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Performance Evaluation of a Hybrid Solar-Powered Evaporative Cooling System for Residential Buildings in Hot Regions

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Abstract: In this study, the thermal performance of a hybrid solar power evaporative cooling system for an Iraqi summer climatic condition is investigated numerically by using, the SimScale Computational Fluid Dynamics (CFD) platform, for a residential room. A 3-D model was created to simulate the air flow distribution and temperature differences in the indoor area. From the simulation results it was seen that the indoor air temperature was reduced by around 10-13°C as compared to the outside ambient temperature by introducing the proposed system. Moreover, the hybrid system optimised the temperature distribution inside the working space, by almost 25–30%, and the PV panels integration reduced the use of grid electric energy, by almost 100%, for the daytime operation. The airflow analysis showed there were only small recirculation areas at the room corners which resulted in good air circulation and improved thermal comfort. The proposed cooling system is overall energy efficient and environmentally friendly for cooling applications in residential buildings under hot-arid climatic conditions and has the potential to minimize energy consumption requirements for cooling compared to conventional air-conditioning systems.

Keywords: Evaporative cooling, Solar energy, SimScale, Residential building, Thermal comfort.

1. Introduction

Many buildings use conventional air conditioning systems as a way to achieve thermal comfort in the interior during the summer months, especially in hot-arid environments where the summer temperatures are often over 45°C and a significant amount of electrical energy is used with these systems, which contributes to greenhouse gas emissions. As a result, research has been undertaken into sustainable and energy efficient cooling technologies. Solar energy is regarded as one of the most promising renewable energy resources that is abundant and environmentally friendly. The combination of solar PV (photovoltaic) with cooling technologies can help to lessen reliance on traditional electricity and to cut operating costs. Evaporative cooling is one of the cooling techniques that is known to be effective and low energy consuming particularly in hot and dry climate where the evaporation process could significantly reduce the temperature of the air. Hybrid solar powered evaporative cooling systems offer an environmentally friendly solution for residential applications, by utilizing the benefits of both solar energy and evaporative cooling. The systems use electricity produced by solar PV to drive fans and water pumps, and cool via water evaporation. This method can help to make use of energy more efficiently and decrease the environmental footprints of conventional cooling techniques. This study examines the thermal performance characteristics of the hybrid evaporative cooling system with solar energy for cooling residential buildings in hot-arid climate. A numerical model is designed to analyse the temperature

distribution inside and estimate the efficiency of proposed system to increase thermal comfort and reduce energy consumption.

With growing demand for sustainable cooling solutions, scientists have started exploring the integration of renewable energy resources with evaporative cooling to create hybrid cooling systems. A hybrid evaporative cooling system powered by transpired solar collector and underground heat exchanger was developed by Abed [1]. They verified through both experiment and simulation that the developed system kept the temperature of the house 2-6 degrees lower than the ambient temperature and saved a considerable amount of cooling energy consumption. The same authors subsequently reported that the integration of an underground heat exchanger with evaporative cooling reduced the indoor temperature by up to 12°C, and the cooling load by about 50%, as compared with conventional cooling system. Numerous numerical studies have also been carried out to enhance the thermal comfort inside a building by using hybrid cooling systems. [2] numerically simulated a solar chimney system comprising an evaporative cooler, an earth air heat exchanger and a solar chimney using CFD techniques. The results yielded by their research revealed significant enhancement in distribution of indoor air flow and thermal comfort in Iraqi climatic conditions. They also found that the passive ventilation and evaporative cooling approach was effective in achieving the desired reduction in indoor air temperature whilst limiting electricity usage. Due to the rapid development of renewable energy technologies, the hybrid solar assisted evaporative cooling systems have gained more and more attention. Xue [3] gave a review of the hybrid evaporative cooling systems with solar energy technologies. They noted that such systems have the potential to significantly cut down on the use of electricity and greenhouse gas emissions, while also offering efficient cooling capabilities. The authors further found that hybrid solar-evaporative cooling technologies are well suited for hot-arid climate conditions as the availability of solar radiation also matches the peak cooling demand. The use of passive cooling methods in parallel with evaporative cooling systems has also been studied recently. The paper titled: Hybrid evaporative cooling and domed roof configuration has been published in Sustainable Cities and Society, 2022, and proposed a hybrid configuration of evaporative cooling and domed roof to achieve cooling for the building. The CFD study showed that the system provided better air circulation, better thermal comfort and significant reduction in the cooling energy consumption of the building as compared to the conventional cooling systems. In more recent studies, Khikmatullayevich studied the combined evaporative cooling system with PV modules for residential buildings. They have found considerable enhancements in the indoor thermal environment in their experimental study when operating in very high solar radiation conditions. The authors pointed out that solar radiation and window heat gain are a significant percentage of the cooling load, and discussed the need to incorporate renewable energy technologies into residential cooling applications. Recently, buildings in hot and dry climates have made improvements in the application of evaporative cooling technologies, the subject of a recent review published in Buildings. The review found that evaporative cooling is one of the most energy efficient systems in comparison to the conventional vapor compression air-conditioning, especially in regions of low relative humidity. Moreover, the review revealed that the overall performance of evaporation cooling systems has significantly improved in recent years due to innovations in cooling pad, water management system and hybrid configurations. There has been some research interest in the combination of evaporative cooling and PV technologies. In the arid climate, Mahmood [4] conducted experimental studies for hybrid evaporative and groundwater cooling for photovoltaic applications. Their results indicated that the evaporative cooling function significantly lowered operating temperature of the PV and enhanced electrical efficiency, confirming the potential of using evaporative cooling in combination with renewable energy systems. Furthermore, Wang [5] conducted a review on the solar-assisted heat pump systems based on photovoltaic, solar thermal, and photovoltaic-thermal technologies for building cooling applications. They concluded that PVs-assisted systems have a good techno-economic performance and high energy savings. Likewise, Aili [6] also concluded that evaporative cooling has a better cooling performance in hot and dry regions because it is more effective when humidity

levels are low. Furthermore, Mihalakakou conducted a review on the different earth-to-air heat exchanger (EAHE) technologies and found that they can lower building cooling loads and increase the thermal comfort inside the building. In general, the previous studies have shown that evaporative cooling systems with solar energy, passive ventilation, EAE, thermal storage and PV technologies can considerably enhance cooling performance and also minimize the energy use and environmental impact. While efforts have been made in this field, few studies have numerically investigated the thermal performance of hybrid evaporative cooling system (ECS) for residential building in hot-arid climate of Iraq via CFD simulation. Based on the above, the present study is aimed at investigating the thermal performance of a hybrid solar-evaporative cooling system for thermal comfort inside a residential room by applying SimScale platform and to test the system's performance in enhancing the thermal comfort inside the room and decreasing the cooling energy demand[7].

2. Methodology

Three dimensional Computational Fluid Dynamics (CFD) model was developed to study the thermal performance of a hybrid solar – evaporative cooling system for a residential room in a hot arid climate. Numerical simulations were done on the cloud-based simulation platform SimScale[8].

2.1 Geometry Description

The selected room for the study was 4 m x 4 m x 3 m (L x W x H) room. Air inlet was installed in the room for connection with the evaporative cooling unit and air outlet was installed to provide continuous ventilation[9].

2.2 Hybrid Cooling System

The cooling system design includes photovoltaic (PV) panels, a fan, water pump, and an evaporative cooling pad. The cooling process has been accomplished by evaporation of water, and the cooling functionalities of the cooling components have been driven by solar energy generated by the PV panels[10].

2.3 CFD Simulation

Solutions were numerically analyzed in SimScale, using the CFD module. The governing equations of the airflow and heat transfer within the room were solved to simulate the flow and heat transfer. Turbulent flow model was used to precisely calculate the creation of air circulation and temperature distribution in the indoors.

2.4 Boundary Conditions

The simulations were carried out in a base state of summer when the hot arid condition is common in the regions. So the temperature and the relative humidity of the outdoor air were taken to be 48° C, 20%RH. The cooled air from the evaporative cooling unit entered the room through a square inlet having a dimension of 0.5 m × 0.5 m at an air velocity of 1.5 m/s and entered the room at 31°C. The outlet opening was specified to be a pressure outlet in an atmosphere[11].

2.5 Material Properties

It was assumed that the air is used as a working fluid, and the room walls are made of a normal brick wall. Heat transfer through the walls was included in the simulation model.

2.6 Simulation Cases

Two different cases were investigated:

Case 1: No cooling system in the room.

- Case 2: Room with an Evaporative Cooling System using Solar Power.

2.7 Performance Indicators

The performance of the proposed system was checked by using the following:

- Air temperature distribution inside building.
- Average room temperature.
- Airflow distribution.
- Cooling effectiveness.

Potential energy savings that can be realized from solar-powered operation. As in figure (1)



Figure (1): solar PV panels.

2.8 Proposed Hybrid Solar-Powered Evaporative Cooling System

The proposed Hybrid cooling system is a combination of photovoltaic (PV) power generation system with direct evaporative cooling system for energy efficient cooling application for residential building in hot arid region. The PV panels generate direct current (DC) electricity, as shown in Figure 2. A MPPT charge controller is used to control the generated electrical energy for the purpose of extracting as much energy as possible from the system while maintaining the stable operation. The electricity is then utilized for the operation of the DC fan and water pump and a storage battery is included to maintain water pump and fan operation when sunlight levels are low. The water pump pumps the water from the water tank to the top of the evaporative cooling pad, and the water is evenly distributed over the surface of the pad. A closed loop recirculation system recovers excess water for re-use, thereby reducing water usage. At the same time, the DC fan pumps the hot outdoor air, around 48°C, to the wetted evaporative cooling pad. In the process, some of the water will evaporate and take up latent heat from the air that is being blown, and the dry-bulb temperature will drop significantly. Therefore, the cooled supply air air temperature is provided into the residential room in the range of 30-32°C. This configuration combines renewable solar power for cooling elements and reduces conventional electrical power consumption, thus providing a better thermal comfort in the interior of the building and a lower energy consumption. The system is especially appropriate for hot-arid areas, where the cooling loads are highest when the sun is shining the most[12].

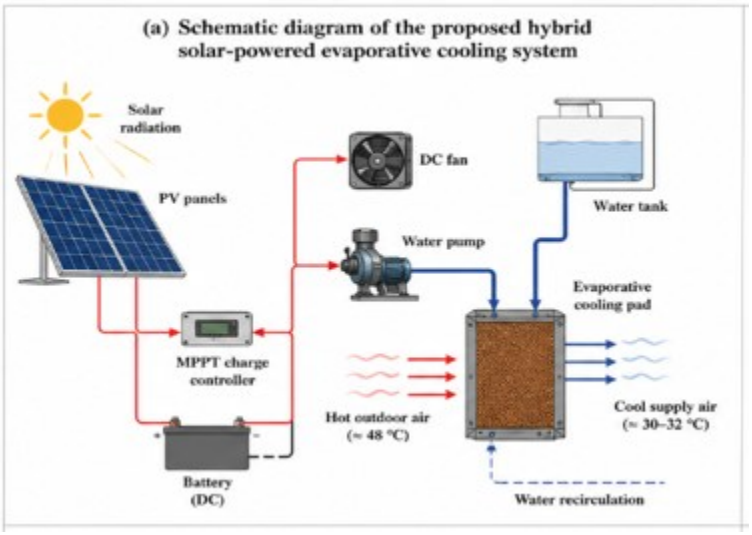


Figure (2). Schematic diagram of the proposed hybrid solar-powered evaporative cooling system

Figure 3 show a Geometry and boundary conditions of the computational model as showed below:

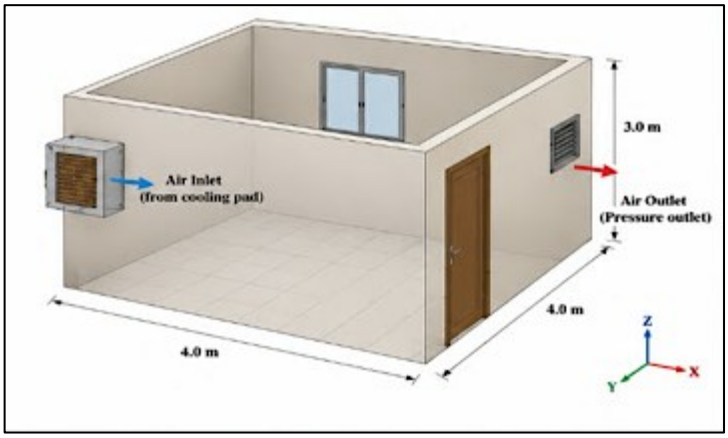


Figure 3. Geometry and boundary conditions of the computational model.

3. Results and Discussion

The three-dimensional CFD model of residential room for the present study is shown in Figure 4. The model is made up of one air inlet (representing evaporative cooling unit) and one air outlet (at the other side to provide continuous ventilation). This arrangement enables to cool the air and take it through the occupied zone to exit from the room, which helps to improve indoor air circulation. The simplified geometry was chosen to minimize the amount of calculation while still embodying the geometry of a typical residential space. Further, the configuration of inlet and outlet allows to develop appropriate boundary conditions for the assessment of the thermal performance of the proposed hybrid solar-powered evaporative cooling system. The computational mesh created for the numerical simulation is shown in figure 5. The mesh was sufficiently fine to properly capture the flow and heat transfer properties within the room. Special refinement was used in the regions where the velocity and temperature gradients were considered to be large, such as close to the inlet air and surrounding walls. The quality of the computational mesh is critical for maintaining numerical stability and accuracy of the predicted results. The adopted mesh is therefore considered as good enough to represent the computational domain, and to obtain acceptable computational time. The streamlines of flow for different airflow inside the room with the hybrid evaporative cooling system in operation are depicted in figure 6. These cool incoming air comes into the room at a relatively high velocity while the cool air is slowly diffused among the occupied space and

allowed to flow out from the outlet. Several recirculation zones are seen near the corners which shows good mixing between the cool air supplied and indoor air. This airflow helps in regulating temperature and improves indoor thermal comfort, and is a beneficial characteristic of the airflow pattern. In addition, the gradual decrease in air velocity from the inlet is primarily due to wall friction and to the loss of air momentum when it is moving. Figure 7 shows the temperature within the house room in the domain. The colder air is near the air inlet through which cooled air enters the room while the air temperature rises from the other side of the room where the air was coming out onto the warmer air in the interior room.[13] The measured temperature difference shows the effectiveness of the evaporative cooling system under practical conditions in reducing the temperature of the indoor air. The results also show that the cooling effect operates over wide area of the occupied zone, thus demonstrating the ability of the proposed cooling system to achieve satisfactory cooling conditions in hot-arid climatic conditions. The temperature distribution along a section plane passing through the room is shown in Figure 8. The cooled air penetration into the indoor environment is clearly shown with the cutplane visualization, and the increase in temperature is clearly visible with the distance from the air inlet. This is a result of both convective heat transfer and air mixing within the room. The sectional temperature profile also shows that the cooling system is effective in decreasing the temperature of the inside space over the major part of the space. As a result, the occupants' thermal environment is more favorable than it would be in a building with natural ventilation. The result of the simulation is shown as a surface temperature distribution of the room walls in Figure 9. As can be seen the results show that the majority of wall surfaces are still within the relatively high temperature ranges due to the continuous heat gain from the hot outdoor environment. However, lower surface temperatures are seen near the air inlet due to the cooling effect that is generated by the air supplied. It was confirmed that temperature distribution has a large impact on the thermal performance inside the building when considering heat transfer through the building envelope. The outcome shows the need to integrate the effective cooling system with suitable thermal insulation to further decrease the cooling loads in the interior space and contribute to the overall energy efficiency of the system[14].

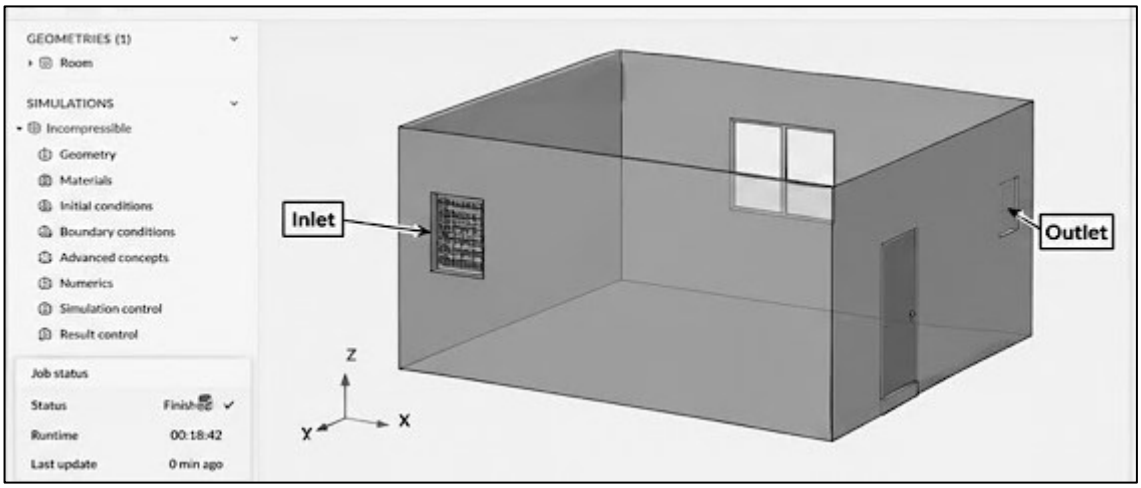


Figure 4 Computational geometry of the residential room with inlet and outlet boundary condition

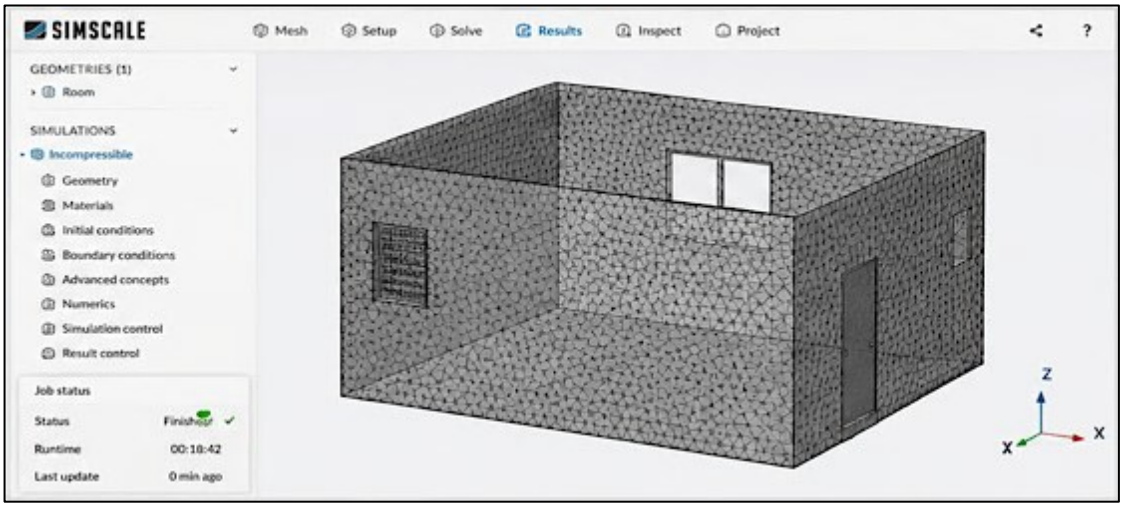


Figure 5 Computational mesh generated for the numerical simulation of the residential room.

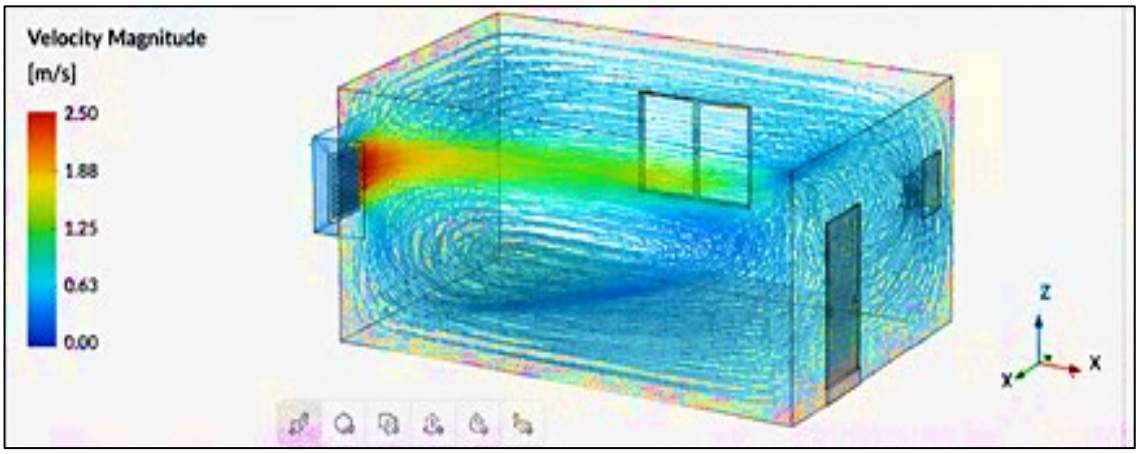


Figure 6 Airflow streamlines inside the residential room under hybrid solar-powered evaporative cooling.

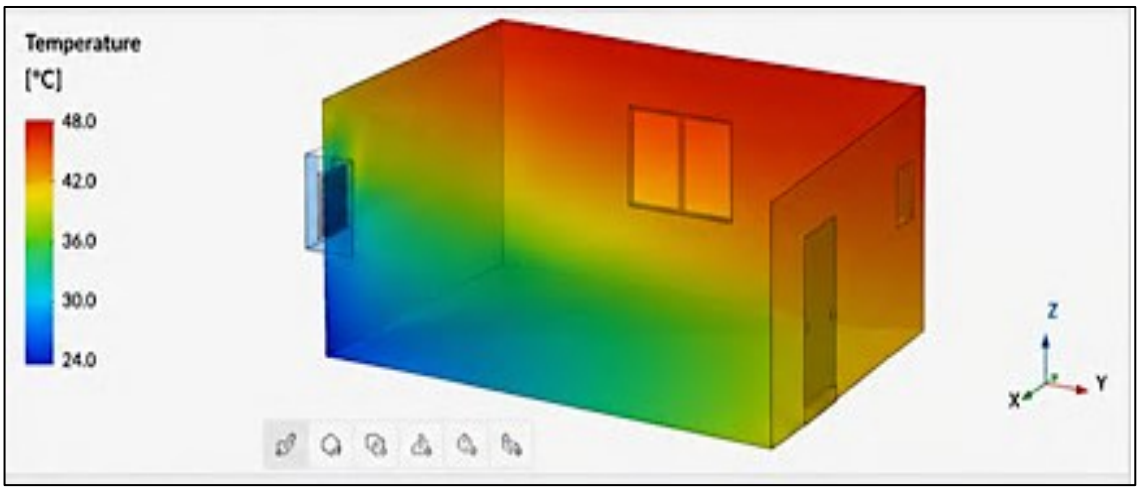


Figure 7 Temperature contour showing the indoor air temperature distribution within the residential room.

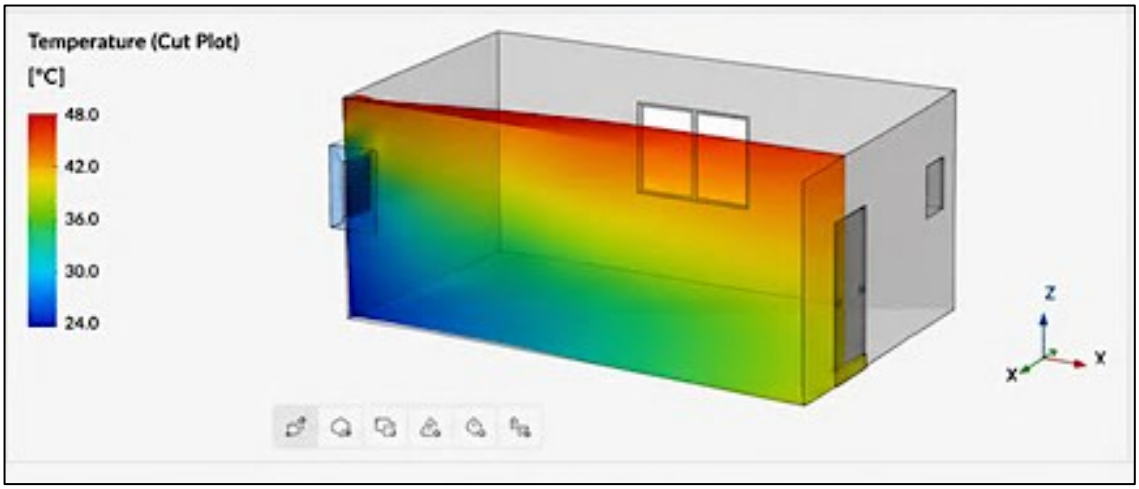


Figure 8 Cross-sectional temperature distribution (cut-plane) inside the residential room.

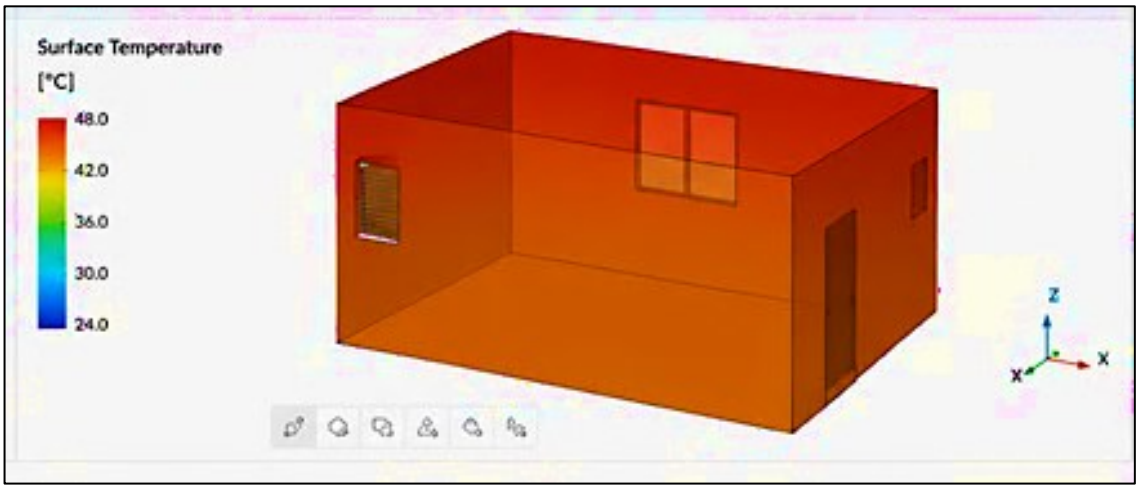


Figure 9 Surface temperature distribution of the residential room during the numerical simulation.

The numerical outcomes show that, the proposed hybrid solar power assisted evaporative cooling system is a significant improvement of the indoor thermal environment in hot arid climatic condition. The evaporative cooling unit creates an air flow that improves air flow in the room and equalises the temperature in the room. The temperature contours show that the air-cooled space has a reduction in temperature through the occupied space which is evident when compared to the temperature outside. Localized recirculation areas are identified near the room corners, however, the rooms' cooling performance is not impaired. The results are in line with the studies conducted by Abed and Ghaffouri and Jubear, which showed that implementing renewable energy technologies with evaporative cooling methods can significantly enhance thermal comfort and help conserve energy. Also, the airflow and the temperature patterns generated in the obtained results reveal the feasibility of the proposed system in hot arid areas of residential applications using high intensity of solar radiation to operate the cooling system and to reduce the reliance on conventional electrical energy[15].

4. Conclusions

In the present research, the hybrid solar-powered evaporative cooling system designed for a domestic room in hot-arid climate is numerically analysed for its thermal performance on the SimScale CFD platform. Considering the results obtained, the following can be stated: The proposed cooling system was efficient in achieving the desired reduction in the temperature of the indoor space by providing cooled air and increased air flow around the room. The temperature

contours showed that the temperature inside the building was significantly low especially near the air inlet, this shows the effectiveness of the evaporative cooling process. In the third case, the airflow streamlines showed good distribution of the supplied air throughout the room, whereas, small regions of recirculation were noticed close to the corner of the room due to the geometry of the room. The numerical result indicated that the incorporation of PV technology with the evaporative cooling system is an energy efficient and environmentally friendly system for cooling the indoor spaces in residential buildings in the hot-arid regions. Heat gain through the building envelope was one of the main sources of indoor heat gains, thus emphasizing the need for better wall insulation to maximize the cooling performance. The proposed hybrid system shows great potential in terms of reduction of dependence on traditional air-conditioning system, which ultimately reduces the electric power consumption and greenhouse gas emission. Further research is needed to validate the numerical model through experimental testing, to optimize the airflow distribution, and to study the system for other climates and building layouts.

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