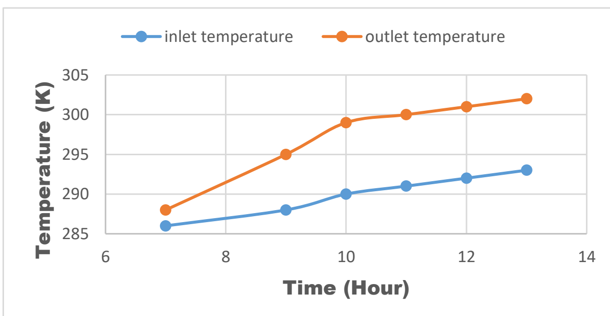


Figure 9: Temperature variation at inlet and outlet of the hybrid solar wall.

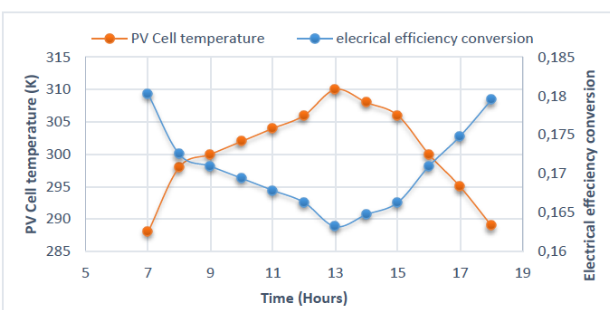


Figure 10: The hourly change in the efficiency and temperature of the PV cell in both models.

5 Conclusion

The aim of this work is to present a thermal performance of hybrid solar wall integrated in a passive solar building in Tlemcen. The numerical simulation using the segregated solver with real climatic data conditions of Tlemcen city.

Firstly, this study shows that the solar wall is an effective solution for the passive heating of the buildings. By adapting a solar wall, the temperature of air of the room can reach 28°C when the ambient temperature is lower than 21°C.

Secondly, the results obtained show that our hybrid solar wall ensures a good cooling of the photovoltaic cell that enabled us thereafter to reach a better electric output.

It is interesting to note that the excess heat released by the PV cell is used for heating the room passively; despite that, the PV cell is cooled down by the fresh air aspired from the room.

There exist several improvements to increase the effectiveness of our solar wall, like the use increases the insolation of surrounding walls to limit the heat losses toward the outside, or the integration of the PCM to prolong the operating time of our wall of storage.

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