CFD Analysis of Photovoltaic Greenhouse Cooling System Through Natural Convection as a Nature-Based Solution to a Sustainable Agriculture in Niger, Sahel Region

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Abstract

The use of solar photovoltaic technology coupled with plant-based evaporative coolers in cooling down greenhouses is regarded as one of the greenest technology to attain a more sustainable agriculture even in adverse weather conditions such as in the Sahel. The aim of this study was to investigate the cooling effect of PV powered eco-friendly coolers onto a greenhouse microsystem. With the help of a weather station, temperature, relative humidity, wind speed, and solar irradiance data from inside and outside greenhouse were collected and analyzed. ANSYS fluent software was used to simulate the flow patterns under various weather events. When exposed to the highest solar irradiation event (1355.6 w/m^2, 34.3 °C and 71% relative humidity), the greenhouse cooling system could create a drop of 4.9 °C and an increase of 15% relative humidity. The lowest temperature attained in the greenhouse was 15.7 °C (at night) whereas the highest temperature (in the afternoon) was 37.8 °C against 40.8 °C outside. Flow patterns showed a well-distributed heat around crop's coverage area in the greenhouse. Energy production for cooling averaged around 4199.016 Wh/day despite the observation of 7620.792 Wh/day of energy loss due to full battery state. Optimization is necessary for cost-effectiveness of the greenhouse cooling system.

Keywords

Renewable energy · Computational fluid dynamic · Heat transfer · Insect screen · Evaporative cooling

Introduction

Greenhouse cooling has been of major concern in Sahelian region where temperature is relatively hotter with a predominant low relative humidity environment. Unfavorable climatic conditions are mostly caused by the changing climate leading to delays in rainy seasons, extended drought, and many adverse weather conditions forcing farmers to loose productivity and be exposed to food insecurity (Kumar et al. 2009). At first, greenhouses have been proposed by many researchers to help grow crops, especially market gardening (tomatoes, lettuce, zucchini, etc.) in those areas, yet these imported technologies were not adapted to our Sahelian environment, hence worsening the case. In fact, due to greenhouse effect, those imported greenhouse technologies heated up with time, created a saturated hot microclimate, and became a burden to crops (Manuwa and Odey 2012). Therefore, microclimate parameters of the greenhouse became a big step toward a sustainable market gardening. Parameters such as temperature, relative humidity, CO_2 content, and internal irradiation ought to be under control. In recent research advances, the experiment conducted by Gupta and Chandra (2002) on a 24 m^2 plastic covered greenhouse using negative pressure fan and pad system as cooling material caused a decrease in air temperature of 4–5 °C inside the greenhouse compared to outside (Gupta and Chandra 2002). Arbel et al. (2003) combined forced ventilation and misting/fog system and the system was able to maintain a temperature of 28 °C and relative humidity of 80% at noon (Arbel et al. 2003). Photovoltaic shading, which was experimented by Cossu et al. (2014), showed that PV greenhouses with 50% roof coverage decreased the yield of tomatoes compared to conventional greenhouses, but generated a large income from the energy produced. Roslan et al. (2018) proposed a dye-sensitized solar cell (DSSC) greenhouse shading instead of conventional PV shading as a way to selectively control radiation. DSSC could be designed to filter solar radiation allowing only light of wavelength between 400 and 700 nm to penetrate the greenhouse microclimate. DSSC of such properties have been developed by many researchers in a cost-effective manner and could be used in that regard (Cossu et al. 2014; Hernandez-Martinez et al. 2011; Kallo et al. 2021; Roslan et al. 2018; Sanda et al. 2021). Another cooling method was the evaporative cooling pads technology which was proven to be effective when outside climate is hot and dry. It is working under an adiabatic process of cooling greenhouse using warm and low-moisture outdoor air. The effectiveness of such a cooling system has been proven by many researchers (Aziz et al. 2017; Barzegar et al. 2012; Djibrilla et al. 2021a; Khobragade and Kongre 2016). More recently, the integration of renewable energy in energy or cooling system of the greenhouse could make cooling eco-friendly, reduce energy cost, and even provide income for the farmers (Marucci and Cappuccini 2016; Ureña-sánchez et al. 2012). All these technologies for cooling a greenhouse have advantages and drawbacks. Therefore, developing a more adapted cooling greenhouse using locally developed technologies is one of the best mitigation and adaptation measure for achieving a sustainable agriculture in the context of climate change. This paper explored the thermal behavior of a photovoltaic greenhouse microsystem cooled by an innovative nature based cooler technology for a sustainable horticulture in the Sahel.

Materials and Methods

Experimental Area and Setup

This study was conducted at the department of Say at 40 km from Niamey in Sahel Agro company land where a 50 m^2 photovoltaic greenhouse was installed for tomatoes production (Fig. 1). A weather station (Ambient Weather WS-2902) placed at 3 m above the ground level at about 30 m away from the greenhouse was taking continuous weather data with some of its sensors placed inside the greenhouse as well. Coolers ($L \times W \times H = 1 \times 0.1 \times 1$ m) installed at the greenhouse's side were used to cool down the PV greenhouse where PV system was used as the energy source for powering the coolers. The greenhouse was covered by special semitransparent insect screen material. Coolers were made from cellulosic materials working under evaporative cooling principle as described in Djibrilla et al. (2021a).

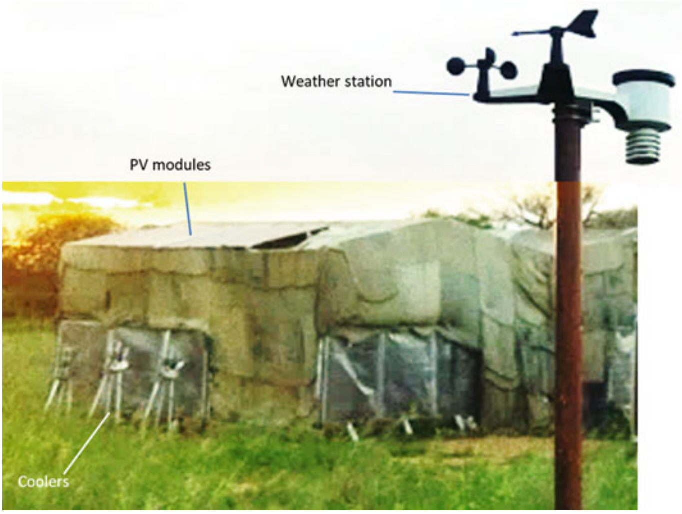

Fig. 1 A photograph of the experimental greenhouse at the department of Say (ground/field photo, 21 July 2022)

Computational Fluid Dynamic (CFD) Analysis

Flow patterns and thermal behavior of cooling photovoltaic greenhouse under natural convection were simulated using ANSYS fluent R2 2022 student version. The area of the greenhouse was 50 m^2. The greenhouse was drawn using Space Claim 2022 with 2 m high crop row, 4 mm wall thickness, and solar panels of 1650 × 995 × 40 mm, which was then transferred to workbench for computational fluid dynamic (CFD) analysis before meshing.

The flow inside the greenhouse was assumed 3D, steady state, incompressible ideal gas, and turbulent (Ferziger et al. 2020). The radiation was simulated by the discrete ordinates (DO) model as described in Chui and Raithby (1993). All boundary conditions as wall thickness, wind speed and temperature etc. were derived from actual materials datasheet (covering material and PV modules) used on the field and from weather station data installed. The external air data was directly taken from weather station output. The inlet air entered from 1.5 × 1 m coolers blowing at variable rates depending on the upcoming wind velocity obtained from the weather station taking into account case scenarios and coolers wind filtering capacity as described in Djibrilla et al. (2021b). The outlet direction was opposite to that of the inlet. Pressure drop boundary conditions were applied at the outlet. All side walls were assumed semitransparent with mixed (radiative and convective) thermal settings. Solar modules were assumed opaque with mixed (radiative and convective) thermal conditions (Djibrilla et al. 2021b; Fatnassi et al. 2015; Raithby and Chui 1993).

The configuration was pressure-based type solver with velocity formulation to be absolute under steady-state adiabatic conditions. These conditions are using Reynolds averaged Navier-Stokes (RANS) equations to resolve numerically the problem of energy distribution within the greenhouse through finite volume method. The

Table 1 Wind speed conversion data for simulation (Djibrilla et al. 2021a)

Cases for event simulation	v_{wind} from weather station (m/s)	v_{wind} from coolers (m/s)
Low T_{in}	0 (considered as 0.1)	0.02
High T_{out}	2.6	0.55
Low T_{out}	0 (considered as 0.1)	0.02
High wind	11.5	2.43
High solar radiation	1.5	0.32

specific source of fluid flow is directed by the viscosity loss term known as Darcy law and an internal loss term. The energy distribution inside the greenhouse and its covering material is calculated by RANS equation (Fidaros et al. 2008):

$$\rho U_j \frac{\partial \Phi}{\partial x_j} = \frac{\partial}{\partial x_j}\left(\Gamma \frac{\partial \Phi}{\partial x_j}\right) + S^{\Phi}$$

where Φ stands for the three velocity components U, V, and W, the temperature T(K), the spectral intensity I, the kinetic energy of turbulence k, the dissipation rate ε, the specific humidity w ($kg_{water}/kg_{moist\ air}$) and pressure P, and the parameters Γ and S^{Φ}, which represent the diffusion coefficient and source of term of Φ.

The SIMPLEC algorithm was used for pressure-velocity coupling leading to the formulation of mass conservation equation (Versteeg and Malalasekera 1995). The discretization of the terms in the Reynolds averaged transport equation was materialized by the second-order upwind (SOU) scheme (Tamamidis and Assanis 1993).

As described in Djibrilla et al. (2021a), wind at a specific speed crossing the evaporative cooling system gets its speed reduced by 21.113%. The latter represents input wind speed from the coolers. Input data from wind speed that are null were converted to a low reasonable value to avoid calculation error from the CFD system (see Table 1).

Energy Production Estimate from the Greenhouse

For the cooling system energy source, solar photovoltaic system was used with 12 solar modules of 260 Wp each and 4 batteries of 150 Ah each for optimum day use (12 h) whereby the load was 4200 Wh/day. Data has been taken for the whole experimental period and also data from PVGIS-SARAH2 (Huld et al. 2012) was used for energy estimate simulation. Inputs used for the simulation are shown in Table 2.

Results and Discussion

Weather Station Data Analysis

Table 1 summarizes data collected from weather station into maximum, minimum, average, and median value as well as most repeated value. Relationship between these values is presented in Figs. 2 and 3.

Table 2 Provided inputs

Location [Lat/Lon]:	13.000	2.000
Horizon:	Calculated	
Database used:	PVGIS-SARAH2	
Discharge cutoff limit [%]:	20	
Consumption per day [Wh]:	4200	
Slope angle [Ã,Â°]:	15	
Azimuth angle [Ã,Â°]:	180	

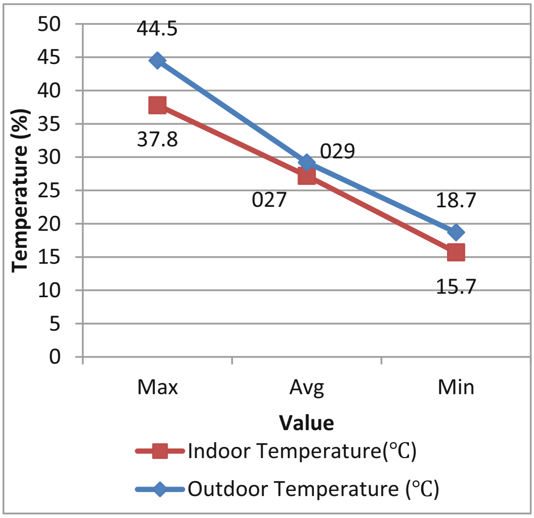

Fig. 2 Indoor versus outdoor temperature

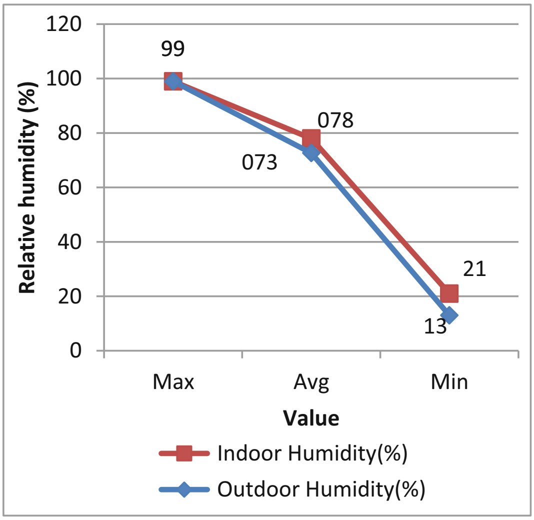

Fig. 3 Indoor versus outdoor relative humidity

The cooling of the greenhouse made the temperature of the greenhouse microclimate to be lower than outside with a difference of 6.7 °C between highest values and 3 °C between lowest values. Relative humidity was at its highest (99%) for both inside and outside greenhouse due to a rain event. However, the average and lowest values of relative humidity differed by 5.33% and 8%, respectively. This shows that the microclimate reduces stresses of plants due to dry environment. The RH conservation is better seen though Table 3 whereby a middle value of 81% RH inside against 76% outside was obtained.

The most occurring wind comes from azimuth 223° or the southern-west direction and the maximum wind speed was 11.5 m/s (Table 3) with a sudden wind burst known as gust speed having a maximum of 13.3 m/s (Table 4). Solar radiations could reach an intensity of 1355.6 w/m^2 (table 3) while the maximum rain fall event was 36.3 mm (Table 3).

Tables 4 and 5 give details on climatic conditions for the various event scenarios. Depending on the case scenario occurring in day time or in the night, solar radiation effect was turned on or off. High wind speed and low temperature events occurred in the night while high solar radiation and high temperature events occurred during the day.

Energy Production Estimate

Figure 4 presents the energy estimate analysis from the whole greenhouse energy system. The consumption (roughly 4200 Wh) was provided by batteries in a consistent manner since looking at the percentage of days during which the batteries were full, a value of 99.16% of days of full battery on average was recorded. It was in August that the lowest values of 96.57% of days with full batteries were observed. Energy loss due to batteries full varied from 8604.8 Wh (in July) to 5403.31 Wh (in December). This excess or energy loss could be channeled for further use such as storing it in another form such as green hydrogen (Haider et al. 2020). Furthermore, additional duty could be added or increasing the load to consume the excess energy such as providing nearby with energy since cooling is most needed during the day. However, the batteries could not keep providing energy for 12 h night work to make the cooling system work 24 h. Therefore, to avoid additional cost of investment, the storage in another form could be one of the best option.

CFD Analysis

Simulations were done according to various case scenarios applied onto the greenhouse (Fig. 5). Results of the simulations were viewed on planes YZ (X = 1.6 m or 4.6 m) and XY (Z = −1 m).

At high wind speed occurring during the night (Fig. 6) and coming from the southeast (127°), temperature spread rapidly and evenly within the greenhouse except at the extreme top or roof. Heat accumulation at the roof was also noticed

Table 3 Summarized weather data

	T_{in} (°C)	RH_{in} (%)	RH_{out} (%)	Dew Point (°C)	T_{out} (°C)	v_{wind} (m/s)	Wind direction (°)	Solar rad (w/m^2)	Event rain (mm)
Maximum	37.8	99	99	26.3	44.5	11.5	359	1355.6	36.3
Average	27.24	77.98	72.61	22.98	31.69	1.41	204.15	216.51	1.57
Minimum	15.7	21	13	2.8	18.7	0	0	0	0
Median	26.6	81	76	22.6	28.9	1.1	213	1.2	0
Most Repeated value	25	99	99	23.4	25.3	0	223	0	0

T_{in} is indoor temperature, T_{out} is outdoor temperature, RH_{in} is inside greenhouse relative humidity, RH_{out} is outdoor relative humidity, v_{wind} is wind velocity, °C represents degree Celsius, and ° represents degree in terms of direction/orientation

Table 4 Temperature, relative humidity, and wind data

Cases for event simulation	T_{in} (°C)	RH_{in} (%)	RH_{out} (%)	Dew point (°C)	T_{out} (°C)	v_{wind} (m/s)	Gust (m/s)	Wind direction (°)
Low T_{in} and T_{out}	15.7	72	44	6.2	18.7	0	0	349
High T_{out}	36.1	54	49	24.3	44.5	2.6	3.6	267
High wind	24.9	97	86	22.7	25.2	11.5	13.3	127
High solar radiation	29.4	86	71	23.8	34.3	1.5	1.5	170

Table 5 Solar radiation and rain event data

Cases for event simulation	Solar radiation (w/m^2)	Daily rain (mm)	Weekly rain (mm)	Monthly rain (mm)	Yearly rain (mm)
Low T_{in} and T_{out}	0	0	0	31.5	179.7
High T_{out}	471.1	0	0	15.8	125.6
High wind	0	0	38.1	0	109.8
High solar radiation	1355.6	0	1	9.4	119.2

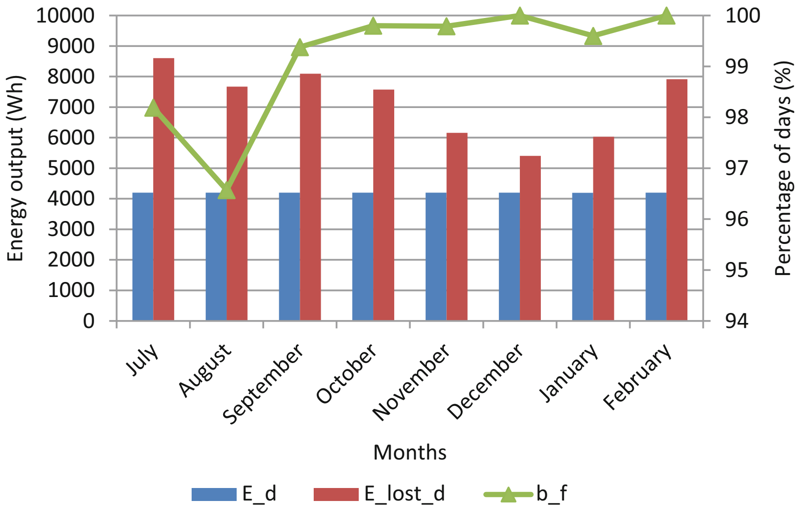

Fig. 4 Energy estimate (Huld et al. 2012). E_d represents the monthly average of daily energy production per day (Wh/day); E_loss_d, the monthly average energy not captured per day (Wh/day). These were calculated due to full battery; b_f represents the percentage of days when battery became full

by Saberian and Sajadiye (2019). This spread is shown well by the velocity profile (up to 3.083 m/s) causing high pressure difference inside(−0.8386 Pa to 5.216 Pa). This case of high speed made the density of air almost constant throughout the interior (1.184 kg/m^3). Velocity of air stream is key for heat propagation (Campen 2005).

The case scenario of high sun radiation event occurred during a day with wind coming from the southeast (170°) (Fig. 7). Temperature was at its lowest value right from the cooling wall inlet (26.85 °C) and at the highest value or at hotter point at the upper edge of the greenhouse and a part of the ground via radiation. Temperature rapidly increased due to heat transferred by photons from the sunshine. The far edge away from the blower happened to be cooler and air got denser there with less pressure. It is probably due to the fact that this corner place is away from sun rays though accumulating humid cooler air as being closer to the exit. The covering material which is filtering near-infrared radiation played a role in keeping the temperature constant within the greenhouse as indicated by Kumar et al. (2009). Besides, the temperature results obtained at night were lower than those obtained in the days as also noticed by Ahmed et al. (2010) when using evaporative cooling pads.

The low temperature scenario occurred at latter part of the night toward dawn whereby wind speed was very low and even not well detected by the weather station sensor (see Fig. 8). At that moment, the temperature nearby the inlet cooler was 15.7 °C. Pressure was low and constant along the canopy height. The atmosphere was less dense except at the inlet.

In Fig. 9, hot air entered and spread throughout the greenhouse. This event occurred when coolers were down for maintenance after cultivation and the outside weather conditions were hot as well. The accumulated heat accompanied with heat radiated by the soil made the ground hot with some point reaching temperature

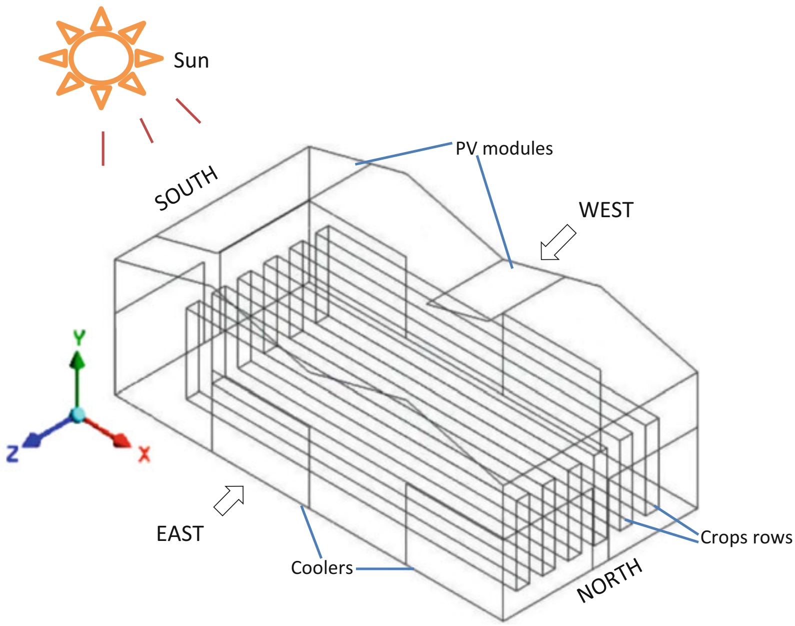

Fig. 5 Greenhouse position and orientation

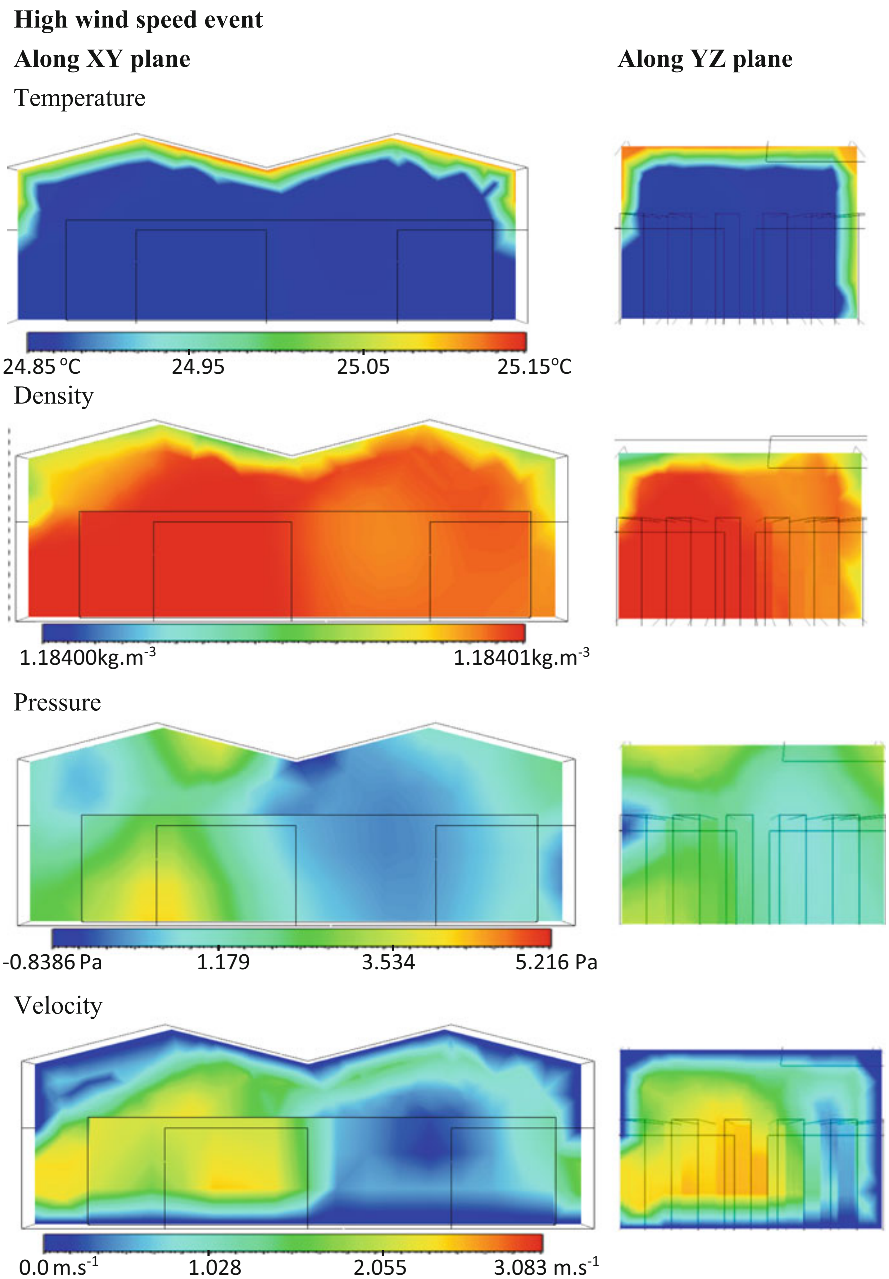

Fig. 6 Temperature, density, pressure, and velocity contours at high wind speed event

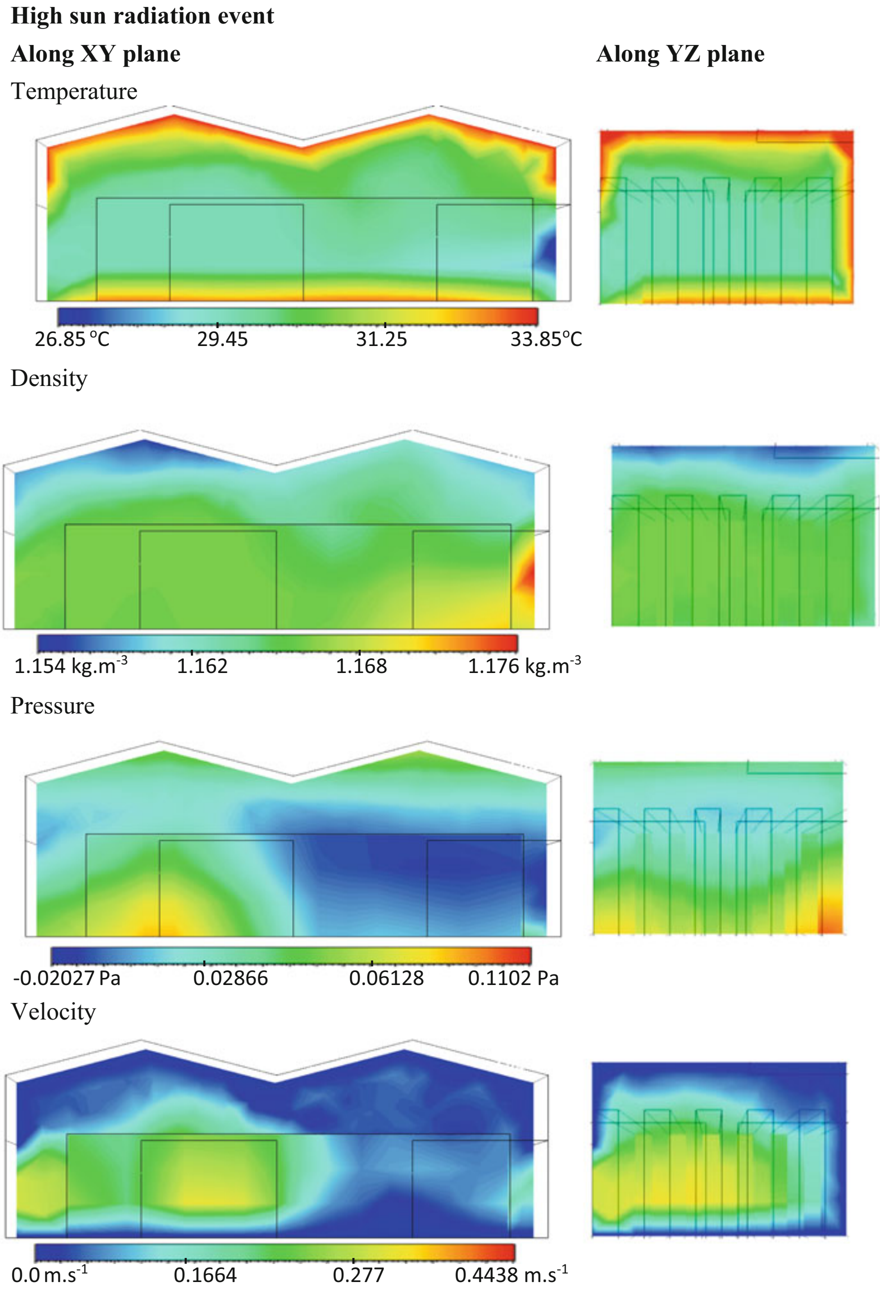

Fig. 7 Temperature, density, pressure, and velocity contours at high sun radiation event

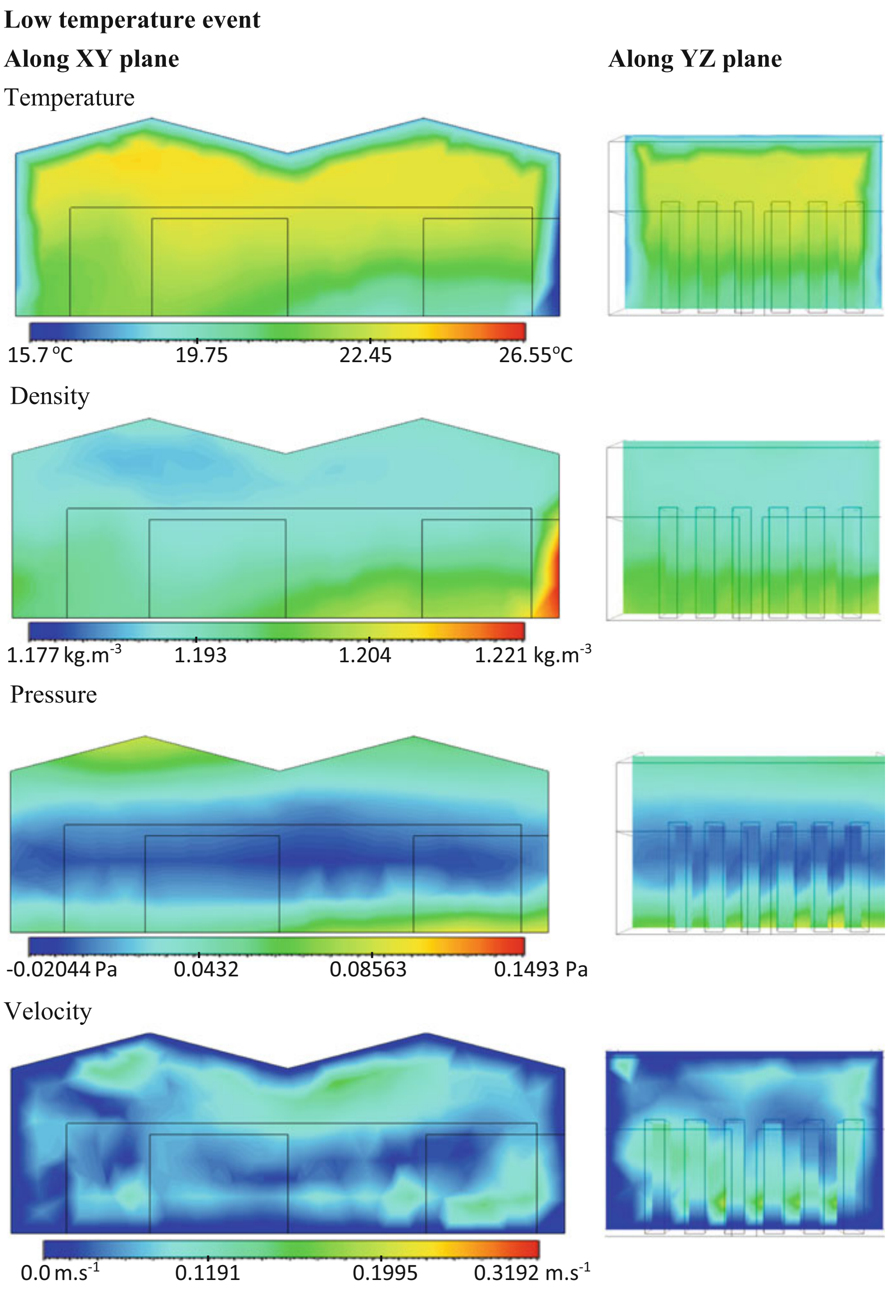

Fig. 8 Temperature, density, pressure, and velocity contours at low temperature event

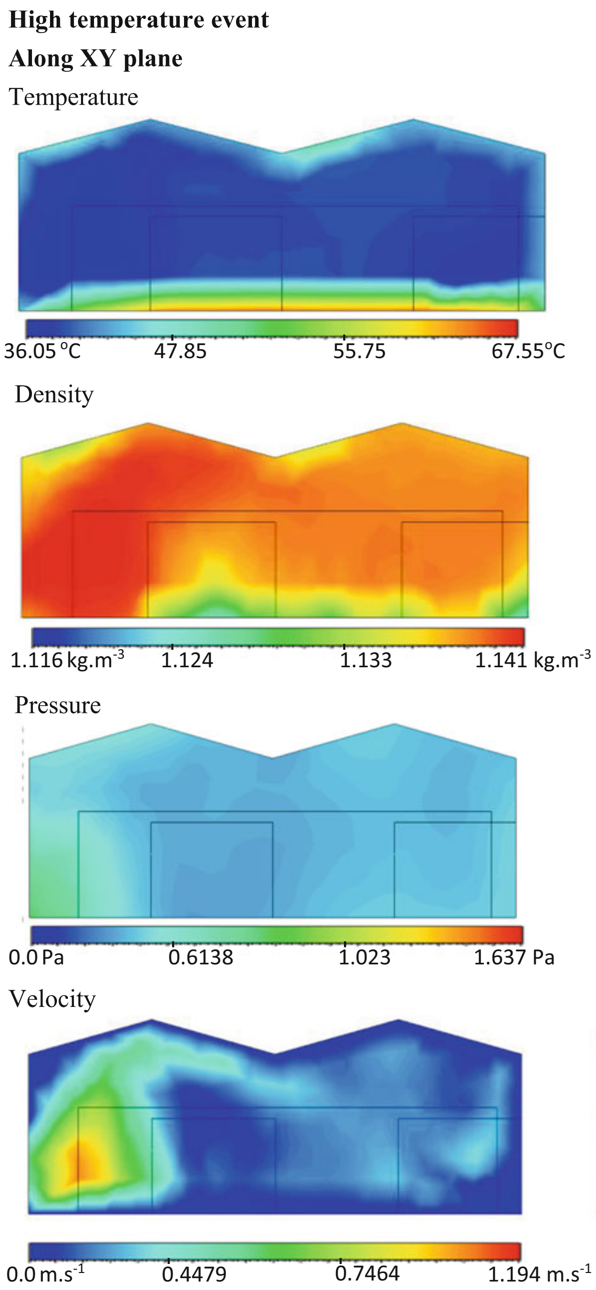

Fig. 9 Temperature, density, pressure, and velocity contours at high temperature event

beyond 60 °C. However, most temperature was between 36.05 °C and 47.85 °C. As suggested by Kumar et al. (2009), during hot season ventilation with ventilation area between 15% and 30% at the ridge of the greenhouse could reduce the temperature for a while as well as the use of cladding material with the ability to reflect near-infrared radiation.

Conclusion

A new greenhouse with local cooling system powered via a renewable source of energy (solar photovoltaic) has been proven to help reach desirable optimum temperature for crop cultivation even when outside environment is relatively hotter and harsh. Flow patterns and thermal behavior of cooling photovoltaic greenhouse under natural convection were simulated and analyzed using ground data and ANSYS software. The rate of distribution of the temperature and other parameter depend on outside conditions as the walls were semitransparent with radiative and convective heat transfer occurring. Energy used for the cooling, mostly during the day, was in excess due to high sun days, yet not enough to power the system for 24 h. Optimization could make the system more cost-effective.

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Competing Interest Authors have no competing interests to declare that are relevant to the content of this article.

Data Availability All data generated or analyzed during this study are included in this published article and its related optional files.

References

Ahmed EM, Abaas O, Ahmed M (2010) Performance evaluation of three different types of local evaporative cooling pads in greenhouses in Sudan. Saudi J Biol Sci 18(1):45–51. https://doi.org/10.1016/j.sjbs.2010.09.005

Arbel A, Barak M, Shklyar A (2003) Combination of forced ventilation and fogging systems for cooling greenhouses. Biosyst Eng 84(1):45–55. https://doi.org/10.1016/S1537-5110(02)00216-7

Aziz A, Mainil RI, Mainil AK, Listiono H (2017) Effect of water temperature and air stream velocity on performance of direct evaporative air cooler for thermal comfort. AIP Conf Proc 1788(1):030024. https://doi.org/10.1063/1.4968277

Barzegar M, Layeghi M, Ebrahimi G, Hamzeh Y, Khorasani M (2012) Experimental evaluation of the performances of cellulosic pads made out of Kraft and NSSC corrugated papers as evaporative media. Energy Convers Manag 54(1):24–29. https://doi.org/10.1016/j.enconman.2011.09.016

Campen JB (2005) Greenhouse design applying CFD for Indonesian conditions. Agrotechnol Food Innov 691:419–424

Cossu M, Murgia L, Ledda L, Deligios PA, Sirigu A, Chessa F, Pazzona A (2014) Solar radiation distribution inside a greenhouse with south-oriented photovoltaic roofs and effects on crop productivity. Appl Energy 133:89–100. https://doi.org/10.1016/j.apenergy.2014.07.070

Djibrilla ASM, Abdoulkader AH, Illyassou KM, Aissetou DY, Rabani A (2021a) Investigation of evaporative cooling pad material from *Hyphaene thebaica* fibers. J Eng Res Rep 21(9):64–75. https://doi.org/10.9734/JERR/2021/v21i917491

Djibrilla ASM, Abdoulkader AH, Illyassou KM, Aissetou Y, Rabani A (2021b) Performance of evaporative cooling pads made from different plant materials of sub-Saharan area (Niger). LC Int J STEM 2(4):38–49. https://doi.org/10.5281/zenodo.0000000

Fatnassi H, Poncet C, Bazzano MM, Brun R, Bertin N (2015) A numerical simulation of the photovoltaic greenhouse microclimate. Sol Energy 120:575–584. https://doi.org/10.1016/j.solener.2015.07.019

Ferziger JH, Peric M, Street RL (2020) Computational methods for fluid dynamics, 4th edn. Springer, Cham. https://doi.org/10.1007/978-3-319-99691-6

Fidaros D, Baxevanou C, Bartzanas T, Kittas C (2008) Flow characteristics and temperature patterns in a fan ventilated greenhouse. Acta Horticult 797:123–130. https://doi.org/10.17660/actahortic.2008.797.15

Gupta MJ, Chandra P (2002) Effect of greenhouse design parameters on conservation of energy for greenhouse environmental control. Energy 27:777–794

Haider AS, Sajid M, Iqbal S (2020) Forecasting hydrogen production potential in Islamabad from solar energy using water electrolysis. Int J Hydrogen Energy. https://doi.org/10.1016/j.ijhydene.2020.10.059

Hernandez-Martinez AR, Estevez M, Vargas S, Quintanilla F (2011) New dye-sensitized solar cells obtained from extracted bracts of *Bougainvillea glabra* and spectabilis betalain pigments by different purification processes. Int J Mol Sci 12:5565–5576. https://doi.org/10.3390/ijms12095565

Huld T, Müller R, Gambardella A (2012) A new solar radiation database for estimating PV performance in Europe and Africa. Sol Energy 86:1803–1815

Kallo MS, Ayouba Mahamane A, Saidou Boulhassane A, Adamou R (2021) Dye-sensitized solar cell using natural anthocyanin dyes extracted from Sorghum Spp (Poaceae) sheaths. IOSR J Appl Chem 14(9 Ser.I):1–9. https://doi.org/10.9790/5736-1409010109

Khobragade NN, Kongre SC (2016) Experimental performance of different evaporative cooling pad material of direct evaporative cooler in hot and dry region. Int J Innov Technol Res 4(3): 2920–2923. http://www.ijitr.com

Kumar KS, Tiwari KN, Jha MK (2009) Design and technology for greenhouse cooling in tropical and subtropical regions: a review. Energ Buildings 41:1269–1275. https://doi.org/10.1016/j.enbuild.2009.08.003

Manuwa SI, Odey SO (2012) Evaluation of pads and geometrical shapes for constructing evaporative cooling system. Mod Appl Sci 6(6):45–53. https://doi.org/10.5539/mas.v6n6p45

Marucci A, Cappuccini A (2016) Dynamic photovoltaic greenhouse: energy efficiency in clear sky conditions. Appl Energy 170:362–376. https://doi.org/10.1016/j.apenergy.2016.02.138

Raithby GD, Chui EH (1993) A finite-volume method for predicting a radiant heat transfer in enclosures with participating media. Trans ASME J Heat Transfer 112:415–423

Roslan N, Ya ME, Radzi MAM, Hashimoto Y, Jamaludin D, Chen G (2018) Dye sensitized solar cell (DSSC) greenhouse shading: new insights for solar radiation manipulation. Renew Sust Energ Rev 92:171–186. https://doi.org/10.1016/j.rser.2018.04.095

Saberian A, Sajadiye SM (2019) The effect of dynamic solar heat load on the greenhouse microclimate using CFD simulation. Renew Energy 138:722–737. https://doi.org/10.1016/j.renene.2019.01.108

Sanda MDA, Badu M, Awudza JAM, Boadi NO (2021) Development of TiO_2 – based dye-sensitized solar cells using natural dyes extracted from some plant-based materials. Chem Int 7(1):9–20

Tamamidis P, Assanis DN (1993) Evaluation of various high order accuracy schemes with and without flux limiters. Int J Numer Methods Fluids 16:931

Ureña-sánchez R, Callejón-ferre ÁJ, Pérez-alonso J, Carreño-ortega Á (2012) Greenhouse tomato production with electricity generation by roof-mounted flexible solar panels. Sci Agric 69(4): 233–239

Versteeg HK, Malalasekera W (1995) An introduction to computational fluid dynamics. In: The finite volume method. Longman, Harlow, England: Longman Scientific & Technical, London pp 102–206