Thermal Model Development for Solar Greenhouse Considering Climate Condition

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Abstract

Water crisis in the Middle East, leads policy makers to consider development of greenhouses on large scale. Typical greenhouses usually use energy carriers like natural gas and gasoline to provide suitable microclimate for plants. The consequence of greenhouse development will be huge amount of fossil fuels consumption, producing CO_2 and forcing loads to gas, gasoline and electricity networks. Considering excellent solar energy potential in the Middle East, solar greenhouses seems to be an innovative solution.

In this research, after studying different solar greenhouse experiences around the world, a successful model has been chosen, redesigned and improved. Solar greenhouse is designed to utilize solar energy by its passive energy system and minimize external energy demand. In order to investigate its performance, a mathematical thermal model has been developed to predict inside air temperature, which is the most important parameter in greenhouse performance. Solar Greenhouse Thermal Model (SGTM) is based on solar collector analysis and trombe wall calculations in buildings, it receives hourly climate data (solar radiation, wind speed and ambient temperature) and calculate hourly solar greenhouse inside air temperature during the year. SGTM has been validated and can be used to predict solar greenhouse inside air temperature in any region.

Results of using SGTM show that solar greenhouse is suitable for Tehran climate condition, and it works passively without auxiliary heating system in the winter, but it needs auxiliary cooling system in the summer. Sensitivity analysis indicates that the greenhouse size play a vital role in its thermal performance. So, there is an optimal size for solar greenhouse in each climate condition.

Keywords: Solar Greenhouse, Thermal Model, Solar Energy, Water Crisis

1. Introduction

World is dealing with several concerns, Water-Food-Energy nexus is one of them that has great impacts on people life directly. However, the water nexus may be more important than the others in the Middle East. Agriculture sector uses 84 percent of total water usage in the MENA region (Statista (2015)), which indicate essential actions must have done. Development of Greenhouses in large scale is one of the solutions which has attracted the attention of policy makers and leads them to consider development of greenhouses on large scale.

Greenhouses are designed to provide suitable microclimate for growing plant efficiently. Higher production per area, less water consumption and higher production quality are the main advantages of greenhouses but greenhouses consume energy carriers like natural gas, gasoline and electricity to provide desired microclimate. So, the consequence of greenhouses large scale development will be huge amount of fossil fuels consumption, producing CO_2 and forcing loads to gas, gasoline and electricity networks.

The Brundtland Commission's report (1988) defined sustainable development as "development which provides the current generations needs without compromising the future generations ability to meet their own needs", which imposed the idea of limitations by the state of technology on the environment's ability to meet present and future needs. Sustainable development concept and great solar energy potential in Middle East make solar greenhouses to seem an interesting idea and an innovative solution.

Passive design of solar greenhouse is utilizing solar energy for heating without any additional heating system, specifically it supports the idea of maximizing solar gain and minimizing heat loss to eliminate the dependence of fossil fuels for heating/cooling (Schiller and Plink (2016)) . Santamouris et al. (1994) categorized solar greenhouses in passive solar greenhouses and active solar greenhouses. Passive solar greenhouses have an integrated design to collect heat or the greenhouse works as a solar collector, the design is based on maximizing the solar gains but active solar greenhouses have equipment separated from the greenhouse to utilize solar energy, and an independent heat storage system. Several passive heating and cooling systems have been used in solar

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greenhouses around the world, Sethi and Sharma (2007 and 2008) reviewed and evaluated them and discussed the representative application of each technology, also they studied several cases for each technology and drive experimental equations for evaluating these technologies. These researches focused on heating and cooling systems that used on different structure designs.

There is a kind of solar passive greenhouses mainly located in northern region of China (Wang et al. (2014)), they are used to grow vegetables in the winter without any auxiliary heating. The building parameters have an important impact on the solar energy utilization and temperature in the greenhouse (Tong et al. (2013)). Tong et al. (2013) reviewed all researches that discussed solar greenhouse building parameters, they concluded all the building parameters are related to each other and to the local climate condition in solar passive greenhouse system and they should be analyzed together.

In this study, in the first step after studying different solar greenhouse experiences around the world, a successful model has been chosen, redesigned and improved, considering principles of solar passive design. Secondly, an innovative mathematical thermal model has been developed to predict inside air temperature annually in any climate condition, in order to investigate its performance. Thirdly, sensitivity analysis has been done on structural parameters to investigate effect of structural parameters on thermal performance of solar greenhouse.

2. Methodology

2.1. Solar Greenhouse Design

In order to design a solar passive greenhouse, orientation toward sun, insulate the areas that do not collect solar energy and underground, maximizing the light and heat in winter and reduce it in summer, using thermal storage techniques and supplying sufficient ventilation are the main principles that should be considered (Schiller and Plink (2016)).

Also, van't Ooster et al. (2007) represent a systematic procedure to develop a zero fossil greenhouse concept for the Netherlands. This design procedure contains following steps:

- Step 0: Design objective definition
- Step 1: Brief of requirements definition
- Step 2: Required functions definition
- Step 3: Working principles definition
- Step 4: Conceptual designs derivation
- Step 5: Conceptual designs evaluation

A solar passive greenhouse is designed based on above design principles. This is a south oriented elliptic shape greenhouse, covered by transparent material and a thermal insulation cover to prevent heat loss at night, a thermal storage wall (layered) is installed in the north of the greenhouse (Fig.1). Solar radiation transmits into the greenhouse during the day, south oriented elliptic shape roof from east to west collect solar radiation from sunrise to sunset efficiently, then is absorbed by heat storage wall and soil of the ground, which increase their temperatures because absorbed solar radiation is converted to sensible heat. Temperature difference between the surfaces and inside air causes heat transfer via convection, into the thermal storage wall via conduction, to store heat in it and keeping greenhouse warm at night, and into the ground via conduction. Part of absorbed solar energy is transformed into the latent heat by crop transpiration and evaporation from wet surfaces.

Thermal insulation covers the elliptic shape roof to prevent heat loss during the night. Stored heat in thermal storage wall transfers through convection to keep inside air warm.

Solar photovoltaic panels and solar collectors can be installed in the roof to supply electricity demand of greenhouse (for irrigation, lightening, fans, motors, climate control system, etc.) and to supply additional heat demand.

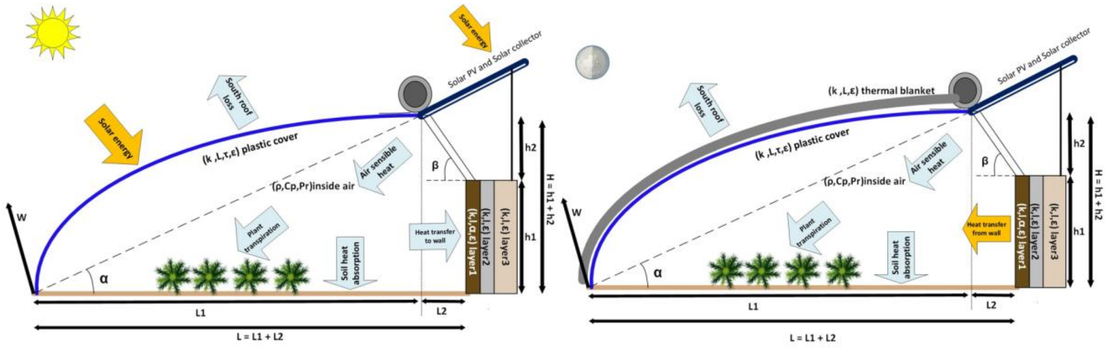

Figure 1: Cross sectional conceptual view, heat transfer mechanism and structural parameters of solar passive greenhouse at day and night

2.2. Thermal Model Description, Equations and Validation

The most important parameter in greenhouse performance is inside air temperature. Several energy analysis have been done to evaluate greenhouse performance. De Zwart (1996) developed a comprehensive greenhouse climate simulation model that included three sub models: CO_2, water vapor and thermal. The basis of equations was energy and mass balances and was developed for different temperature layers of greenhouse. Chen et al. (2015) developed a greenhouse energy demand model which was based on mass and energy balance considering physiological behavior of plants.

Thermal Model (SGTM) is based on solar collector analysis and trombe wall calculations in buildings (Duan et al. (2016)), it receives hourly climate data (solar radiation, wind speed and ambient temperature) and calculate hourly solar greenhouse inside air temperature during the year. Fig.2 shows how different parameters are connected in SGTM.

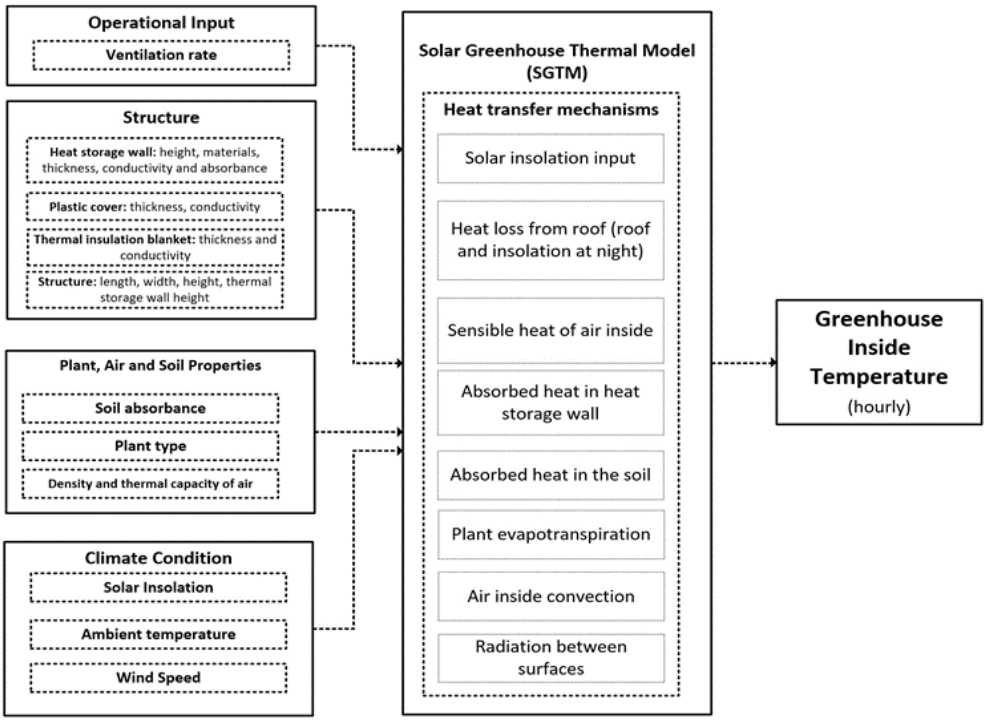

Figure 2: Data circulation diagram of SGTM

Seven surface of temperature has been considered (Fig.3) and for each surface energy balance equation has been developed. It is assumed that there is steady state condition, each surface has a constant temperature and air inside temperature is uniform.

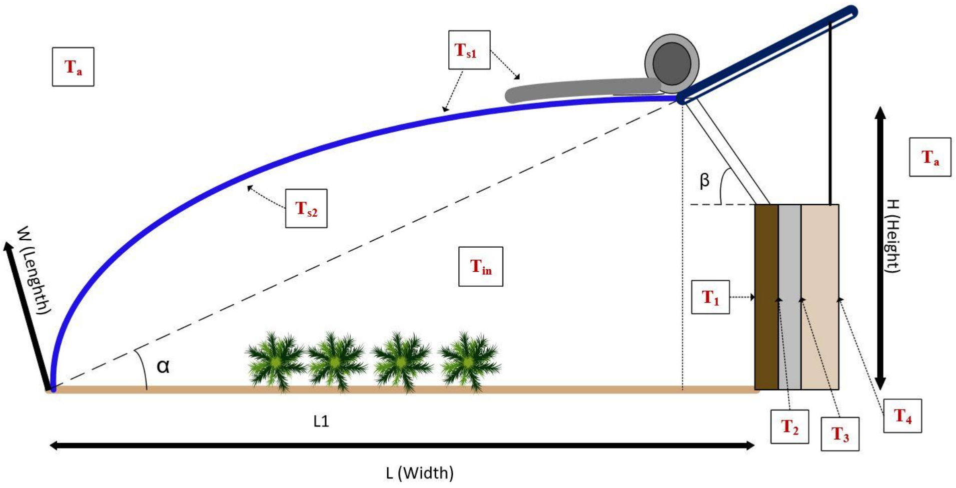

Figure 3: Temperature levels of SGTM

First level of equations belongs to the outer surface of plastic roof, equation 1 indicates the energy balance for it:

$$h_{c,cover-out}A_{cover}(T_{s1}-T_a)+h_{r,cover-out}A_{cover}(T_{s1}-T_a)+\frac{k_{cover}}{L_{cover}}A_{cover}(T_{s1}-T_{s2})= I\alpha_{cover}A_{cover} \qquad \text{(eq. 1)}$$

$$h_{c,cover-out}=5.7+3.8u_w \qquad \text{(eq. 2)}$$

$$h_{r,cover-out}=\varepsilon_{cover}\sigma(T_{s1}+T_s)(T_{s1}^2+T_s^2) \qquad \text{(eq. 3)}$$

$$T_s=0.055T_a^{1.5} \qquad \text{(eq. 4)}$$

Where T_{s1}, T_{s2}, T_s and T_a are respectively the temperature of outer surface of plastic roof, inner surface of plastic roof, sky temperature (equation 4) and ambient temperature, $h_{c,\ cover-out}$ refers to convection heat transfer coefficient from plastic roof to out of greenhouse and calculate through equation 2, $h_{r,\ cover-out}$ refers to radiation heat transfer coefficient from plastic roof to sky and calculate with equation 3.

Second level of equations belongs to internal surface of plastic roof and energy balance for it express as equation 5.

$$\left(h_{r,cover-wall}+\frac{k_{air,cover-wall}}{L_{air,cover-wall}}\right)A_{wall}(T_{s2}-T_1)+\frac{k_{cover}}{L_{cover}}A_{cover}(T_{s2}-T_{s1})+ h_{c,cover-air}A_{cover}(T_{s2}-T_{in})=0 \qquad \text{(eq. 5)}$$

$$h_{r,cover-wall}=\frac{\sigma(T_{s2}^2+T_1^2)(T_{s2}+T_1)}{\frac{1-\varepsilon_{cover}}{\varepsilon_{cover}A_{cover}}+\frac{1}{A_{cover}F_{cover-wall}}+\frac{1-\varepsilon_1}{\varepsilon_1 A_{wall}}} \qquad \text{(eq. 6)}$$

$$h_{c,cover-air}=\frac{k_{air,cover-wall}Nu}{L_{air,cover-wall}} \qquad \text{(eq. 7)}$$

Where T_1 and T_{in} are respectively temperature of inner surface of heat storage wall and inside air temperature.

Third level of equations belongs to internal surface of heat storage wall and energy balance for it express as eq. 8.

$$h_{c,wall-air}A_{wall}(T_1 - T_{in}) + \left(h_{r,wall-cover} + \frac{k_{air,wall-cover}}{L_{air,wall-cover}}\right)A_{wall}(T_1 - T_{s2}) + \frac{k_1}{L_1}A_{wall}(T_1 - T_2) + h_{r,L_1-L_2}A_{wall}(T_1 - T_2) = I\alpha_{wall}\tau_{cover}A_{wall} \qquad \text{(eq. 8)}$$

$$h_{r,L_1-L_2} = \frac{\sigma(T_1^2+T_2^2)(T_1+T_2)}{\frac{1}{\varepsilon_1}+\frac{1}{\varepsilon_2}-1} \qquad \text{(eq. 9)}$$

$$h_{c,wall-air} = \frac{k_{air,wall-cover}Nu}{L_{air,wall-cover}} \qquad \text{(eq. 10)}$$

Where T_2 refers to the connection of first and second layers of heat storage wall temperature. Energy balance for connecting layers which express with T_2 and T_3 (connection of second and third layers of heat storage wall temperature) express with following equations:

$$\left(h_{r1} + \frac{k_1}{L_1}\right)A_{wall}(T_2 - T_1) + \left(h_{r2} + \frac{k_2}{L_2}\right)A_{wall}(T_2 - T_3) = 0 \qquad \text{(eq. 11)}$$

$$h_{r1} = \frac{\sigma(T_1^2+T_2^2)(T_1+T_2)}{\frac{1}{\varepsilon_1}+\frac{1}{\varepsilon_2}-1} \qquad \text{(eq. 12)}$$

$$h_{r2} = \frac{\sigma(T_2^2+T_3^2)(T_2+T_3)}{\frac{1}{\varepsilon_1}+\frac{1}{\varepsilon_2}-1} \qquad \text{(eq.13)}$$

$$\left(h_{r3} + \frac{k_2}{L_2}\right)A_{wall}(T_3 - T_2) + \left(h_{r4} + \frac{k_3}{L_3}\right)A_{wall}(T_3 - T_4) = 0 \qquad \text{(eq. 14)}$$

$$h_{r3} = \frac{\sigma(T_3^2+T_2^2)(T_3+T_2)}{\frac{1}{\varepsilon_3}+\frac{1}{\varepsilon_2}-1} \qquad \text{(eq.15)}$$

$$h_{r4} = \frac{\sigma(T_4^2+T_3^2)(T_4+T_3)}{\frac{1}{\varepsilon_3}+\frac{1}{\varepsilon_2}-1} \qquad \text{(eq.16)}$$

Sixth layer is outer surface of heat storage wall. Equation 17 refers to energy balance for this surface.

$$h_{c,wall-out}A_{wall}(T_4 - T_a) + \frac{k_3}{L_3}A_{wall}(T_4 - T_3) + h_{r4}A_{wall}(T_4 - T_3) + h_{r,wall-out}A_{wall}(T_4 - T_a) = 0 \qquad \text{(eq. 17)}$$

$$h_{r,wall-out} = \varepsilon_3\sigma(T_4 + T_s)(T_4^2 + T_s^2) \qquad \text{(eq. 18)}$$

Where T_4 is outer surface of heat storage wall temperature.

Last level is energy balance for greenhouse air inside control volume, assuming there is no temperature distribution and T_{in} as inside air temperature.

$$h_{c,cover-air}A_{cover}(T_{in} - T_{s2}) + h_{c,wall-air}A_{wall}(T_{in} - T_1) + \rho_{air}\dot{V}C_{p,air}(T_{in}(t) - T_{in}(t-1)) + ach\ V_{inside}\rho_{air}C_{p,air}(T_{in,h} - T_a) + A_{ground}\lambda E(t) + U_{cover}A_{cover}(T_{s2} - T_a) + I\tau_{cover}\alpha_{soil}A_{ground} = I\tau_{cover}A_{cover} \qquad \text{(eq.19)}$$

Where λE(t) refers to the crop transpiration and expresses with Penma-Monteith formula (Chen et al. (2014)):

$$\lambda E(t) = \frac{I_a \tau_a \Delta + 2LAI(\frac{\rho c_a}{r_a})(e_s(t) - e_a(t))}{\Delta + \gamma(1 + \frac{r_c}{r_a})} \qquad \text{(eq. 20)}$$

$$\Delta = \frac{2504000}{(T_{in} - 35.6)^2} \exp(\frac{17.27(T_{in} - 273.16)}{T_{in} - 35.86}) \qquad \text{(eq. 21)}$$

Ventilation happens by using of fans which causes force convection. Nusselt number force convection in non-circular ducts can be calculated by circular ducts equations by substitution of hydraulic diameter (Bergman and Incropera (2011)).The distance between the wall and cover is also assumed hydraulic diameter.

$$D_h = \frac{4A_c}{P} \qquad \text{(eq. 22)}$$

Where A_c and P are respectively cross sectional area of duct and wetted environment. Nusselt number is calculated by Colburn equation (Bergman and Incropera (2011)):

$$Nu_D = 0.023 Re_D^{0.8} Pr^{1/3} \qquad \text{(eq. 23)}$$

Equations 1, 5, 8, 11, 14, 17 and 19 form a system of non-linear equations and the output will be temperature of greenhouse levels, the main result is inside air temperature.

In order to predict reliable results with SGTM, a validation has done. The best way to check the accuracy of model results is to compare them with experimental data. Tong et al. (2009) studied a similar solar greenhouse located in Shenyang, China (latitude: 41.8ºN, longitude 123.4ºE, altitude: 42 m). The greenhouse was 60 meter long and 12.6 meter wide with 5.5 meter ridge height, a 0.6 meter layered heat storage wall made of bricks and XPS foam as a thermal insulation material. The plastic roof was made of 0.12 mm PVC film, covered with a 20 mm thick cotton blanket during the night time. Other necessary data like solar insolation, ambient temperature, and physical properties, was reported in this paper as well. The typical weather file of Shenyang downloaded from the U.S. Department of Energy and used for wind speed data.

The highest temperature difference between SGTM model and experimental data is 2.8 Kelvin and the average of differences is 0.89. Figure 4 shows the model results compering to experimental data.

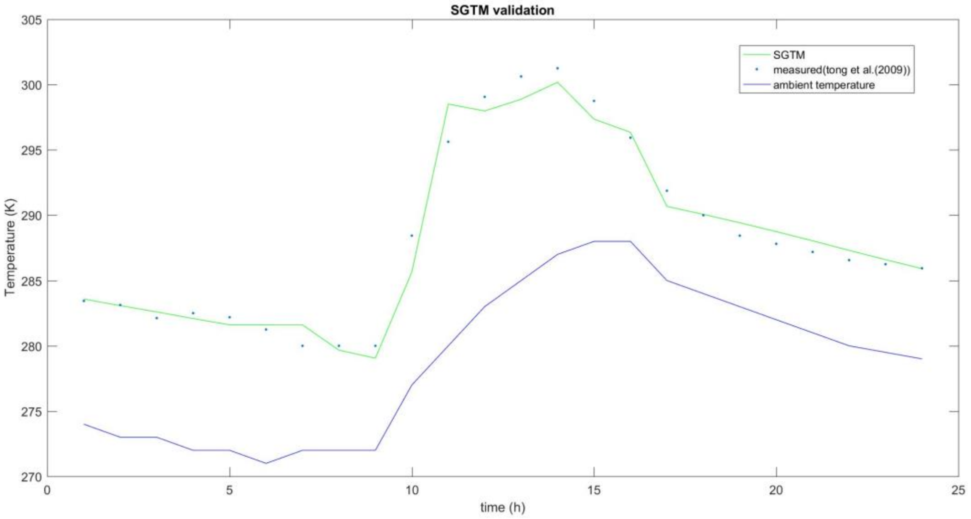

Figure 4: Validation of SGTM model for hourly greenhouse air inside temperature with experimental data in 20 February 2004 in Shenyang, China (Tong et al. (2009))

2.3. Simulation Outline

To investigate solar greenhouse performance in Tehran climate condition, a solar greenhouse is considered with 5.5 meter height, 12 meter width and 100 meter length and the 3 layered heat storage wall is 3 meter high and 0.6 meter thick.

Table 1: Natural and physical properties of solar greenhouse structure

Location	Thickness (m)	Thermal conductivity (W/m.K)	Emissivity ε	Absorptance α	Transmission τ
Plastic cover	0.00012	0.17	0.9	0.03	0.88
Thermal insulation	0.036	0.09	0.9	0.75	0
Heat storage wall inside layer	0.36	0.81	0.93	0.6	0
Heat storage wall middle layer	0.12	0.03	0.9	-	0
Heat storage wall outside layer	0.12	0.81	0.93	0.6	0

3. Results and Discussion

3.1. Solar Greenhouse Performance in Tehran

The aim of using solar greenhouse is to maximize solar energy utilization and minimize using of active energy systems to provide desirable micro-climate for plants. There are two extreme states to investigate greenhouse thermal performance in order to know if it will work properly in a specific climate, hottest and coldest months of the year. July and January are the hottest and coldest months in Tehran based on typical weather file downloaded from the U.S. Department of Energy.

Typical vegetable plants can tolerate temperature range 10 to 32, as it has shown in Figure 5, during the average day of July, greenhouse will be overheated, and it is caused of huge amount of solar radiation and high ambient temperature which means it is necessary to use a cooling system or some energy management solutions like shading and using an optical object to send excessive solar insolation to outside. Figure 6 shows solar greenhouse will work properly in winter and the inside temperature will not be less than 286 Kelvin although the ambient temperature is less than the minimum temperature all the time and it is near to 273 kelvin.

Solar greenhouse can be used in hot climates like Tehran without any auxiliary heating. To prevent overheating in summer a cooling system can be used or can be planned to operate greenhouse only in cold seasons, also some other passive systems can be designed to adjust inside air temperature in a better range like ground to air heat exchanger (Sethi and Sharma (2007 and 2008)).

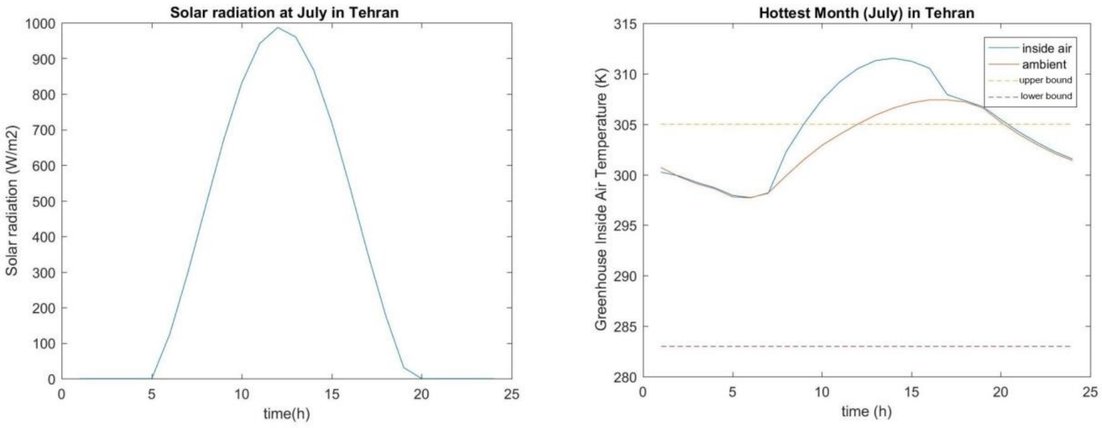

Figure 5: Solar insolation (left) and thermal performance of solar greenhouse (right) at July in Tehran

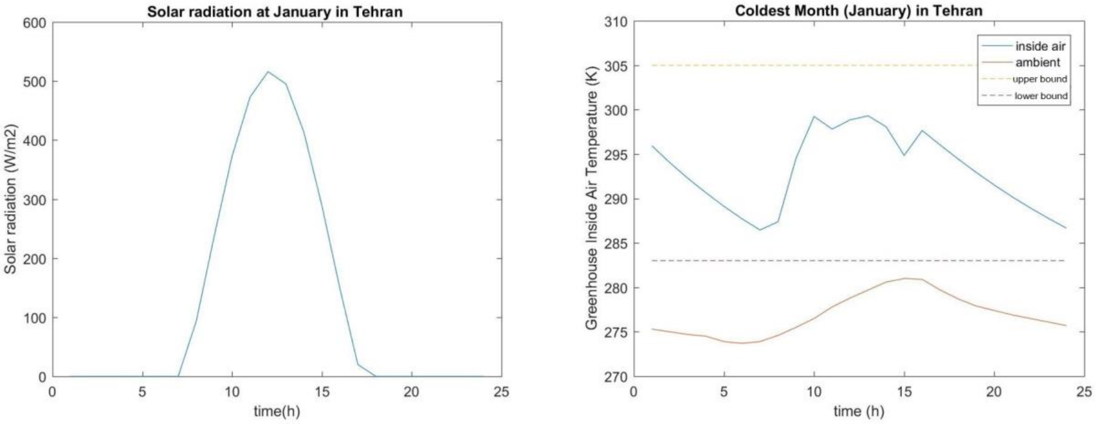

Figure 6: Solar insolation (left) and thermal performance of solar greenhouse (right) at January in Tehran

3.2. Sensitivity analysis

Passive solar greenhouse can be assumed as a solar collector. Like any kind of solar collector its sizing has an essential role in its performance that is determined based on climate condition, to investigate the effect of changing the structural parameters, three cases have been defined and studied. Size parameters of greenhouse structure are α and β which define the ratio of height to width and L and H which define the height and width.

- Case 1

  In this case, α and β remain constant and the total size of greenhouse is changed, which is equal to change the inside air volume. As it has shown in figure 7, the solar greenhouse thermal performance gets better by increasing the size of greenhouse in hottest month of year and it works well in all the cases in coldest month of year, so the bigger solar greenhouse works better in Tehran climate condition. Also bigger greenhouse has a better temperature distribution which is better for crop transpiration.

Table 2: Solar greenhouse structural parameters details for case 1

Number of the case	H (m)	L (m)	α	β
Case 1.1	4.58	10	30	45
Case 1.2	5.5	12	30	45
Case 1.3	6.42	14	30	45
Case 1.4	7.5	16	30	45

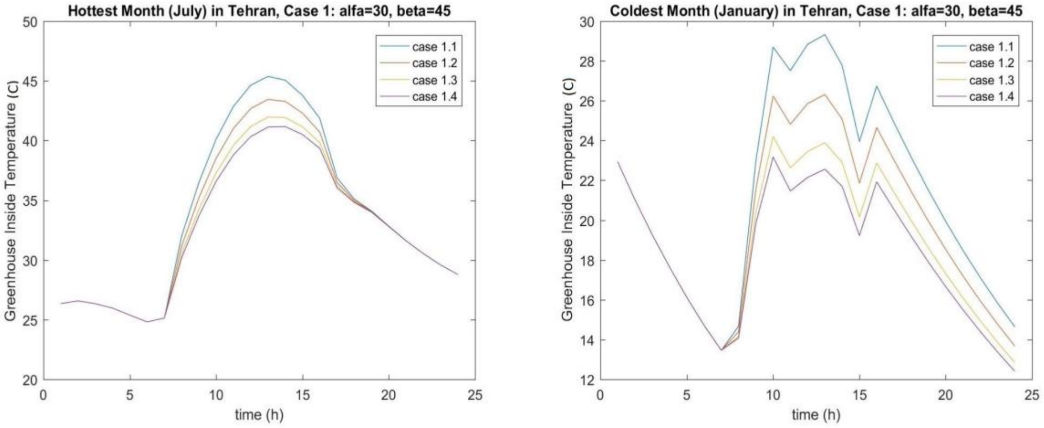

Figure 7: Solar greenhouse thermal performance in case 1

- Case 2

  In this case β and H are constant and α and L are changed to investigate the effect of α angle in thermal performance of solar greenhouse, α angle's function is like tilt angle function in solar collector, but in this case the best tilt angle for winter is important to keep greenhouse warm in winter.

  As it has shown in figure 8, case 2.1 (α=36) has the best performance in hottest month of year and the bigger α angles have better performance in coldest month of year.

Table 3: Solar greenhouse structural parameters details for case 2

Number of the case	H (m)	L (m)	α	β
Case 2.1	5.5	10	36	45
Case 2.2	5.5	12	30	45
Case 2.3	5.5	14	25	45
Case 2.4	5.5	16	22	45
Case 2.5	5.5	9	40	45

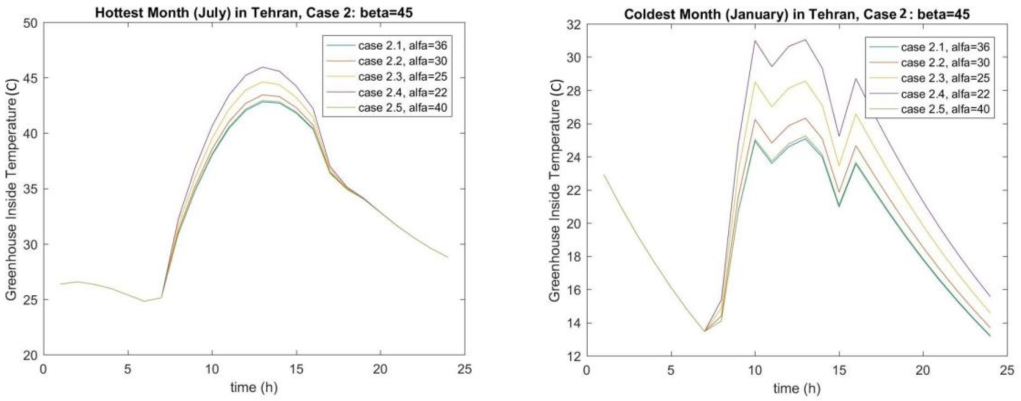

Figure 8: Solar greenhouse thermal performance in case 2

- Case 3

  In this case the effect of β angle and heat storage wall height are investigated. As it has shown in figure 9, bigger β has worse performance not only in summer but also in winter, because bigger beta equals to more area for plastic roof and more area to collect solar energy, in simpler words it leads to a bigger solar collector. The bigger heat storage wall also has overheating in both summer and winter, because of using more thermal mass to store heat.

  Bigger beta and heat storage wall values will effect positively on greenhouse performance in cold climates.

Table 4: Solar greenhouse structural parameters details for case 3

Number of the case	H (m)	L (m)	α	β	Heat storage wall height (m)
Case 3.1	5.5	10	30	45	5
Case 3.2	5.5	10	30	78	3
Case 3.3	5.5	12	30	45	3

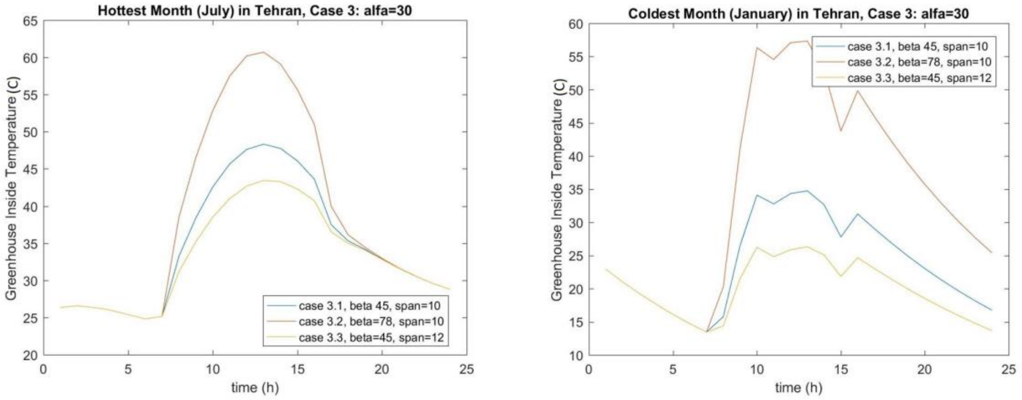

Figure 9: Solar greenhouse thermal performance in case 3

4. Conclusions

In this research a solar greenhouse is designed and its performance is evaluated by developing a thermal model in order to calculate inside air temperature. This study shows that:

- Solar greenhouse thermal model receives climate condition data, plant type, size and materials of structure and operational data and puts them in a system of non-linear equations to predict greenhouse air inside temperature in any region.
- Solar greenhouse can operate without auxiliary heating in winter in hot climates like Tehran, but there is necessary to use an active cooling system (like fan and pad) or use passive systems (shading, ground to air heat exchanger) to cool it in summer. The other solution is to plan greenhouse to operate seasonally.
- The sensitivity analysis has showed that the structural parameters of greenhouse have a great impact on greenhouse thermal performance. It can be concluded that the bigger greenhouse with α angle around 36 and beta angle around 45 is the best structure between the studied cases. It shows that there is an optimum structure for each climate.
- Although greenhouse inside air temperature stays in appropriate range most of the time, there is a specific temperature range for each plant. If the greenhouse keeps in that range, the production performance will be higher, so auxiliary heating and cooling systems can be designed and used. The energy demand of them will be much less than typical greenhouses.

5. Acknowledgment

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5.2. Links

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7. Appendix: Unites and Symbols

Table 5: Symbols definition and units

Quantity	Symbol	Unit
Specific heat	C_p	J kg^{-1} K^{-1}
Thermal conductivity	k	W m^{-1} K^{-1}
Absorptance	α	
Emittance	ε	
Density	ρ	kg m^{-3}
Transmittance	τ	
Radiation heat transfer coefficient	h_r	W m^{-2} K^{-1}
Convection heat transfer coefficient	h_c	W m^{-2} K^{-1}
Area	A	m^2
Temperature	T	K
Solar radiation	I	W m^{-2}
Overall heat transfer coefficient	U	W m^{-2} K^{-1}
Stefan-Boltzmann constant	σ	W m^{-2} K^{-4}
View factor	F	
time	t	s
Wind speed	u_w	m s^{-1}
Thickness	L	m
Volumetric flow rate	$\dot{V}$	m^3 s^{-1}

Air change per hour	ach	
Nusselt number	Nu	
Reynolds number	Re	
Prandtl number	Pr	
Latent heat of vaporization	λ	kJ kg^{-1}
Plant canopy leaf area index	LAI	
Canopy transpiration rate	E(t)	Kg m^{-2} s^{-1}
Saturated vapour pressure of air	e_s	Pa
Water vapour pressure of air	e_a	Pa
leaf aerodynamic	r_c	s m^{-1}
Stomatal resistances of the leave	r_a	s m^{-1}
psychometric constant	γ	kPa K^{-1}
slope of the water vapor saturation curve	Δ	Pa K^{-1}
Hydraulic diameter	D_h	m
Environment	P	m