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A Pseudo Dynamic Model for Simulation of Greenhouse Energy Requirement

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ABSTRACT

A pseudo dynamic thermal model has been developed for simulating the heating/cooling energy requirement of conventional greenhouses based on lumped estimation of heat flow parameters in greenhouses. Most of the parameters of greenhouse energy flux have been considered in the model including the sensible heat usage in plant transpiration, and also heat gain from environmental control systems. The developed model can simulate the hourly heating/cooling requirement of greenhouses based on input information about desired indoor environment, dimension and thermal properties of constructional materials, characteristics of selected crop, and local weather data. This model would be beneficial for researchers, engineers and growers to estimate the energy requirement of greenhouses, thereby model would be a useful tool for their decision making about the energy efficient design, and feasibility analysis of greenhouses for a particular locations.

Keywords: Greenhouse, Heating, Ventilation, Infiltration, Solar Radiation, Simulation.

INTRODUCTION

Greenhouse technology has been practicing for crop production for about over two centuries in the world. Heating and cooling of greenhouses are required in most of the regions to grow the crops throughout the year. However, the heating and cooling costs of greenhouses in northern latitudes

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including Canada are about 75 to 85 percent of total operating costs of crop production excluding cost associated with labor (Rorabaugh et al., 2012). Therefore, the prediction of energy requirement in heating and cooling are important for energy efficient design, and also for economic feasibility analysis to grow the certain crops in greenhouses under particular weather conditions.

A large number of mathematical models have been developed for predicting the thermal environment of greenhouses under different conditions. Most of these models (Cooper & Fuller, 1983; Mahrer and Avissa, 1984; Levit & Gasper, 1988; Chuo *et al.* 2004; Singh *et al.,* 2006; Sengar & Kothari, 2008) have been developed by forming individual energy balance equations for interactive components (plant, soil, cover, air) of greenhouses. These models are very complex for long time simulation because of large number input parameters, and also need significant modification for the different types of greenhouses. However, a few simplified models have been developed based on lumped estimation of greenhouse heat transfer parameters in order to minimize the complexity of the models. Initially, some simplified steady state models were developed to determine the size of heater and fan (Morris, 1956; Walker, 1965; Chiapale *et a*l., 1981). Later, a couple of improved steady-state models have been developed (Chandra, 1976; Simpkins *et al*., 1979; Chandra and Albright, 1981, Breuer and Short, 1985, Tunc *et al*., 1985, Garzoli, 1985) for evaluating the energy saving potential of greenhouse shapes, sizes, orientations, and types of coverings. However, the precision of these models are limited because of neglecting dynamic variations of solar radiation, and validity restricted to certain types of greenhouses and climates (Sethi *et al.,* 2013). An elaborate steady-state dynamic model (HOTICREN) was developed by Jolliet *et al*. (1991) by improving the existing models presented by earlier researchers (Horguchi, 1978; Bailey *et al.,* 1985; Garzoli, 1985). However, HOTICREN model neglects some major sources of greenhouse energy fluxes. Hill (2006) developed a details thermal model for nursery greenhouse, and included most of greenhouse heat exchange parameters in his model. However, the model is developed with large number of empirical equations without validation, and the model also very complicated because of these huge number of input parameters. In addition, the heat gain form environment control systems including supplemental lighting, air re-circulation system, and CO_2 enrichment facilities, have not considered in the model.

The objective of the research is to develop a complete pseudo dynamic model including solar radiation sub model for predicting the heating/cooling energy consumption in greenhouses to maintain a suitable indoor environment. The thermal model has been developed based on the theoretical analysis of different parameters of greenhouse thermal environment. Then model was used to simulate a selected greenhouse, and preliminary validation was conducted.

DEVELOPMENT OF THE THEORITICAL MODEL

Thermal environment of greenhouses is very complicated as compared to the residential and commercial building because of dynamic heat and mass transfer process, and the process of plant photosynthesis in greenhouses. Therefore, the following assumptions are considered for simplification of the model.

1. Indoor air is uniformly mixed, and air temperature is uniform,
2. Indoor air velocity is constant,
3. Heat storage capacity of plants, walls and roofs materials is negligible,
4. Indoor air and plants temperature are same,
5. Heat capacity of covering materials and plants is negligible,
6. Physical properties of all materials in the greenhouse are constant,
7. Radiation heat exchange between the wall and the roof is negligible, and
8. Floor heat conduction is one dimensional steady state.

The energy balance of a typical conventional greenhouse is shown in figure-1. The thermal model has been developed based on the following sensible heat balance equation:

$$q_h + q_m + q_s = q_e + q_{vi} + q_g + q_p + q_t$$

Where q_h is the heat gain from heating system, q_m is the heat gain from environment control equipment including supplemental lighting, motors of recirculating fans, and CO_2 generator, q_s is the incoming solar insolation, q_e is the heat transfer through the covering by conduction, convection, and radiation, q_{vi} is the heat exchanged caused by infiltration and ventilation, q_g is the amount of heat transfer through greenhouse floor, q_p is the heat exchanged along the perimeter of greenhouse, and q_t is the sensible heat used in the process of plant transpiration.

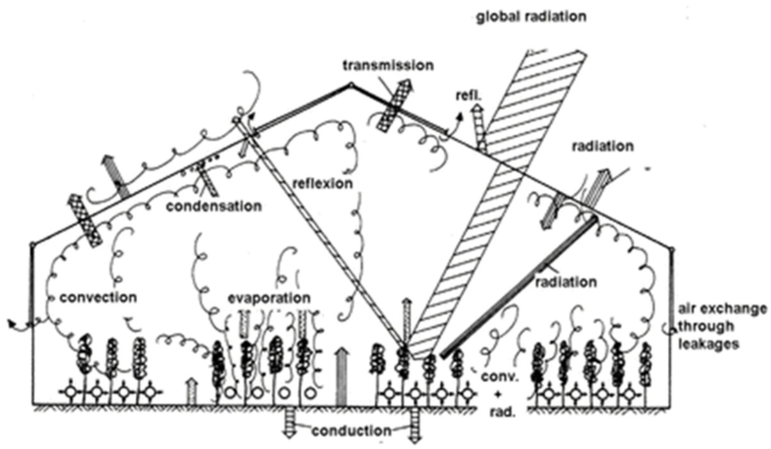

Figure 1.General energy balance of a greenhouse. Source: Erik, 2009

Based on the above sensible energy balance equation, the following section described the theoretical principles that was considered for estimating the different components of heat transfer in greenhouses.

Solar radiation

The total solar radiation in greenhouses is the sum of the incoming solar radiation through different surfaces exposed to the outside. The solar radiation on any surface is basically consists of three components such as direct beam radiation, diffuse radiation, and reflected radiation. According to Liu and Jordan, 1963, the sum of these three components of solar radiation on an inclined surface can be expressed as follows:

$$E_t = E_b \frac{\cos\theta}{\cos\theta_z} + E_d \left(\frac{1+\cos\beta}{2}\right) + E_{th}\ \rho_r \left(\frac{1-\cos\beta}{2}\right)$$

Where, E_t is the total solar radiation on inclined surface (W/m^2), E_b is the diffuse radiation on horizontal surface (W/m^2), θ is angle of incidence of surface, θ_z is the zenith angle of the sun, E_d is the diffuse radiation on horizontal surfaces (W/m^2), β is the slope of surface, E_{th} is the total solar radiation on horizontal surface (W/m^2), and ρ_r is the reflectivity of outdoor ground.

The clear sky global solar radiation on horizontal surface is estimated according Hottel (1976), and the angle of incidence and zenith angle of the sun can be expressed as follows (Duffie and Backman, 2006):

$$\cos\theta = \sin\delta \sin\varphi \cos\beta - \sin\delta \cos\varphi \sin\beta \cos\gamma + \cos\delta \cos\varphi \cos\beta \cos\omega + \cos\delta \sin\varphi \sin\beta \cos\gamma \cos\omega + \cos\delta \sin\beta \sin\gamma \sin\omega$$

$$\cos\theta_z = \cos\varphi \cos\delta \cos\omega + \sin\varphi \sin\delta$$

Where, δ is the declination angle, φ is local latitudes, γ is the surface azimuth angle, and ω is the hour angle.

Then, the actual solar radiation is obtained by multiplying the clear sky solar radiation with the cloud cover factor.

Heat from supplemental lighting

Supplemental lighting can supply significant amount of heat to increase indoor air temperature, and the intensity of heat addition depends on the types of lighting systems in greenhouses. The sensible heat addition from supplemental lighting can be calculated as follow (ASHRAE, 2013):

$q_{sl} = WF_a A_f$

Where q_{sl} is the heat gain from supplemental lighting (W), W is the light installed light wattage per unit area (50 W/m^2, Castilla, 2013), A_f is the floor area (m^2).

Heat from CO_2 generator

The heat addition from CO_2 enrichment facilities is only considered when CO_2 produce in the greenhouses with CO_2 generator. The heat gain from combustion of fuel in carbon dioxide generator can be calculated as follows:

$$q_{co_2} = C \times NHV \times MFR \times A \times PR$$

Where, C is the conversion factor (0.278), NHV is the net heating value (MJ/kg), MFR is the carbon dioxide supply rate in greenhouses ($kg/m^2.hr$), A is the area of greenhouses (m^2), and PR is the CO_2 production rate.

The supply rate carbon dioxide is assumed constant, and about 4.5 g m^{-2} h^{-1} is recommended to maintain 1000 ppm in closed greenhouses (Van Berkel and Vereer, 1984).

Heat from electric motors

The instantaneous sensible heat gain from electric motors of recirculating fans can be calculated as follows (ASHRAE, 2013):

$q_{em} = N_f \frac{P}{E_m} F_{um} F_{ul}$

Where, N_f is the required number of fans in greenhouses, P is the motor power rating (W), E_m is the motor efficiency, F_{um} is the motor load factor (1.0), F_{ul} is the motor use factor (1.0).

Conduction and convection through greenhouse covering

The heat transfer cussed by conduction and convection through greenhouse covering are separated into two groups depending on the nature of the surfaces: basically transparent surfaces and non-transparent surfaces.

Heat transfer through transparent surfaces

The overall coefficient of heat transfer due to the combine action of conduction and convection can be determined as follows (Tiwari, 2003):

$$U = \begin{cases} [\frac{1}{h_i} + 2\frac{L_1}{K_1} + \frac{L_2}{K_2} + \frac{1}{h_o}]^{-1} & \text{,for the double layer covering} \\ [\frac{1}{h_i} + \frac{L_1}{K_1} + \frac{1}{h_o}]^{-1} & \text{, for single layer covering} \end{cases}$$

Where, h_i, and h_o are the convection coefficient for the indoor and the outdoor surfaces ($W/m^2.K$), respectively K_1, and K_2 are the thermal conductivity of the covering and the air gap (W/m.K), respectively, L_1, and L_2 are the thickness of the covering and the air gap (m), respectively.

The convection coefficient in outdoor surface of transparent cover is given as follows (Papadakis et al., 1992):

$h_o = 0.95 + 6.76V_a^{0.49}$

The convective coefficient in indoor surfaces is calculated by the following empirical equations (Singh et al., 2006):

$h_i = 2.8 + 3.0V_i$

Where, V_a and V_i are the outdoor and the indoor air velocity (m/s), respectively.

Heat loss through the non-transparent surfaces

The combine coefficient of conduction and convection in non-transparent wall can be determined by the following equation (Tiwari, 2003):

$$U = [\frac{1}{\alpha_i} + \sum \frac{K}{\Delta x} + \frac{1}{\alpha_o}]^{-1}$$

Where α_i and α_o are the surface film coefficients of heat transfer in inward and outward surfaces of the wall (W/m^2-K), respectively, K is the thermal conductivity of the material elements in wall (W/m-K), $\triangle x$ is the thickness of elements (m).

Heat conduction through greenhouse floor

The heat conduction through the greenhouse floor can be expressed as follows (Tunc et al., 1985):

$q_s = \frac{K}{H} \times A_f \times (T_i - T_s)$

Where *K* is the thermal conductivity of the soil (W/m.K), H is the depth from ground surface where soil temperature almost constant (m), T_i is the indoor set point temperature, T_s is the constant soil temperature (K).

The soil temperature extending from the depth of 1 m is not very sensitive to the change of surface temperature. It is considered the constant soil temperature is about 15˚C at a depth of 3 m below the soil surface (Florides & Kalogirou, 2004).

Heat transfer along the perimeter

The heat transfer along the perimeter of greenhouses is proportional to the temperature difference between the greenhouses and the outdoor, and can be estimated as follows (ASHRE, 2013):

$q_p = F_p\, P \times (T_i - T_o)$

Where F_p is the perimeter heat loss coefficient (W/m.K), P is the perimeter of the floor (m),T_o is the outdoor temperature.

Longwave radiation transfer

The amount of heat exchange due to transfer of longwave radiation from greenhouses to outside can be estimated by the following equation (Vadiee, 2011):

$q_r = \sigma \times [F_c \times (1-\varepsilon_c) \times (T^4_i - T^4_c) + F_s \times \varepsilon_c \times (T^4_i - T^4_{sky})] \times A_c$

Where, σ is the Stefan-Boltzmann Constant (5.6703×10^{-8} W/m^2K^4), F_c is the view factor between the ground (soil and canopy) and the cover, F_s is the view factors between the sky and the cover, T_{sky} is the sky temperature (K), T_c is the cover temperature (K), A_c is the area of the cover (m), ε_c is the emissivity of the cover.

Bakker et al (1995) suggested the following linear function to determine the cover temperature.

$T_c = \frac{2}{3}\, T_o + \frac{1}{3}\, T_i$

The sky temperature is estimated according to the following equation (Swinbank, 1963):

$T_{sky} = 0.0552 \times (T_o + 273.16)^{1.5}$

Infiltration and ventilation

The air exchange into the greenhouses can be caused by the combined action of natural (wind and stack pressures) and mechanical force, or only by the natural forces (closed greenhouse). The air exchange in greenhouses is the sum of the air flow caused by infiltration and ventilation. Depending on the types of ventilation system, the air exchange can be expressed as follows:

$$Q = \begin{cases} Q_{in} + Q_{v,} & \text{when natural ventilation is in operation} \\ Q_{e}, & \text{when mechanical ventilation is in operation} \\ Q_{in}, & \text{for closed greenhouse without ventilation} \end{cases}$$

Where Q is the air-exchange rate into the greenhouses (m^3/s), Q_e is the air flow rate of exhaust fan in mechanically ventilated greenhouse (m^3/s), and Q_v is the rate air exchange caused by the natural ventilation system (m^3/s), Q_{in} is the rate of infiltration in greenhouses (m^3/s).

Now, the sensible heat transfer due to air exchange from the greenhouses is given by:
$q_{vi} = \rho Q \times [C_{pa} (T_i - T_o)]$
Where ρ is the air density (kg/m^3), C_{pa} is the specific heat of air (KJ/kg.K)
The air exchange rate of greenhouses caused by natural ventilation system has been studied by several researchers (Bot, 1983; Boulard & Baille, 1995, Perez et al. 2004). Perez et al. (2004) proposed the following equation for calculation of natural ventilation rate through the ventilators with flaps in the roof or in the sidewalls of a greenhouse.

$$Q_v = \frac{A}{2} C_d \sqrt{2g\left(\frac{h}{4}\right) \times \frac{T_i - T_o}{T} + C_w V_a^2}$$

Where, A is the sum of the areas of the ventilation openings (m^2), C_d is the coefficient of discharge, h is the vertical dimension of the ventilation opening (m), and T is the mean absolute temperature, C_w is the global wind pressure coefficient.
The coefficient of discharge can be determined by the following equation (Bot, 1983):

$$C_d = \frac{1}{\sqrt{1.9 + 0.7\exp(-\frac{L}{32.5H\sin\alpha})}}$$

Where H and L are the width and length of the ventilator (m), respectively, α is angle through which a flap ventilator is opened.

Energy used in plant transpiration

The water diffusion from growing media is comparatively very low as compared to water vapor diffusion from the plants surface. Therefore, the flux of water vapor from plant canopy to the surrounding air-water vapor mixture has modeled according to Nobel (1974):

$$M_T = 2A_p\rho\,(w_p - w_i)/R_p$$

Where, A_p is the effective area of the plants (m^2), ρ is the air density (kg/m^3), R_p is the total plant resistance to water vapor diffusion per unit leaf area, (sm^{-1}), w_p is the saturated humidity ratio of the air at plant temperature (Plant temperature assumed same as air temperature), w_i is the humidity ratio of air at indoor set point temperature.
The effective area of the plants is determined from the leaf area index (LAI) value, and the average of leaf area index of three different stages of plant life is used in the model. It is also assumed that equal transpiration rate from the upper and lower sides of leaf, so the effective plant area is multiplied by 2.
In general, the resistances involved in water vapor diffusion of plants are sum of the stomatal resistance and aerodynamic resistance. The stomatal resistance can be calculated from the following relationship (Boulard et al., 2002):

$$R_s = 305 \times \left(\frac{L_f}{V_i}\right)^{0.5}$$

Where R_s is the stomatal resistance (sm^{-1}), L_f is the characteristics length of the plant leaf (m), and V_i is the indoor mean air speed (m/s).
On the other hand, the aerodynamic resistance is given by (Boulard et al., 1991):

$$R_a = 200\left(1 + \frac{1}{\exp(0.5(\tau E_t - 50))}\right)$$

Where, R_a is the aerodynamic resistance (sm^{-1}), E_t is the total outside solar radiation on horizontal surface (W/m^2), τ is the transmittance of the greenhouse cover.
The plants temperature are assumed as same as of the indoor air temperature, so the sensible heat used in plant transpiration can be determined by the following equation (Nobel, 1974):

$$q_{tr} = M_T L$$

Where, L is the latent heat of vaporization at leaf temperature (KJ/kg.K).

DEVELOPMENT OF COMPUTER SOFTWARE

The flow chart of programming based on the developed model is shown in Figure-2. The programming language MATLAB was used to develop the computer software for predicting the heating and cooling energy requirement of conventional greenhouses to maintain the desirable indoor environment.

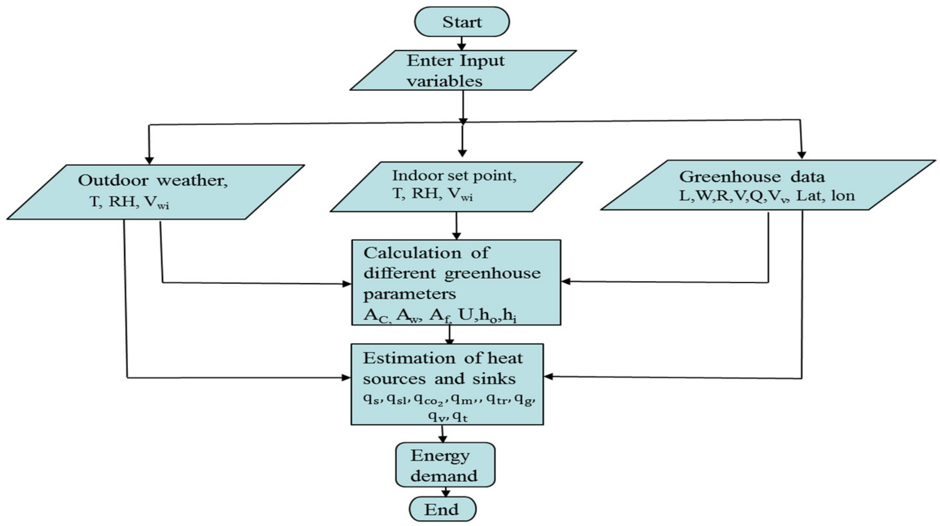

Figure 2. Flowchart of programing for the simulation of the model.

SIMULATION OF THE MODEL

A single span gable roof greenhouse (269.56 m^2) located at on a farm 20 km north-east of St. Louis, Saskatchewan, near the city of Prince Albert (53.22^{o}N latitude, 105.68^{o}W longitude and 428 m elevation), covered with air inflated double layer polyethylene was used for simulation of the model. The greenhouse was 9.2 m wide, 29.3 m long and 4.3 m high at the ridge, and tomato plants were grown in the greenhouse. The north wall made of steel siding and 1 inch polystyrene insulation, and the south wall is made of polycarbonate (PC) board.

Typical meteorological year data (TMY) of Saskatoon were used as ambient temperature for the simulation. The indoor set point temperature 21˚C for day and 18˚C for night were selected based on recommended optimum temperature for tomato production. The indoor relative humidity was assumed 70% over the simulation period. In general, the supplemental lighting needs to turn on when the natural PAR radiation is below 10-15 W/m^2 (Baille, 1999). However, it was considered that supplemental lighting to be turned on every day after 6 pm, and turned off after 7 am. Similarly, it was assumed that CO_2 generator keep in operation between 7 am to 9 am every day. The recirculating fans were assumed to be in operation over the simulation period. The others values of constant parameters used in the simulation are given in Table 1.

Table1 Different constant value used for the model simulation

Constant parameters	Symbol	Value
Latent heat of water vaporization	L	2502 KJ/kg
Specific heat of air	C_{pa}	1.0 KJ/kg.K
Air density	ρ	1.2 kg/m^3
View factor between cover and sky	F_s	1.0
View factor between cover and canopy	F_c	0.8
Average outdoor wind speed	V_a	4.25 m/s
Indoor air velocity	V_i	0.2 m/s
Could cover factor		0.6

Transmissivity of double layer polyethylene		0.76
Transmissivity of polycarbonate		0.79
Emissivity of the cover	ε	0.90
Motor efficiency	E_m	0.9
Rated power of recirculating fan motors	P	373 W
Number of recirculating fans	N_f	2
Thermal conductivity of greenhouse soil		1.5 W/m.k
Thermal conductivity of polyethylene		0.33 W/m.K
Thickness of polyethylene		0.06 m
Thermal conductivity of polycarbonate		0.19 W/m.K
Thickness of polycarbonate		0.08 m
Thermal conductivity of polystyrene insulation		0.03 W/m.K
Thickness of polystyrene		0.0254 m
Thermal conductivity of plywood		0.12 W/m.K
Thickness of plywood		0.012 m
Parameter heat loss factor	F_p	1.17 W/m.k
Air exchange rate	N	2.0
Light allowance factor	F_a	1.2
Reflectivity of the ground	ρ_r	0.5
Characteristics length of tomato leaf	L_f	0.027 m
Leaf area index	LAI	2.5
Indoor surface film coefficient	α_i	4.2 W/m^2.K
outdoor surface film coefficient	α_o	34 W/m^2.K

RESULTS AND DISCUSSION

Figure-3 shows the predicted hourly heating and cooling energy requirement for the selected greenhouse, and the outdoor temperature from typical metrological yea data. This heating/cooling requirements are based on the selected indoor day time set point temperature 21˚C, and 18˚C for night time. The negative value of energy requirement indicates cooling requirement, and positive value indicates heating requirement. The predicted results indicate that heating almost required over the year, because the night temperature usually fall down below the set point temperature.

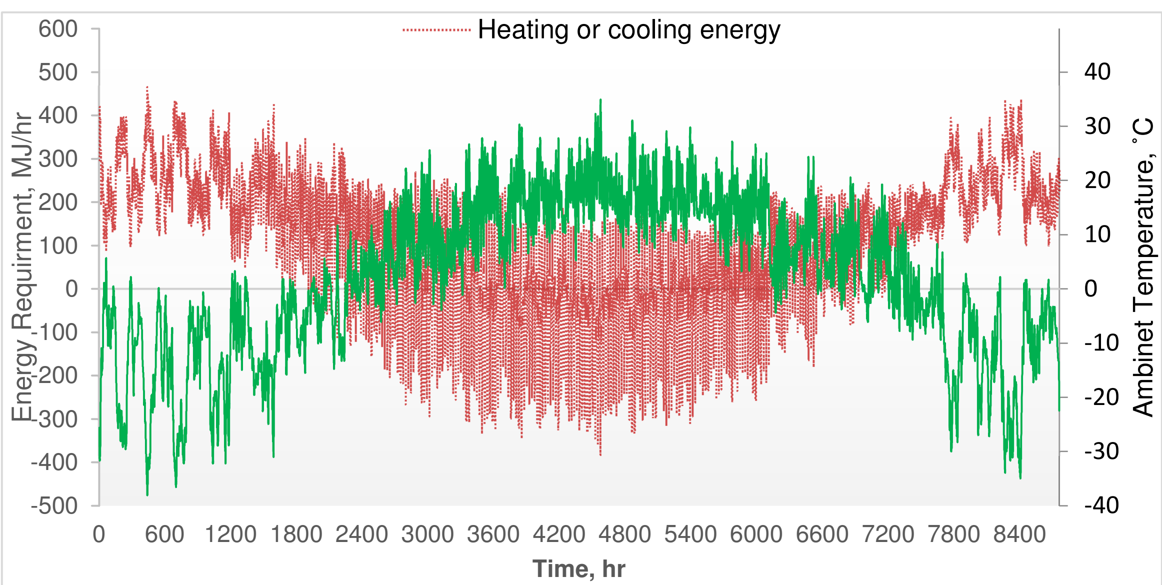

Figure 3. Predicted heating and cooling requirement.

The total predicted heating energy requirement of the greenhouse is about 1052.3 GJ for one calendar year. Figure 4 shows the daily variations of different components of heat loss from the greenhouse over the year. The results indicate that the maximum heat transfer occur because of exchange of long-wave radiation through transparent cover. The predicted results also show that the convection and infiltration heat losses are nearly equal in magnitude. The convection heat loss includes the total amount heat transfer from greenhouse through the process of conduction and convection through covering and floor. From figure-5, it shows that the heat transfer through the perimeter of the building is comparatively very low as compared to other sources of heat sinks, but the amount can be significant for long time. All of the sources of heat loss except sensible heat used in plant transpiration are linearly depend on the outdoor temperature. The use of sensible heat in the process of plant transpiration has significant contribution in the greenhouse energy balance. The energy use in transpiration found maximum during summer, because plant transpiration is greatly depends on the incoming solar radiation.

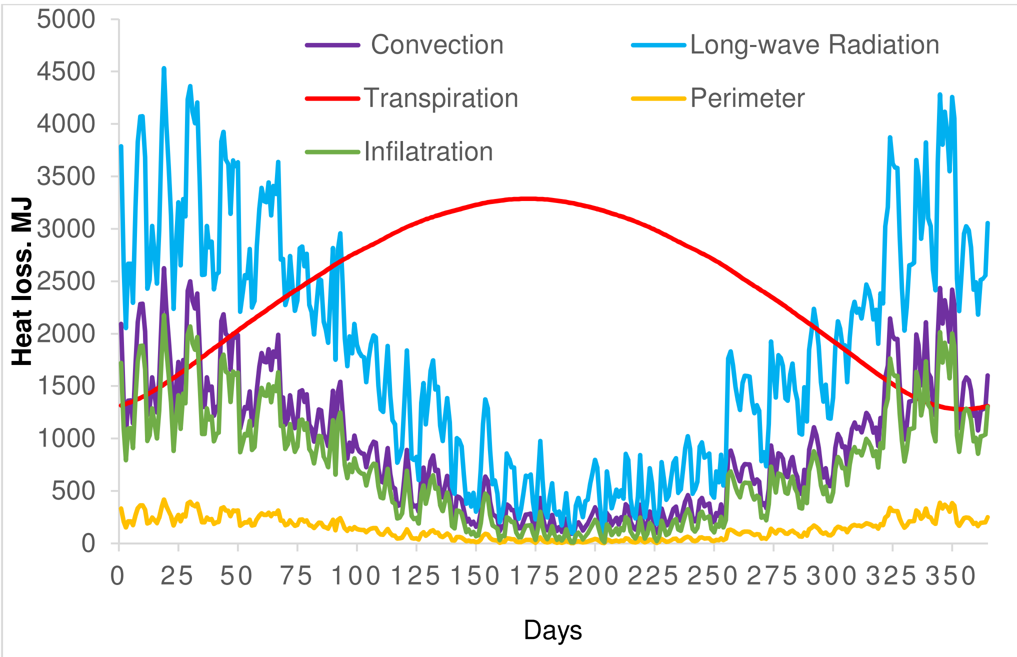

Figure 4. Variation of different sources of heat loss from the greenhouse.

The variations of total heat loss and total heat gain without supplying heat auxiliary heating are shown in figure-5. The heat gain in the greenhouse include solar radiation, heat from supplemental lighting, CO_2 generator, and electric motors of recirculating fans. However, the solar radiation consists more 80% of total heat gain in the greenhouse. The high fluctuation in heat gain curve during summer season indicates that heat added from outside though the process of conduction, convection, and radiation, because outdoor temperature exceeds the indoor set point temperature.

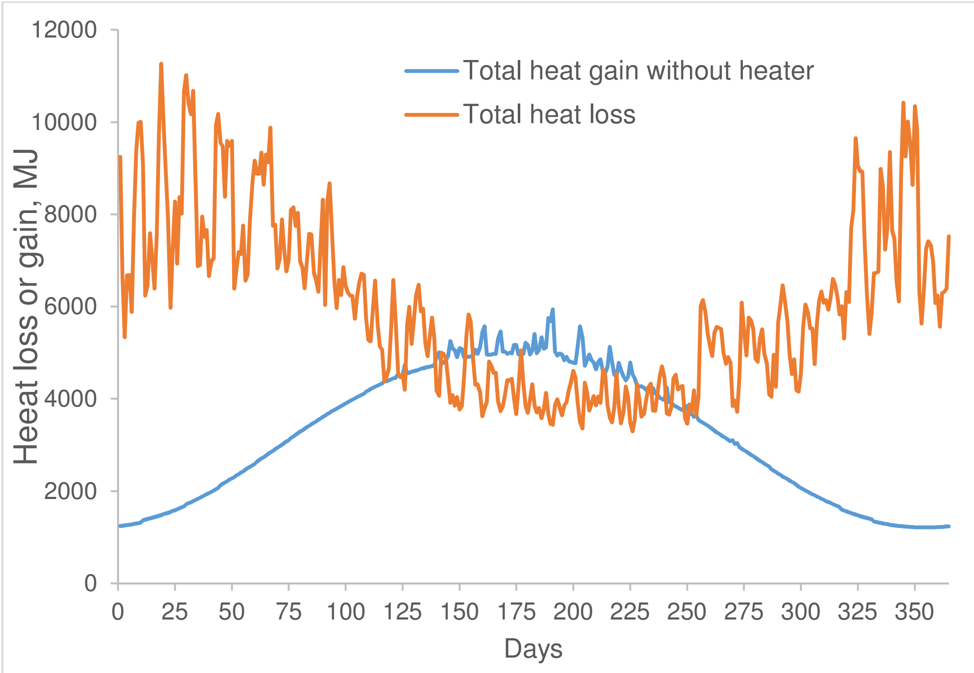

Figure 5. Daily total heat loss and total heat gain in the greenhouse.

VALIDATION OF THE MODEL

The preliminary validation of the model has been done by comparing the predicted results with the data provided by the greenhouse grower. The greenhouse was heated from coal fired furnace heating system, and about 43200 kg of coal required to heat the greenhouse from January to middle of December. Based on approximate heating value (30 MJ/kg) of coal, and 70% furnace efficiency, the total heating energy supplied to the greenhouse was about 910 GJ, which is very close to the predicted value (1052.2 GJ).

CONCLUSION

The thermal model have been developed based on lumped estimation of greenhouse heat sources and sinks. This model would be able to predict the energy requirement of various types of conventional greenhouses based on input information about greenhouse structure and indoor environment, local weather data, and information about the selected crops for the greenhouse. Therefore, the model will be beneficial for researchers, engineers and growers for their decision making regarding the energy efficient design and the feasibility analysis of the greenhouses. Based on preliminary result, the model prediction is very close to actual figure. However, details experimental data are required for precise validation of the model.

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