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Experimental Study of Thermal Behavior of Greenhouse Heated by Solar Thermal Energy in Continuous Mode

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Abstract— **Greenhouses are designed to create a controlled environment with optimal conditions for growth. It allows extending the growing season, protecting crops from unfavorable weather conditions, and controlling parameters such as temperature, humidity, and light. This study investigates a continuous solar heating system for an agricultural greenhouse. The system includes forty solar thermal collectors for water heating. Throughout the day, the heated water is stored in a 15m3 tank. The stored hot water is utilized to provide heat to the pilot greenhouse during the night. Experimental measurements of the inner air and soil temperature inside the greenhouse were performed in the technical Center of Protected and Geothermal Cultures, Chenchou, Gabes in Tunisia. A modeling and simulation of the studied system has been elaborated to predict internal temperatures of the greenhouse. This model includes the overall amount of heat stored in the greenhouse as well as its global heat losses. The model input parameters are the measured weather data and the thermo-physical properties of greenhouse constituents including the soil, the indoor air and the cover. Theoretical results matched well with actual measurements. Results show that the temperature in the pilot greenhouse is higher than that in the control greenhouse during the night due to the heating system. The temperature difference between the control and pilot greenhouses is approximately 4°C. Moreover, the pilot greenhouse temperature remains above 12°C during the nighttime. An estimation of the necessary energy for the heating system has been made. The infiltration losses do not exceed 55 W. The maximum conduction convection losses are about 1419 W.**

Keywords— **Agricultural greenhouse, Heat Storage, Solar thermal collector, Heat release, Microclimate Control**

I. INTRODUCTION

Greenhouses are commonly used to ensure the fruits and legumes production with high yields, particularly in off-season conditions or challenging environments. They create an optimal microclimate for the robust development of crops. During winter periods, heating becomes necessary to increase temperatures and reduce air humidity within the greenhouse. Traditional heating systems employed for greenhouse heating involve fossil fuels such as natural gas and LPG. Given the increase in greenhouse gases emissions and the ongoing rise in global energy demand, the solution that can be adopted as an alternative technology is the exploitation of thermal solar energy in thermal processes [1], [2], [3]. Ihoumi et al [4] evaluated the performance of solar copper coil heating system used to heat a greenhouse from an experimental comparison between two greenhouses. The first one is related to the heating system and the second is a passive greenhouse. Results indicated that the nighttime inner temperature of the heated greenhouse is 4 °C higher compared to the passive one. Moreover, 527 l of water are needed to sustain the inner temperature. The solar copper coil heating system has a low CO_2 emission rate of 176 g/day compared to that for a heating boiler (about 41000 g/day) [4]. Gourdo et al. studied a greenhouse with a cylindrical PVC tank filled with rocks as a heating system. They concluded that the rock-bed system increases the nighttime air temperature inside the greenhouse by 1 to 2 °C and decreases the relative humidity by 3% compared to the reference greenhouse [5]. Pavlov et al. investigated the greenhouse with roof radiant heating, the infrared radiation heat flux is provided from an artificial heat source during the winter and from sun in hot season. They proposed a theoretical modeling

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which includes a set of equations of both heat and mass transfers for the greenhouse and soil. Model results show that the inner air temperature decreases when increasing the air exchange rate. Moreover, the water consumption for the soil increases with heat exchange rate growth and external air temperature decrease [6]. Anifantis et al. analyze the theoretical energy efficiency of a photovoltaic, hydrogen and ground source gas heat pump integrated in a stand-alone system for heating a greenhouse tunnel during the winter. They conducted a performance study for three types of greenhouses cover materials, a single layer polyethylene film, a double acrylic and an air inflated-double layer polyethylene film. The heating system has a global energy efficiency of 14.6% over the year. The studied system increased the greenhouse air temperatures by 3 to 9 °C depending on the ambient air temperatures and the greenhouse cover material utilized [7]. Jahangir et al. reported that the appropriate phase change material PCM for heat storage for greenhouses should be chosen according to the climate and location. The Energetic analysis indicated that using PCM can save up to 14,577 kWh electricity in greenhouses per year. The amount of energy saved depends on the type of PCM. The bioPCM-Q27 reduces an important amount of electricity consumption compared with the other ones [8]. Ahamed et al have developed a new simulation model for Chinese style mono slope Solar Greenhouses. They found that the average difference between the experimental and the calculated ground temperature is about 1.4 °C, and about 1.8 °C for the north wall [9].

The thermal efficiency of solar greenhouse design has been experimentally and numerically assessed by Chen et al. Analytical correlations were derived from parametric analysis data to calculate the passive solar greenhouse dimensions [10]. A soil temperature model has been established by Deng et Al. Results show that the soil heat gain is mainly due to solar radiation absorption during the day while the heat losses by the soil is due to the water evaporation during daytime and thermal radiation during the night. They also concluded that, for each 0.1 reduction in the evaporation coefficient, the average soil temperature rises by approximately 2°C [11]. Al-Kayssi et Al have reported that increasing the soil moisture content enhances the solar energy absorption and therefore increases the heat storage capacity. Moreover, a high soil moisture content reduces the gap between daytime and nighttime soil temperature which ensures the plants' roots protection against brusque change of soil temperature [12]. Wang et Al have estimated the greenhouse soil diffusivity from soil temperature using the amplitude method and the min-max method. Both methods present good results. The daily soil temperature at various depths was projected based on both surface temperature and the annual average soil temperature [13].

In this paper, a continuous heating system of an agricultural greenhouse by solar thermal energy has been studied. The system is composed of forty solar thermal collectors for water heating which will be stored in a $15m^3$ tank during the day. The stored hot water will then be used for heating the pilot greenhouse. The aim of this work is to model and simulate the indoor air temperature and soil temperature variation within the greenhouse environment. The global heat balance includes the heat stored in the greenhouse as well as the heat losses to the surroundings. The temperatures experimental measurements performed in the technical Center of Protected and Geothermal Cultures, Chenchou, Gabes allow to confirm the accurateness of the proposed model.

II. System Description

The experimental installation is located in the technical Center of Protected and Geothermal Cultures, Chenchou, Gabes in Tunisia. The system studied consists of a two-chapel with a north south orientation and covered by a 200 μm polyethylene plastic film, two of which are used for tomatoes culture. The first called pilot greenhouse is used to test the solar heating processes, and the second is a control greenhouse. Each chapel greenhouse has an ogival-shaped roof, two naves; each nave has a width of 9.6 m [10], [9].

The heating system is composed of three main parts as shown in Fig. 1. The installation is equipped with 40 flat thermal collectors GiordanoC8/11 SU, each with a surface area of 2 m^2. This collector consists of a box composed of a pre-painted galvanized steel frame and a bottom made of aluminum sheet attached to the insulation. The box is composed from bottom to surface by Polyurethane and fiberglass insulation, a flat absorber of a copper grid laze and a transparent cover made of tempered glass with low iron content. The volume between the absorber and the transparent cover is filled with air. These collectors are gathered into 8 parallel arrays, each array contains 5 collectors mounted in parallel. The collector's inclination is about 45°. The isothermal water storage tank, with a capacity of 20 m^3, is primarily constructed using cement and polystyrene as insulation. This is done to retain hot water and distribute it to the greenhouse during the night.

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The heating system inside the greenhouse primarily consists of a supply pipe with a diameter of 40 mm and an average length of 9 m, along with a return pipe with the same characteristics. The secondary heating network is composed of corrugated polypropylene pipes with a 25 mm diameter. These pipes are overlaid in loops with a total length of 65 m and are positioned near the root system for better temperature distribution. In total, there are 10 loops within a greenhouse, with a combined length totaling approximately 650 linear meters [14], [15].

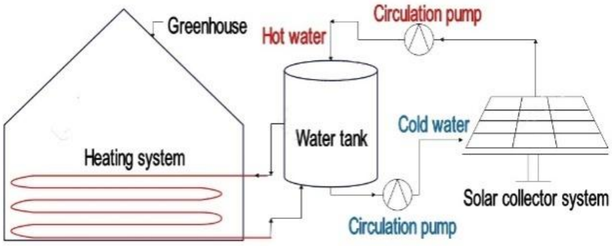

Fig. 1 System description

III. Greenhouse Thermal Balances

The thermal balance involves the exchange of heat between the greenhouse environment, the plants, and the external atmosphere. It can be expressed through various equations that account for the heat inputs and outputs.
The Amount of energy stored in the greenhouse is given by [16]:

$$Q_u = Q_{gain} - Q_{loss} \tag{1}$$

The Greenhouse global losses are the sum the various heat losses and given by:

$$Q_{loss} = Q_{soil} + Q_{rad} + Q_{cc} + Q_{inf} + Q_{cond} \tag{2}$$

The greenhouse receives thermal energy from the sun Q_S during the day, and thermal energy from the heating system Q_{heat} during the night. The thermal gain is then the sum of the two powers indicated below:

$$Q_{gain} = Q_S + Q_{heat} \tag{3}$$

The losses through conduction -convection are expressed as follows [17]

$$Q_{cc} = U \times A_C \times (T_i - T_a) \tag{4}$$

The global heat transfer coefficient is expressed as a function of the convective and conductive coefficients through the wall, i.e.:

$$U = [\frac{1}{h_o} + \frac{L_c}{K_c} + \frac{1}{h_i}]^{-1} \tag{5}$$

The convective exchange coefficient with the inside air is correlated by:

$$h_i = 1.52|T_i - T_a|^{1/3} + 5.2(\frac{R}{A_C \times L})^{1/2} \tag{6}$$

and the convective heat coefficient with the external air as a function of the wind speed V_w .is expressed by:

$$h_0 = 2.8 + 1.5V_w \tag{7}$$

The infiltration losses equation is given by

$$Q_{inf} = \rho_a C_a R \frac{T_i - T_a}{3600} \tag{8}$$

The Radiation losses are estimated as follows [17]

$$Q_{rad} = h_0 \times A_C(1 - \tau_C)(T_i - T_{sky}) \tag{9}$$

Where the sky temperature equation is given by

$$T_{sky} = 0.0552(T_a)^{1.5} \tag{10}$$

The condensation of water occurs when the temperature of the inner surface of the cover T_c is lower than the dew point of the indoor air, 1kg of water requires 2.47MJ to convert the liquid into vapor (latent heat of vaporization), and the same amount will be released during condensation on the inner cover surface. The equation for heat losses due to condensation is [18]:

$$Q_{cond} = C \times h_{vs} \times A_C \tag{11}$$

Where C is given by

$$C = \frac{1.64 \times 10^3 \rho_{air}}{(1 - \frac{(1-\varepsilon)P_{ex}}{P_{atm}})}(H_{ex} - H_{in})(T_{se} - T_c) \tag{12}$$

And

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$$H_{in} = \frac{(\varepsilon \times P_{in})}{P_{atm}} \quad (13)$$

The saturated vapor pressure at the temperature of the greenhouse inner cover is

$$P_{in} = 2.22 \times 10^{11} \times e^{\frac{5385}{T_{ci}}} \quad (14)$$

The air humidity outside the greenhouse is as follows

$$H_{ex} = \frac{(0.622 \times P_{ex})}{P_{atm}} \quad (15)$$

The saturated vapor pressure at the temperature of the cover outside the greenhouse is given by

$$P_{ex} = 6.107 \times 10^{(7.5(\frac{T_a}{273.3}+T_a))} \quad (16)$$

The losses through the ground are expressed by equation (17), where the ground temperature is assumed to be the ambient temperature. The heat flow depends on the heat exchange surface area, the heat transfer due to the difference between the inner soil temperature and the ground temperature, the thermal conductivity of the soil and equivalent soil thickness, the value of which is assumed to be 2m [19]. Table 1 shows data for all soil characteristics.

$$Q_{soil} = \frac{A_g(T_{in} - T_s)}{\frac{1}{0.7h_{ing}} + \frac{\delta_g}{\lambda_g}} \quad (17)$$

$$\mathrm{h_{ing}} = (\mathrm{Nu_{ing}} \times \frac{\lambda_{in}}{w_{hg}}) \quad (18)$$

$$Nu_{ing} = C_w(Gr_{ing} Pr_{in})^{n_{in}} \quad (19)$$

$$Gr_{in.g} = (g \times \beta_g \times (T_{in} - T_g) * \frac{w_{hg}^3}{V_{in}^2}) \quad (20)$$

$$\beta_g = \frac{1}{\frac{T_{in}+T_g}{2}} \quad (21)$$

TABLE I
SOIL CHARACTERISTICS

	A_g	Pr_{in}	λ_{in}	λ_g	C_w	n_{in}	δ_g
Value	595.2	0.704	2.53×10^{-2}	1.49	0.135	¼	20

The received solar flux by air inside the greenhouse is given by the following expression:

$$Q_s = \tau \times \gamma \times A_c \times G \quad (22)$$

Where:

τ =85%, γ =0.4,

The heating system during nighttime generally involves using the greenhouse floor as a large radiator. Tubes through which hot water circulate are on the surface of the greenhouse floor. Heat from the hot water is transferred through the tube to the air inside the greenhouse. The materials used for tubes are usually copper or steel. The total heat supplied by the floor heating system can be defined by the following equation [15]:

$$Q_{heat} = A \times h_s \times U_P(T_{hs} - T_{in}) \quad (23)$$

$$T_{hs} = \frac{T_{ecr}+T_{ret}}{2} \quad (24)$$

Table 2 shows the characteristics of the heating system.

TABLE III
HEATING SYSTEM CHARACTERISTICS

	E_{poly}[mm]	U_{poly}[W/m^{2}k]	n_t	L_t[m]	d_i[mm]
Value	1	11.611	12	30	25

The heating system exchange surface is calculated as follows

$$A_{hs} = n_t \times A_p \quad (25)$$

Then A_{hs}=61.26 m^2

$$A_p = \Pi \times di \times L_p \quad (26)$$

$A_p = \Pi \times (25 \times 10^{-3}) \times 65 = 5.1$ m^2

The global heat exchange coefficient is given by

$$Up = \frac{1}{\frac{1}{h_i} + \frac{e}{U_{poly}} + \frac{1}{h_e}} \quad (27)$$

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$$\mathrm{hi} = \frac{\mathrm{Nu}\times\lambda_w}{\mathrm{d}_i} \tag{28}$$

$$\mathrm{h_e} = \frac{\mathrm{Nu}\times\lambda_{\mathrm{air}}}{\mathrm{d_i}} \tag{29}$$

$$\mathrm{Nu} = \alpha \times Re^{\beta} \times Pr^{1/3} \tag{30}$$

The average temperature of heating fluid is given by

$T_{av\text{-}w}$=40°C

$$Re = \frac{\rho\times\dot{V}_w\times d_i}{\mu_w} \tag{31}$$

TABLE IIIII
COEFFICIENTS FOR A FLOW AROUND A CYLINDER

Re_D	A	B
$1-40$	0.75	0.4
$40-1000$	0.51	0.5
$10^3 - 2.10^5$	0.26	0.6
$2.10^5 - 10^6$	0.076	0.7

The fluid flow rate is equal to Q_{V1} = 0.5l/s

The flow rate per pipe is calculated as follows

$$Q_{vt1} = \frac{0.5}{\mathrm{n_t}} = 0.042\ l/s$$

The water speed is

$\dot{V}_{\mathrm{water}} = \frac{Q_{vt1}}{A_{hs}} = 0.085\ m/s$

The Reynolds number is therefore equal to

Re = 4155.5

According to table 3, 10^3< Re< 2 10^5then α = 0.26 et β = 0.6

$$Pr = \frac{C_p\times\mu_w}{\lambda_w} \tag{32}$$

Pr =4.351, Nu =54.10

The average air temperature $T_{av\text{-}air}$=10°C and the average speed $\dot{V}_{\mathrm{air}}$ =1 m/s

$$Re = \frac{\rho\times\dot{V}_{air}\times di}{\mu_{air}} \tag{33}$$

Re =1761.29

10^3< Re< 2×10^5 then α = 0.26 et β = 0.6

$$Pr = \frac{C_p\times\mu_{air}}{\lambda_{air}} \tag{34}$$

Pr =0.712

IV. RESULTS AND DISCUSSIONS

A. Variation in solar radiation and wind speed

The experimental study is conducted at the technical center for protected crops of Chenchou in Gabes region of altitude 33.888 and longitude 10.097 in southern Tunisia [20]. The wind speed and solar radiation are illustrated in Fig. 3 and Fig. 4 between 14 and 23 March 2022. Fig. 2 shows that the sunshine reaches its maximum value of 800W/m² between 13:00 and 14:00. However, there was a drop in sunshine on 21 and 17 March 2022, when the values did not exceed 400W/m². The temperature follows a similar variation. The maximal temperature range is between 25°C and 16°C when sunshine is at its lowest peak. Night-time temperatures are lower; reaching values below 12°C, unfavorable for the growth of greenhouse crops, especially tomatoes, which require a temperature above 12°C. Greenhouse heating system is used to overcome this issue.

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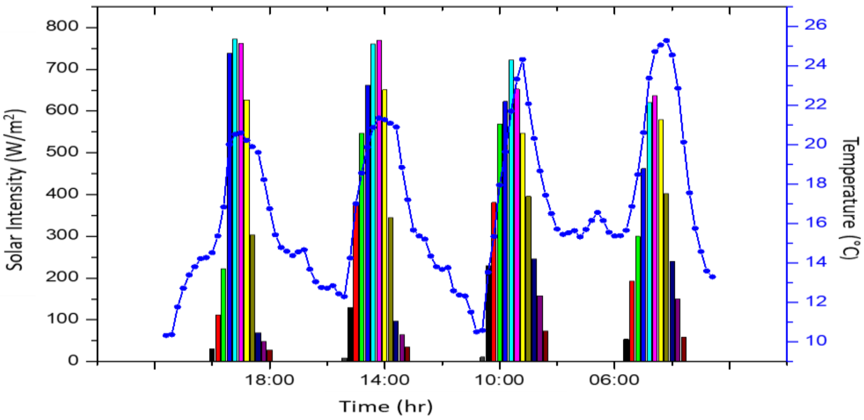

Fig. 2 Solar radiation and ambient temperature over the period 14/03/2022 to 17/03/2023

According to Fig. 3, the wind speed varies between 0 and 4.7 m/s. The speed is low during the first four days, the maximum value is between 1.5 and 2 m/s. The wind speed reached 4 m/s over the next 3 days, the average maximum value was close to 3m/s. Then it became stronger on the last days reaching 4.7 m/s. The speed wind values are in agreement with those for solar radiation and ambient temperature.

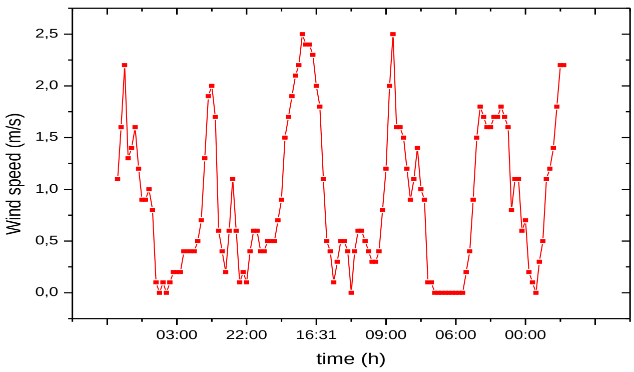

Fig. 3 Variation in wind speed

B. Variation in Greenhouse and Control Greenhouse Temperature

Fig. 4 illustrates the temperatures variation of the pilot greenhouse and the control greenhouse over time. The temperatures range is from 10°C to 45°C. It is observed that the temperature in the pilot greenhouse is higher than that in the control greenhouse during the nighttime period. This result demonstrates the impact of the heating system. The temperature difference between the control and pilot greenhouses is approximately 4°C. Indeed, the temperature in the pilot greenhouse remains above 12°C during the nighttime period, providing favorable climatic conditions for greenhouse cultivation. This outcome also highlights the effectiveness of storing solar thermal energy for use as a heating source for the greenhouse during the night.

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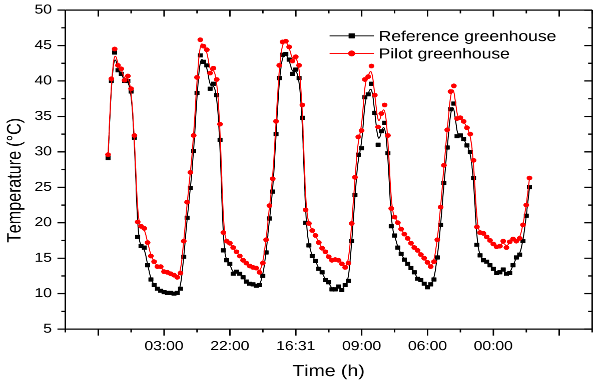

Fig .4 Variation in Greenhouse and Control Greenhouse Temperatures

C. Comparison of ground temperature and air temperature at 2m level

The comparison between the ground temperature and the air temperature at 2 m level is given in Fig. 5. The air temperature remains higher until midnight, when the two temperatures equalize until 6:00. During the second period of the day, the greenhouse effect has a greater influence on the air than on the ground because the air is more exposed to this effect. In effect, the ground temperature is higher before 1pm. This situation is reversed after 1pm, when the air temperature is higher, even during the night.

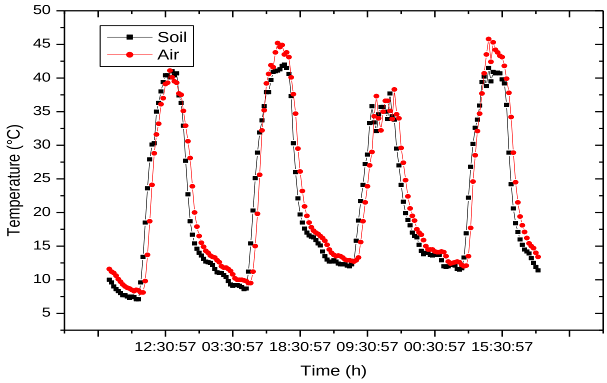

Fig. 5 Comparison of ground temperature and air temperature at 2m

The determination of the energy needed for a greenhouse is crucial for the heating system sizing. It mainly depends on the various thermal losses of the greenhouse. In this section, the simulation of thermal losses, as well as the heat received from solar flux during the day and that from the heating system during the night.

D. Simulation of Thermal Losses

The main energy losses in a greenhouse include losses due to conduction-convection, losses due to radiation, losses through the grounds, Infiltration losses, and Condensation losses

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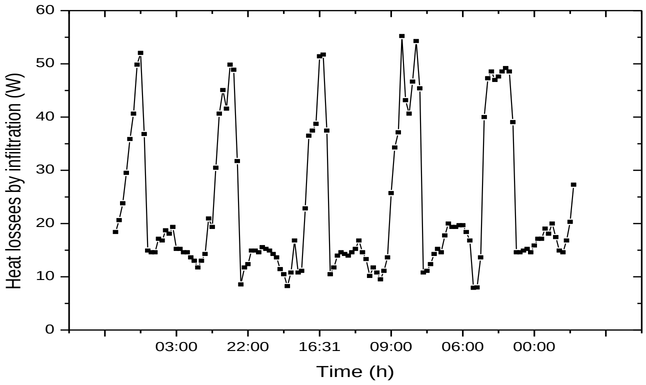

Fig. 6 Variation of infiltration losses

The calculation of different losses, as illustrated in Fig. 6 and Fig. 7 reveals that the infiltration loss is very low, not exceeding 55W. These results indicate that the utilized greenhouses have perfect air tightness. Conduction-convection losses peak is around 1419W, while radiation losses do not exceed 2272W. It is noteworthy that losses are more significant during the daytime, justified by the fact that these losses are modeled based on the air temperature inside the greenhouse, which is highest during the day. During the nighttime period, the highest loss does not exceed 1400W.Moreover; it is clear from Fig. 7 that the loss through the ground is the most significant, reaching 3660W. The condensation loss represents one of the major losses for the greenhouse, reaching 3129W.

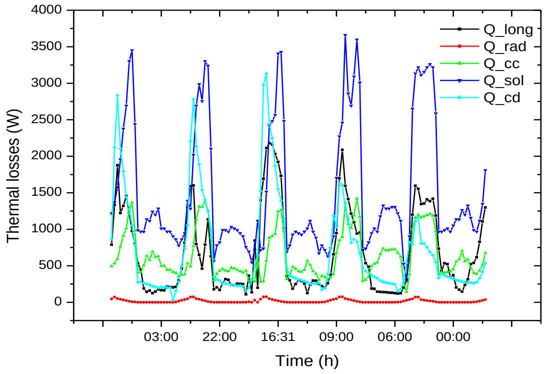

Fig. 7 Variation of various thermal losses

The solar power received by the greenhouse is primarily dependent on the solar flux, following a similar profile to solar radiation. It reaches a maximum average value of 85000 W around 1:00 pm. The heating system, operational during the night, supplies the greenhouse with a maximum power of almost 25000W.

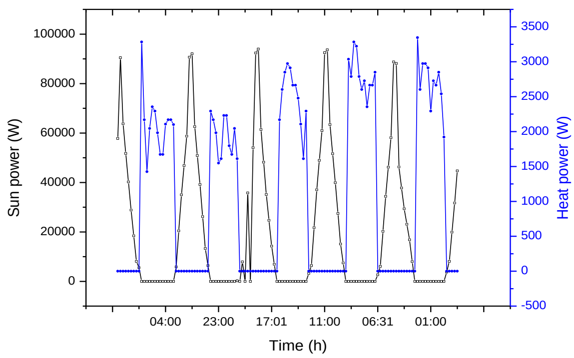

Fig. 8 Variation of Received Energies Over Time

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E. Comparison between Experimental and Simulated Temperature

The variation in experimental and simulated temperatures is illustrated in Fig. 9. It is observed that the simulated temperature ranges between 8°C and 37°C, while the experimental one varies between 13°C and 45°C. The difference between the two temperatures is approximately 5°C. The average error between the experimental and simulated results is 19%. This outcome shows an acceptable agreement between the two sets of results.

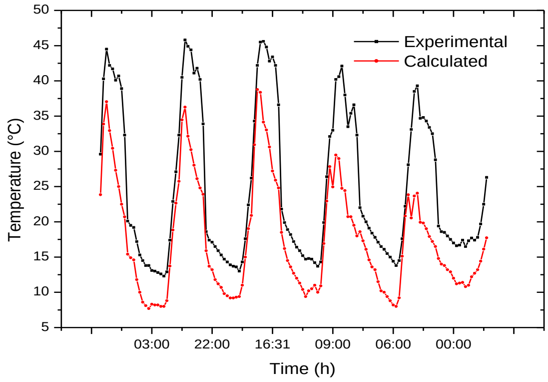

Fig. 9 Variation of simulated and experimental temperatures

V. Conclusions

In this paper, a solar continuous heating system designed for an agricultural greenhouse has been studied. The setup involves forty solar thermal collectors dedicated to water heating. The generated heat throughout the day is stored in a 15m3 tank, and the stored hot water is subsequently employed to warm the pilot greenhouse. The study includes the modeling and simulation for the system. Results indicate that, during the night, the pilot greenhouse temperature is higher than the control greenhouse, with a temperature difference of around 4°C attributed to the heating system. Furthermore, the temperature in the pilot greenhouse remains above 12°C during nighttime. The energy requirement evaluation for the heating system has been conducted; revealing infiltration losses not exceeding 55 W and maximum conduction-convection losses of about 1500 W. Balance equations allows simulating air temperature inside. The averages error between simulated and experimental results is 19%.

VI. List of Symbols

A_C : Greenhouse cover area, m^2,
A_{hs}: Exchange surface area of the heating system, m^2
A_p : Pipes area, m^2
A_g : soil surface, m^2
C_a : Specific heat of air, J/kg K
C_P : Specific heat of water, J/kg K
di: Pipe diameter, m
g : Acceleration of gravity, m/s^2,
$Gr_{in,g}$: Grashof number for a fluid inside an object into the soil.
H_{in} : Air humidity inside the greenhouse.
h_i : Convective exchange coefficient with the air Inside, W/m^2 K
h_o : convective heat coefficient with the external air as a function of the wind speed V_w, W/m^2 K
h_{vs} : latent heat of vaporization, J/kg
$h_{in,g}$: Heat transfer coefficient in the Wall W/m^2K,
K_p: Polyethylene cover thermal conductivity, W/m K
L : Total Width,m
L_c : Cover thickness, m
L_p: Pipe length, m
$Nu_{in,g}$: Interior Nusselt number of soil,
n_t: Number of pipes
P_{atm} : Atmospheric pressure, kPa,
Pr: Prandtl number for air.

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Q_{loss} Greenhouse outlet Energy, W
Q_{gain} Greenhouse Inlet Energy, W
$Q_{soil:}$ Thermal losses through the soil, W
$Q_{cond:}$ Heat losses by condensation, W
Q_{inf}: Heat losses by infiltration, W
$Q_{cc:}$ Heat losses by conduction-convection, W
$Q_{rad:}$ Thermal losses by radiation, W
$Q_{V1:}$ fluid flow rate, l/s
$Q_{vt1:}$ flow rate per pipe, l/s
R: Number of air changes per hour, m^3/s
Re: Reynolds number
S_C : Vertical section of greenhouse, m^2,
$T_{i:}$ Inside Temperature of the greenhouse, K
T_{in} : Inner temperature of greenhouse, K
T_{sky} : Sky Temperature, K.
$T_{a:}$ Ambient Temperature, K
T_{in}: Indoor air temperature, K
T_{hs}: Average heating temperature, K
T_s : Soil temperature, K
T_{ecr}: Temperature of incoming heat transfer fluid, K
T_{ret}: Fluid temperature returns temperature, K
U: Global heat transfer coefficient through the greenhouse walls, W/m^2 K
Up: Heat transfer coefficient of the pipe material, W/m^2K
$\dot{V}_{air}$: Air speed, m/s
V_w : Wind speed,m/s
V_{in} : coefficient of kinetic viscosity of air, m^2/s
w_{hg} : characteristic linear dimension of the grounds.
Greek Symbols
β_g : Compressibility of the fluid near the ground, 1/K
ε : Ratio of molecular weights of water,
ρ_a : Inner air density, kg/m^3
ρ_w : Water density,kg/m^3
τ : Light transmission From the greenhouse cover to solar radiation.
λ_w: Water thermal conductivity, W/m K
λ_{ing}: ground thermal conductivity W/m K
δ_g : Equivalent thickness of the soil, m
γ: Constant of the proportion of solar radiation entering the greenhouse, useful for increasing the internal temperature.
μ_w : Water dynamic viscosity kg/m.s

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