Innovative Design of a Ventilated Modern Greenhouse Powered by PV/T Solar System

Abdullateef A.Jadallah¹, Mohammed K.Alsaadi², Zayn A.Hafidh³
Electromechanical Engineering Department, University of Technology, Iraq.

Abstract: In this paper, a modern design is proposed for ventilating and conditioning of greenhouse integrated thermal solar system in summer season in (33.3°N, 44.4°E) Baghdad, Iraq with respect to East-West orientation. The proposed system involves photovoltaic panels and counter flow double pass (with fins). The photovoltaic solar thermal system is fixed on the roof of single span greenhouse. Experimental work was carried out during summer season. The results show the ventilation process changes the air inside temperature of the greenhouse to make it equal to the temperature required by the plants. The calculated root mean square error is 2.04 and correlation factor is 0.993 for the inside air temperature and 4.98, 0.98 respectively for the ground temperature.

Keywords: Ventilation process, BIPVT, Greenhouse ventilation, Greenhouse, Solar energy.

Nomenclature:

| Symbol | Description |
|--------|-------------|
| A_d, A_p, A_g | Door, Plant, Ground areas (m²) |
| P(T) | Partial vapor pressure at saturation (Pa) |
| C_a | Air specific heat |
| S_t | Total solar radiation falling on the greenhouse cover (W) |
| E_v | Heat transfer through ventilation |
| τ | Transmissivity of the greenhouse cover (-) |
| F_PR | Shape factor between plant and greenhouse room (-) |
| α_p | Plant absorptivity of solar radiation (-) |
| h_a | Convective heat transfer coefficient between the greenhouse floor and inside air (W m⁻²°C⁻¹) |
| α_g | Ground absorptivity of solar radiation (-) |
| h_d | Heat transfer coefficient from the greenhouse door to the ambient air (W m⁻²°C⁻¹) |
| ρ | Reflectivity of the ground(-) |
| M_p | Total mass of plant (kg) |
| ε | Emissivity (-) |

Abbreviations:

| Symbol | Description |
|--------|-------------|
| I.A.T | Inside air temperature (C) |
| G.T | Ground temperature (C) |

1. Introduction

The framework of the glasshouse is made from glass, it used to provide appropriate environment for specific type of plants in the specific season, other times the heat must be pulled out using of
ventilating or cooling system. The air inside room temperature is a significant factor which affects the plants and varies with ambient temperature, wind speed and solar radiation falling on the greenhouse [1]. Photosynthesis is a process which diverts the energy of sun into the nutrition by the plants (i.e., carbohydrates). This process is achieved in suitable circumstances by nature and artificially in glasshouse [2]. Greenhouse shape and orientation are important parameters that affect the amount of the total absorbed solar radiation. According to (Mohtaker and Ajabshirchi, 2016) the single span is acceptable quantum of solar radiation than other shapes of the greenhouses, such as Quonset, Arch, Vinery, uneven span and even span under the same climate conditions [3]. The two main elements that have higher cost which entered in glasshouse construction are the cooling and heating units. Heating process is conventionally supplied by burning diesel, liquid petroleum or fossil fuel that increases emission in the environment [4]. Recently, researches have showed that the photovoltaic systems with or without solar thermal units is satisfied solution in the greenhouse application specially for the rural, desert and distant zones. The solar energy is cheap, clean and zero emission technology. Besides, the maintenance is lower compared with conventional generators, The employing of photovoltaic panels on the top of greenhouse's roof increases the productivity of land and reduces utilized space [5]. One of using of the glasshouses on the planet is drying which is defined as the process of removing the moisture out of the crops after harvesting season to economize the agricultural product [6]. Sun drying, reduces the moisture in the crops by the 16% in 24 h whereas 17 h has been taken in the hothouse [7]. The outlet temperature depends on the solar radiation which considered a main effect, moreover the ambient temperature and mass flux, increases with time from 8 AM to 1 PM then reducing because of the decay of the solar radiation [8]. On the search data of air heating systems of (A. El-Sebaii and S. Aboul-Enein), the outlet temperature is higher in v-corrugated plate than the flat plate and more efficient by 11%-14% [9]. Between the words of (E. Mashonjowa and F. Ronsse) showed that the high investment project for the greenhouse in Zimbabwe were imported from Europe also few of them were successful due to the climatic differences conditions and the lack of experiences of the farmers to control the modern types of the greenhouse. With ventilated greenhouse with sensors devices which distributed in the room of the glasshouse, the thermometer sensed the thermal behavior for cover. Under the sunny condition was the difference 10 C between the measured and numerical results and 2 C in night [10]. (C. Kittas and M. Karamanis) explained the solar radiation is the main parameter to calculate the air temperature under the cover and the forced ventilation improve the conditions inside the greenhouse and reduce the overheating [11]. (M. Z. Jacobson and V. Jadhav) cleared up the tilting and tracking are used in all countries with all latitude to increase the solar radiation that incident on the rooftop of photovoltaic system [12]. (A. Arbel and M. Barak) used a combination between the forced ventilation and fogging system which based on providing water in small possible drops that can enhance the mass and heat exchange between air and water with accepted conditions 28 C in the air inside temperature [13]. In the present paper, an innovative design for a single span greenhouse is built also the temperatures distribution inside the greenhouse is investigated with or without the ventilation process.

2. Materials and Dimensions

A wooden structure of single span greenhouse is built with dimensions of (120cm*44.5cm*70cm). The walls contain 4mm glass cover, while the roof consists of photovoltaic solar panel (120cm*54cm) with packing factor 0.66 and 7mm thickness as shown in Fig.1. The boundaries of the glass layer and PV that are attached with wooden structure are covered with silicon to prevent leakage of air or water. With four small fans are fixed at the top of the north wall to support the ventilation process.
3. Solar Radiation of the Glasshouse

The hourly incident solar radiation was measured using of solar power during summer season in Baghdad, Iraq. The Single span glasshouse is divided into five sections (west wall, east wall, south roof, south wall and north wall). The model is prepared for a clear day also counter (reverse) flow double pass photovoltaic thermal system has been used to dry the crops in summer

The total radiation available on the green house is given by:

\[
S_t = AS_R I_{SR} + AS_W I_{SW} + AW_W I_{NW} + AW_I I_{WW} + AE_W I_{EW}
\]

where \( AS, ASr, Aww, Aew, Anw \) are the Area of south wall, south roof, west wall, east wall and north wall respectively (m\(^2\)). The refraction index \( n \) and extinction coefficient \( K \) are used for calculating transmitted solar radiation falls through the cover of greenhouse.

(Duffie and Beckman, 1991) proposed an expression for refraction radiation transported from air with refraction index \( n_i \) considered as (1) to glass with refraction index (1.526) [14].

4. Thermal Modeling of the Greenhouse:

4.1 Glasshouse plants:

According to Fig.2 the energy balance that determines the plants temperature is:

\[
\alpha_p (1 - \rho) \tau S_t (1 - F_t) = M_p C_p \frac{dT_p}{dt} + h_{pr} A_p (T_p - T_R) + h_r A_p (T_p - T_R) + h_{pr} A_p (T_p - T_R)
\]

where: \((T_p, T_R)\) the plant and air inside temperatures (C) respectively. Also \((F_t)\) the ratio of the transmitted solar radiation falling on walls/ roof inside the greenhouse to the total transmitted solar radiations inside the greenhouse at the same time. Total solar fraction is taken from references. In Addition to the expression \( h_r, h_{pr} \) and \( h_p \) has analyzed in [1].

The Convective and evaporative heat transfer coefficient from the plant to the inside air (W m\(^{-2}\)C\(^{-1}\)) is showed in equation (3a):

\[
h_{pr} = h_p + \frac{0.016 \times h_p [P(T_p) - \gamma P(T_R)]}{T_p - T_R}
\]

(3a)
The Convective heat transfer coefficient between plant and inside air (W m\(^{-2}\)C\(^{-1}\)) is:

\[ h_p = 2.8 + 3(V) \]  

Also the radiation heat transfer coefficient between plant and inside air (W m\(^{-2}\)C\(^{-1}\)) is:

\[ h_r = F_{PR} \varepsilon_\sigma (T_p^2 - T_R^2)(T_p + T_R) \]  

4.2 Glasshouse floor:

The energy balance which calculates the ground temperature is:

\[ a_g (1-a_p)(1-\rho)\tau S_L (1-F_I) = -KA_g \frac{dT}{dx}_{x=0} + h_a A_g (T_{x=0} - T_R) \]  

The expression in the steady state condition of the conduction thermal energy in the ground is

\[ -KA_g \frac{dT}{dx}_{x=0} = h_b A_g (T_{x=0} - T_o) \]  

Fig.2. Working principle of a greenhouse with solar radiation

where: (h\(_b\)) bottom heat transfer coefficient between the greenhouse floor and the ground beneath (W m\(^{-2}\)C\(^{-1}\)). And (T\(_o\)) the temperature which is constant after certain depth of ground also is considered equal to the underground temperature beneath the glasshouse floor (T\(_o\)). Hence the equation (4a) can be written according to the Fig.3:
\[ \alpha_g(1 - \alpha_p)(1 - \rho)\tau S_r(1 - F_t) = h_b A_g (T_{x=0} - T_o) + h_a A_g (T_{x=0} - T_R) \]  \hfill (5)

4.3 Glasshouse air

As shown in Fig.3 the energy balance that carried out to reach the air inside temperature is:

\[ A_p h_{pr} (T_p - T_b) + A_p h_r (T_p - T_R) + h_a A_g (T_{x=0} - T_R) + (1 - \alpha_g)(1 - \alpha_p)(1 - \rho)\tau S_r(1 - F_t) + \rho F_t \tau S_r(1 - \rho) = m_a C_a \frac{dT_R}{dt} + U_t A_c (T_R - T_a) + h_a A_a (T_R - T_a) + E_v \]  \hfill (6)

Where: \((U_t)\) the total heat transfer coefficient of the glasshouse. According to equation (6) the inside air temperature can be simplified as:

\[ T_R = \left[ \frac{\rho F_t + \left( (1 - \alpha_g)(1 - \alpha_p) + \alpha_{ge} H_G \right) (1 - F_t)}{Z + A_p (h_{pr} + h_r) T_p + A_g h_o H_G} \right] \]  \hfill (7)

Where;

\[ Z = A_c U_t + h_a A_d + h_b A_g \]  \hfill (8a)

\[ H_G = \frac{h_a A_g}{h_b A_g + h_a A_g} \]  \hfill (8b)

\[ P(T) = \exp \left( \frac{20.386 - 5132}{T} \right) \times 133.3 \]  \hfill (8d)

Fig.3. Schematic diagram of energy balances of the greenhouse

A computer program is written in MATLAB is built to carry out the necessary determinations to calculate the inside air temperature in each hour of the day in addition to mathematical simplifications \((Z, H_G, \alpha_{ge}, P(T))\) prepared as constants in (table 1):

\[ \alpha_{ge} = \alpha_g (1 - \alpha_p) \]  \hfill (8c)
Table 1

| Constants                          | Value       |
|-----------------------------------|-------------|
| Bottom heat transfer co. ($h_b$)  | 1 W m$^{-2}$C$^{-1}$ |
| Cover area ($A_c$)                | 1.9 m$^2$   |
| Door area ($A_d$)                 | 0.09 m$^2$  |
| Emissivity ($\varepsilon$)        | 0.7         |
| Ground area ($A_g$)               | 0.54 m$^2$  |
| Plant area ($A_p$)                | 0.54 m$^2$  |
| Plant absorptivity ($\alpha_p$)   | 0.4         |
| Plant specific heat ($C_p$)        | 4190 J kg$^{-1}$C$^{-1}$ |
| Reflectivity of the ground ($\rho$)| 1          |
| Shape factor ($F_{PR}$)           | 0.09        |
| Upper heat transfer co. ($h_a$)    | 10 W m$^{-2}$C$^{-1}$ |
| Reflectivity of the ground ($\rho$)| 1          |
| Cover area ($A_c$)                | 1.9 m$^2$   |
| Ground absorptivity ($\alpha_g$)  | 0.75        |
| Ground absorptivity ($\alpha_g$)  | 0.75        |
| Ground area ($A_g$)               | 0.54 m$^2$  |
| Shape factor ($F_{PR}$)           | 0.09        |
| Upper heat transfer co. ($h_a$)    | 10 W m$^{-2}$C$^{-1}$ |
| Upper heat transfer co. ($h_a$)    | 10 W m$^{-2}$C$^{-1}$ |
| Plant area ($A_p$)                | 0.54 m$^2$  |
| Plant absorptivity ($\alpha_p$)   | 0.4         |
| Velocity ($v$)                    | 0.5 m s$^{-1}$ |

5. Statistical Analysis

The accuracy of the modules is determined with different indicators contains root mean square error (RMSE) and correlation coefficient ($r$) were computed according to data series [15, 16].

$$RMSE = \left(\frac{1}{K}\sum_{k=1}^{K}(e_{i,c} - e_{i,m})^2\right)^{0.5}$$

$$r = \frac{\sum_{k=1}^{K}(e_{i,c} - \bar{e}_{i,c})(e_{i,m} - \bar{e}_{i,m})}{\sqrt{\sum_{k=1}^{K}(e_{i,c} - \bar{e}_{i,c})^2 \sum_{k=1}^{K}(e_{i,m} - \bar{e}_{i,m})^2}}$$

6. Experimental Details

Single span glasshouse is built with East-West orientation and (0.54 m$^2$ floor area), at Baghdad (33.3°N latitude and 44.4°E longitude) Iraq. A door is located the east-wall of the greenhouse with screw to serve the mechanism of opening and closing. The south roof consists of photovoltaic panel with 7mm thickness, packing factor 0.66 and 33.2° as slope angle. The length, width and height of greenhouse are 1.16m, 0.47m, and 0.74m respectively. The totals cover area of the glasshouse is (four walls and one roof) 1.9 m$^2$. Four square holes is opened in the top of the north wall to fix the fans sequentially. The hourly solar radiation was measured in solar meter. In addition the inside air and ground temperatures were measured with thermocouples. One sensor is fixed outside the glasshouse to sense the ambient temperature and three inside the glasshouse under shade (0.3m, 0.5m, and 0.7m) far from the door.

7. Discussion and Results

Every wall or roof receives solar intensity according to the sun movement, for example the East-Wall gained a solar radiation from 5 AM – 12 AM then starting to decrease due to movement of sun which reaches to the middle of south wall and roof of the greenhouse. Because of the convergent measured values that is sensed between (15/7/2019) and (16/7/2019) then the measured values for the solar radiation and ambient temperature in (15/7/2019) is decided to be the reference for this study. Also Fig.4 illustrates the hourly solar radiation available on each part of the glasshouse in summer season at 33.3°N (15/7/2019).
Fig. 4. Hourly solar radiation available on each wall and roof of the greenhouse

It can be notice from Fig. 5 that the relationship between the total solar radiations which is gained by the greenhouse and the ambient temperature. The ambient temperature increases from 6 AM to 2 PM when the sun is perpendicular on the earth. The total solar radiation is effects largely because of the exposed area of glass to sun light. At first hours of the light, the rays of sun effected on the east wall of the greenhouse then reaching to south wall and roof which are the biggest areas among the other walls of greenhouse that exposed to sun (the top value of total solar radiation at 1 PM is 730 w). So, the amount of the total radiation increases according to increment in area of glass which gained the sun rays.

Fig. 5. The relationships between the total solar radiation and the ambient temperature with respect to time

(I.A.T) is influenced by the solar radiation gained in each hour of the day. Positive relationship is available between (I.A.T) and the total solar radiation. Fig. 6 shows the experimental and calculating values of the (I.A.T) during the day (15/7/2019) without consideration of ventilation and (16/7/2019) with it.
Fig. 6. The measured and calculated computation of the (I.A.T) during the day (15/7/2019) addition to (16/7/2019) the process of ventilation.

It is noted that the convergence between the measured and determined (I.A.T) without ventilation and closer to what is known as congruence between the ambient temperature and calculated (I.A.T) with ventilation because of the fan pumped an air supplied from inside of the green house. Four fans worked from 8AM-6PM and one fan is worked from 6PM-8AM due to that can explain the difference between measured (I.A.T) with ventilation and calculated (I.A.T) with ventilation in most of hours in day.

The experimental and calculated ground temperatures are illustrated in Fig. 7 with and without ventilation. G.T is affected by the falling radiation from the walls, the inverted radiation from the north wall and underground temperature which are the reasons of the high value of G.T. The range of G.T is expanded between 8 AM – 5 PM because of the increment of total solar radiation which is passed through the glasshouse. In addition to the cover of the south roof with packing factor 0.66 not permeable to huge amount of solar radiation to enter from the roof to the inside. So the south wall is responsible to increment of G.T.

Fig. 7. The measured and calculated determination of G.T during the day (15/7/2019) addition to (16/7/2019) the process of ventilation.
8. Conclusion

The total solar radiation of glasshouse is affected by the solar radiation that is provided by the sun with respect to the radiation fall on the area. Also the increment of (I.A.T) depends on the total solar radiation and ambient temperature. (G.T) is influenced by the total solar radiation, reflected radiation from the north wall, the underground temperature and (I.A.T). Further, the innovative design with large scale the purpose of the counter (reverse) flow double pass photovoltaic solar thermal system dries the crops that converts the hot air from the PVT to small dryer room that includes the harvest fruits.

References:

1-V.P. Sethi, “On the selection of shape and orientation of a greenhouse: thermal modeling and experimental validation”, Sol. Energy 83 (2009) 21e38.
2-R.D. Singh, G.N. Tiwari, “Thermal heating of controlled environment greenhouse: a transient analysis”, Energy Convers. Manage 41 (2000) 505e522.
3-H.G Mobtaker, Y.Ajabshirchi, S.F. Ranjbar, M. Matloobi, “Solar energy conservation in greenhouse: Thermal analysis and experimental validation”, Renewable Energy 96 (2016) 509-519.
4-L. Chai, C. Ma, J. Q. Ni, “Performance evaluation of ground source heat pump system for greenhouse heating in northern China”, Bio systems engineering 111 (2012) 107-117.
5-R.H.E. Hassanien, M. Li, W.D. Lin, “Advanced applications of solar energy in agricultural greenhouses”, Renewable and Sustainable Energy Reviews 54 (2016) 989–1001.
6-R.K. Sahdev, A.K. Dhingra, M. Kumar, “A comprehensive review of greenhouse shapes and its applications”, Front. Energy, DOI 10.1007/s11708-017-0464-8.
7-A. Elkhadraoui, S. Kooli, I. Hamdi, A. Farhat, “Experimental investigation and economic evaluation of a new mixed mode solar greenhouse dryer for drying of red pepper and grape”, Renewable Energy 77 (2015) 1-8.
8-M.A. Karim, M.N.A. Hawlader, “Performance evaluation of a v-groove solar air collector for drying applications”, Applied Thermal Engineering 26 (2006) 121–130.
9-A.A. El-Sebaii, S. Aboul-Enein, M.R.I. Ramadan, S.M. Shalaby, B.M. Moharram, “Investigation of thermal performance of double pass-flat and v-corrugated plate solar air heaters”, Energy 36 (2011) 1076-1086.
10-E. Mashonjowa, F. Ronsse, J.R. Milford, J.G. Pieters, “Modelling the thermal performance of a naturally ventilated greenhouse in Zimbabwe using a dynamic greenhouse climate model”, Solar Energy 91 (2013) 381–393.
11-C. Kittas, M. Karamanis, N. Katsoulas, “Air temperature regime in a forced ventilated greenhouse with rose crop”, Energy and Buildings 37 (2005) 807–812.
12- Mark Z. Jacobson, Vijaysinh Jadhav, “World estimates of PV optimal tilt angles and ratios of sunlight incident upon tilted and tracked PV panels relative to horizontal panels”, Solar Energy 169 (2018) 55–66.
13- A. Arbel, M. Barak, A. Shklyar, “Combination of Forced Ventilation and Fogging Systems for Cooling Greenhouses”, Biosystems Engineering (2003) 84 (1), 45–55.
14-J.A. Duffie, W. Beckmen, “Solar Engineering of Thermal Processes”.
15- M. Zarzo, P. Marti, “Modeling the variability of solar radiation data among weather stations by means of principal component analysis”, Appl. Energy 88 (2011) 2775e2784.
16-O.O. Ajayi, O.D. Ohjeagbon, C.E. Nwadialo, O. Olasope, “New model to estimate daily global solar radiation over Nigeria”, Sustain Energy. Tech. Assess. 5(2014) 28e36.