Incorporating Plants Modelling in Greenhouse Design

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Abstract

The greenhouse, as an agricultural building structure, is necessary for cold regions. It can provide desired environment for local plant cultivation, which increase the supply of local fresh food and the extent of food security. In this paper, a general modelling method has been developed for predicting the performance of a conceptual greenhouse design in cold regions. The greenhouse is divided into typical unit areas for modelling to facilitate the modelling of greenhouse in different sizes. The energy balance equations including that for the plants are built to find the temperatures of different greenhouse components. The weather data of a typical cold days of Edmonton, Canada was used. Using this model, a greenhouse design has been improved to increase the solar heat gain during winter significantly. In the meantime, the heat gain from the lighting system increased while the heat loss of the whole day decreased.

Introduction

Greenhouses are necessary for cold regions. Unlike some tropical areas where have warm and moist climate, the cold places do not have desired environmental conditions for plant growth. In most cases, their natural conditions (mainly the weather) cannot satisfy the basic growth requirements of many plants and can even damage the physiology of many important plants. For cold regions, using greenhouses is the only pathway which can generate desired environment for local plant cultivation. With greenhouses, the diversity of local fresh food increases, and security and quality of many food products can be guaranteed.

In order to have more greenhouses in cold regions, the problems of the great energy consumption and low energy efficiency needs to be diminished. In cold regions, the great energy consumption of the greenhouses for heating in cold regions can impose economic burdens on greenhouse owners and result in the increase in production costs. Up to now, the main energy sources of many conventional greenhouses are the electricity and thermal energy generated from combustion of fossil fuels. They account for 88% of the total energy input for greenhouse tomato production (Hatirli et al., 2006). This is not an efficient way of producing energy, and the long-distance transmission and distribution of electricity and heat further decreases the efficiency. The potential environmental issues are the great demand of freshwater and the release of greenhouse gases and other pollutants during the production and transportation of energy.

To save energy and increase energy use efficiency for the greenhouses in cold regions, an innovative greenhouse design is necessary. The improvement in greenhouse designs can directly reduce energy consumption and increase energy use efficiency. A comprehensive model that incorporates the plants can help predict the performance of greenhouse designs under certain conditions prior to actual experiments and construction. Many scientists conducted research in either the optimization of the greenhouse design, or the development of more accurate models. For instance, in a research which was conducted by Ahamed et al. (2018), the modelling work for a conventional greenhouse was implemented. In addition, Taki. et al. (2016) developed a model for calculating the heat transfer and energy consumption of a greenhouse. The energy balance equations for all the surfaces including the ceiling, the thermal screen, the air below the screen, the air above the screen, the plants, the ground, were built. The outputs were validated by experimental results and showed high accuracy.

However, the main problem existing in these research activities is the errors in the modelling of plants. The plant layer is the most complex layer inside a greenhouse, and it is difficult to set all the physiological details correctly and model the plant temperature accurately. In some papers like Najjar & Hasan (2008), the convective sensible heat transfer and the radiative heat transfer of plants were neglected. In these papers, the plants were not considered as a part of thermal network. The plants only occurred in the calculation of mass transfer part, and the heat loss caused by the evapotranspiration process was neglected.

The objective of this project is to apply a general and easy modelling method in a conceptual greenhouse design. All the temperatures were calculated under the transient state in order to maintain the accuracy of results. Tomato was selected as the plants whose parameters would be used for modelling. The method is easy to implement, and the requirement for data input is minimized. In addition, plants

were incorporated in the greenhouse model, and the related parameters were explored in detail.

The weather data of a typical cold day of Edmonton is used for the modelling work. Edmonton is a city in Alberta, Canada with extremely cold weather. The winter in this city is cold, long and snowy.

Method

Conceptual greenhouse design

The conceptual greenhouse is a conventional greenhouse with transparent ceiling. A monitor-type of sky lights are used for natural daylight harvesting. The boundary of the ground covered under the greenhouse is thermally insulated. The plants were cultivated in the soil ground directly. The lighting system was the hybrid lighting system which consists of High-Pressure Sodium (HPS) and Light Emitting Diode (LED) lamps, the ratio of HPS and LED lamps was 1:4. In each $4m^2$ area, there were 4 LED lamps and 1 HPS lamps, the lighting intensity was 110 W/m^2. The lighting system turned on for the whole day. The ventilation system introduced outdoor air to the greenhouse in order to lower the high relative humidity caused by plant transpiration. The numbers of air exchange per hour was assumed to be two, which is a suitable rate for winter (Buffington et al., 2010).

Thermal networks and general assumptions

In the conceptual greenhouse, the total area was divided into three kinds of unit areas (Figure 1) for modelling. These unit areas have different thermal networks. For the unit areas which are located in the centre of the greenhouse, they have 1-D heat transfer mode in the vertical direction (Figure 2). The thermal network consists of the thermal resistances of the outdoor air (ventilation), the ceiling, the indoor air, the plants, and the ground. The areas at four corners (corner areas) have 3-D heat transfer mode because they have two vertical surfaces linked with the exterior environment. The convective heat exchange between the indoor air and two walls, the two walls and the outdoor air were added. For the rest unit areas which attach to the boundaries (boundary unit areas), since they have one vertical surface attached to the outdoor, they have 2-D heat transfer mode. This study focuses on the central unit areas.

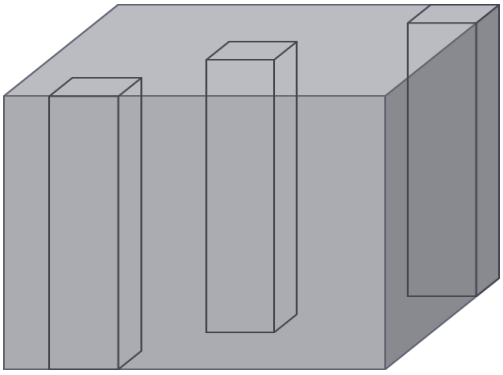

Figure 1: Three kinds of unit areas in a greenhouse

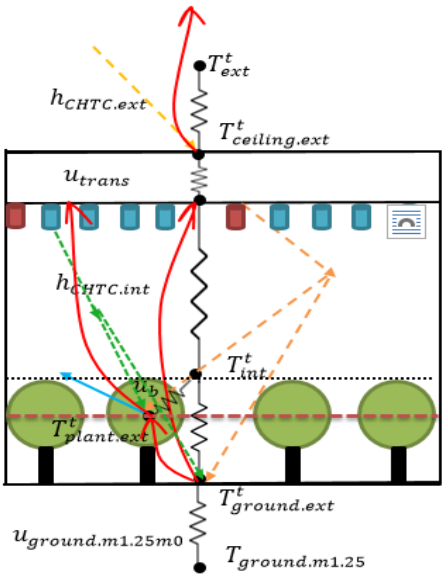

Figure 2:The thermal network of the central unit areas (T is the temperature nodes, from upper to the ground, are: temperatures of the exterior environment, exterior and interior surfaces of the ceiling, the indoor air, the plants, the ground, and the surfaces below 1.25 meters of the ground; h and u: heat transfer coefficient; Red arrows: longwave radiation heat loss; Orange arrows: solar heat gain; Blue arrow: evapotranspiration heat loss; Green arrows: heat gain from the lighting system)

The main assumptions during the modelling procedure were:

- The indoor air was well mixed
- The plant transpiration rate was directly proportional to the transmitted solar radiation.
- There was no evaporation from the ground (soil).

Governing equations

The temperatures of all surfaces were calculated under transient state. In this part, the general principles of calculating the surface temperatures were explained, and the detailed mechanisms of calculating the temperature of each greenhouse surface would be discussed in the following subsections.

The overall heat balance equation is:

$$Q_h = \text{-heat loss+ heat gain}$$

$$Q_h = -\left(Q_{cc}+Q_a+Q_p+Q_r+Q_e+Q_v\right)+Q_s+Q_{sl} \quad (1)$$

Q_h is the overall space heating requirement. Q_{cc} is the heat loss caused by conduction and convection. Q_a is the heat loss caused by air exchange including infiltration/exfiltration and natural ventilation. Q_p is the heat transfer from perimeter to the surrounding environment. Q_r is the heat loss by longwave radiation transfer. Q_e is the heat loss by plant evapotranspiration. Q_v is the heat loss caused by ventilation. Q_s is the heat gain from the solar radiation. Q_{sl} is the heat gain from the supplemental lighting system.

For the transient state, explicit finite difference equations are used for calculating the temperature change.

$$\Delta T = \sum_{i=1}^{n} \frac{Q_i}{\rho_i \cdot c_i \cdot l_i} \quad (2)$$

By expanding the formula, the equation for calculating the temperature change of different surfaces is:

$$T_i^{t+\Delta t} = \Delta T + T_i^t = \frac{(Q_i)\Delta t}{\rho_i \cdot c_i \cdot l_i} + T_i^t \quad (3)$$

Where,

i= symbol of 'i' surface

T_i is the temperature of the target surface

T_{i-1} and T_{i+1} are temperatures of the surrounding surfaces

ρ_i, c_i, l_i are the density, specific heat and characteristic length of 'i' surface, respectively

Δt is the time step.

The heat gain and heat loss sources were somewhat different for the five nodes, and the specific heat balance equations were required to be found for every node in order to complete the model.

The perimeter heat loss (Q_p), was not included in the equation for the central unit areas. For the plants, the heat loss caused by the evapotranspiration should be considered. In addition, since the water vapor was released into the atmosphere and changed the enthalpy of air, Q_p should be included in the heat balance equation of the indoor air.

In order to make the equations more clear to be understood, some statements are needed to be made: 1. The symbols for all the heat loss and heat gain sources were the same as the general equation, and some suffixes were added to indicate the direction of heat transfer. For example, '$Q_{r(ground\rightarrow plant)}$'stands for the longwave heat transfer from the ground to the plant layer. 2. The 'int' and 'ext' in the suffixes mean the location of surfaces. For example, 'air.int' means the indoor air and "air.ext" mean the outdoor air. 3.The solar radiation, and the heat gain from the lighting system were transmitted or absorbed or reflected by the surfaces. '$Q_{s.absorb.ceil}$' means the amount of solar radiation absorbed by the ceiling.

- Heat balance of ceiling (exterior and interior surfaces)

Based on the thermal network shown in Figure 2, the heat balance equations for exterior and interior ceiling surfaces can be written as:

$$Q_{ceil.ext} = Q_{r(ceil.int\rightarrow ceil.ext)} + Q_{s.absorb.ceil} - Q_{cc(ceil.ext\rightarrow air.ext)} - Q_{r(ceil.ext\rightarrow sky)} \quad (4)$$

$$Q_{ceil.int} = -Q_{r(ceil.int\rightarrow ceil.ext)} + Q_{cc(air.int\rightarrow ceil.int)} + Q_{r(ground\rightarrow ceil.int)} + Q_{r(plant\rightarrow ceil.int)} \quad (5)$$

The longwave radiation heat loss for the exterior and interior surfaces were calculated as:

$$Q_{r(ceil.int\rightarrow ceil.ext)} = \sigma\varepsilon_{ceil}\varepsilon_{ceil}F_{ceil.int\rightarrow cell.ext}Area_{ceil}(T_{ceil.int}^4 - T_{ceil.ext}^4) \quad (6)$$

$$Q_{r(ceil.ext\rightarrow sky)} = \sigma\varepsilon_{ceil}\varepsilon_{sky}F_{ground\rightarrow plant}Area_{ceil}(T_{ceil.ext}^4 - T_{sky}^4) \quad (7)$$

$$Q_{r(ground\rightarrow ceil.int)} = \sigma\varepsilon_{ground}\varepsilon_{ceil}F_{ground\rightarrow ceil}Area_{ground}(T_{ground}^4 - T_{ceil.int}^4) \quad (8)$$

$$Q_{r(plant\rightarrow ceil.int)} = \sigma\varepsilon_{plant}\varepsilon_{ceil}F_{plant\rightarrow ceil}Area_{plant}(T_{plant}^4 - T_{ceil.int}^4) \quad (9)$$

$$Q_{r(ground\rightarrow plant)} = \sigma\varepsilon_{ground}\varepsilon_{plant}F_{ground\rightarrow plant}Area_{ground}(T_{ground}^4 - T_{plant}^4) \quad (10)$$

Where,

σ= Stefan-Boltzmann constant

ε= emissivity of objects

F= view factor

T= temperature (K)

The view factors could be estimated by using the two figures provided by Brebbia (1982) in the book "Fundamentals of heat transfer ". After some view factors are known, other view factors could be calculated based on reciprocity relation, summation rule, and decomposition relation.

The sky temperature and the emissivity factor of the clear sky were defined by Clark and Allen(1978):

$$\varepsilon_{clear} = 0.787 + 0.7661\ln\left(\frac{T_{dew}}{273}\right) \quad (11)$$

$$T_{sky} = T_{air.ext}\varepsilon_{clear}^{0.25} \quad (12)$$

In these equations, the area of the ceiling was equal to the entire area of the divided unit ($Area_{divided\ unit} = 1m^2$), but the areas of plants and the ground were different. The area of tomato plants was equivelent to the accumulative area of leaves, and there were several layers of leaves. In order to calculate the total area of tomato leaves, the value of leaf area index (LAI) was required, and the equations can be written as:

$$Area_{plant} = 2LAI \times Area_{divided\ unit} \quad (13)$$

The ground area which is exposed to the ceiling is:

$$Area_{ground} = Area_{divided\ unit}(1 - \%Canopy\ cover) \quad (14)$$

The canopy cover was the percentage of area which was covered by the plants. The equation for calculating it was given by Katerji et al. (2013):

$$\%Canopy\ cover = 1 - \exp(-0.75LAI) \quad (15)$$

The convective heat loss can be measured as:

$$Q_{cc(ceil.ext\rightarrow air.ext)} = h_{ext}Area_{ceil}(T_{ceil.ext} - T_{ext}) \quad (16)$$

$$Q_{cc(air.int\rightarrow ceil.int)} = h_{int}Area_{ceil}(T_{air.int} - T_{ceil.int}) \quad (17)$$

The amount of solar radiation absorbed by the ceiling was:

$$Q_{s.absorb.ceil} = Q_{s.total}\alpha_{cover} \quad (18)$$

Where:

$Q_{s.total}$ = the total amount of solar radiation outside the greenohouse (W)

α_{cover}= absorption of the ceiling

h_{ext}= convective heat transfer coefficient of outdoor environment ($W/m^2.K$)

h_{int} = convective heat transfer coefficient of indoor environment ($W/m^2.K$)

The convective heat transfer coefficient was affected by the geometry of the surface and the flow properties (Cengel, 2014). In this study, in order to simplify the model, the h_{ext} and the h_{int} were estimated as $20W/m^2.K$ and $9W/m^2.K$, respectively.

- Heat balance of the greenhouse air

The temperature node of greenhouse air is the central node which connects all the surfaces together. The assumption for it was that there was no radiation either absorbed or emitted by the indoor air. Therefore, there was no longwave radiation heat loss/gain and solar heat gain for the greenhouse air.

There were three heat balance equations for the greenhouse air, which corresponded to three kinds of unit areas shown in Figure 1. The three equations were:

$$Q_{air.int(central\ areas)}=-Q_{cc(air.int\rightarrow plant)}+Q_{cc(ground\rightarrow air.int)} -Q_{cc(air.int\rightarrow ceil.int)}-Q_v+Q_e-Q_a \quad (19)$$

$$Q_{cc(ground\rightarrow air.int)}=h_{ground}(T_{ground}-T_{ext}) \quad (20)$$

$$Q_v=v_m\rho_{air}(h_{int}-h_{ext}) \quad (21)$$

$$Q_a=0.1Q_v \quad (22)$$

$$h=1.005T+HR(2465+1.85T) \quad (23)$$

Where,

v_m= flow rate of moist air (L/s)

h= enthalpy of air (J)

HR= humidity ratio

ρ_{air} = air density (kg/m^3)

F_p= perimeter heat loss coefficient (W/m.K)

P= perimeter of edges

The equation for calculating ventilation heat loss was given by Cengel (2014).

The evapotranspiration heat loss was added to the air because when the moisture was released, it changed the enthalpy of air. The calculation of it would be discussed in the plant part.

- Heat balance of the plant layer

The heat transfer between the plant layer and its surrounding is more complex than other surfaces in a greenhouse. In order to simplify the general equation, some symbols were added to stand for the sum of two or more heat transfer processes.

The heat exchange of the plant layer with the surrounding environment mainly consists of three parts: the evapotranspiration heat transfer (latent heat transfer) (λ ET), the sensible heat transfer (H), the net radiation (R_n), and the ground heat flux (G). The overall formula was given by Ayata et al. (2011):

$$Q_{plant}= R_n - G -\lambda ET – H \quad (23)$$

The ground heat flux (G) contains the conductive heat transfer the between the ground surface and other nearby surfaces. The conduction between the plant surface and the ground surface is always neglected because the contact area between them is small. The ground heat flux is often the smallest component of energy balance of soil surface.The soil which is moist and covered by plants has significantly smaller G around $20W/m^2$ (Sauer & Horton, 2005). In our study, the soil is assumed to be moist and covered by tomato plants. Consequently, the ground heat flux can be neglected in energy balance equation for the plant surface and the evapotranspiration calculation.

The net radiation is the amount of radiation which is absorbed by the plant layer, it can be calculated as:

$$R_n= Q_{s.absorb.plant}+Q_{sl.absorb,plant}=(Q_{s.transmitted}+Q_{sl})\alpha_{plant} \quad (24)$$

Where,

α_{plant}= shortwave absorption coefficient of the plant layer

$Q_{s.transmitted}$=the amount of solar radiation transmitted into the greenhouse (W)

The total amount of solar radiation transmitted into the greenhouse was:

$$Q_{s.transmitted}=Q_{s.total}\tau \quad (25)$$

Where,

τ= transmittance of the ceiling

The transmittance of transparent materials depends on the incidence angle. In winter time, because of the big incidence angle, the maxmium transmittance was around 0.3~0.4 , which was signicantly lower than maxmium transmittance during summer (above 0.7).

According to ASHRAE (2013), the heat supplied by the lighting system was estimated as:

$$Q_{sl}= WF_{hc}F_aA_f \quad (26)$$

Where,

W= total power of lamps (W/m^2)

F_{hc}= heat conversion factor

F_a= light allowance factor

A_f= area of floor (m^2)= $Area_{divided\ unit}$

The lighting system used in this model was the hybrid (LED+HPS) lighting system. Hybrid system required slightly more energy than the LED system, but they resulted in the highest yield and quality. This was caused by

increased net heat gain and the extra supplement of light with specific wavelengths (Dueck et al., 2011). The rise in net heat gain was good for cold regions, since the requirement for heating can be satsified partially by the extra heat produced.

Plant transpiration is an important energy-consuming component inside greenhouses. The heat is lost as the latent heat, since the energy is used to change the phase of water. In here, in order to simplify the calculation, the evaporation from the soil was assumed to be negligible.

A formula which requires fewer data inputs was given by De Graaf & Van den Ende (1981):

$$E=\frac{0.232\tau Q_{s.total}+7.04}{10^6} \quad (27)$$

This equation is for calculating transpiration rate of plants inside the greenhouses with height >1.7m.

Where,

E= evapotranspiration rate ($kg/m^2.s$)

According to Taki et al. (2016), the formula for calculating the heat loss by the evapotranspiration process are:

$$\lambda ET= Q_e=EL_v \quad (28)$$

Where,

L_v= latent heat of evaporation= 2450kJ/kg

The sensible heat transfer (H) contains the convective heat transfer between the plant layer and the indoor air, and the radiative heat transfer between the ceiling and the plant. For the convection process, the only resistance involved is the boundary layer resistance, which is the thermal resistance of the exterior plant surface to the convective heat transfer.

Based on Bonan (2015), the equation for the boundary layer resistance is:

$$r_b=151\sqrt{\frac{d}{u}} \quad (29)$$

Where,

d= the characteristic length of tomato leaves (m)

u= indoor wind speed (m/s)

The formula for estimating the convective sensible heat loss , based on Jones & Rotenberg (2011), was given as follows:

$$S= Q_{cc(air.int\rightarrow plant)}=\rho_{air}C_{air}\frac{(T_{plant}-T_{air.int})}{r_b} \quad (30)$$

Note that all plant resistances have a unit which is different from the thermal resistance of common materials ($m^2.K/W$). They have the unit s/m, which is second per meter. In the formula of calculating the evapotranspiration heat loss, this unit is offset by the units of specific heat and density of air. Therefore, the unit for calculated latent and sensible heat transfer is still W/m^2.

The radiative heat transfer between the plant layer and the ceiling is calculated as:

$$Q_{r(ceil.int\rightarrow plant)}=\sigma\varepsilon_{plant}\varepsilon_{ceil}F_{ceil\rightarrow plant}Area_{ceil}(T_{ceil.int}{}^4-T_{plant}{}^4) \quad (31)$$

The total sensible heat loss from the plant layer is:

$$H= S+Q_{r(ceil.int\rightarrow plant)} \quad (32)$$

- Heat balance of the ground

Heat loss through floor accounts for approximately 5% of the total heat loss of greenhouses, so it is considered as a main source of greenhouse heating requirement (Nawalany et al., 2014). It depends on the thermal conductivity of soil, interior soil temperature and indoor air temperature. The heat transfer between ground soil and the greenhouse indoor environment can be assumed to be under the transient state. The temperature which was used as the interior ground surface temperature was one of the undisturbed ground temperature (UGT).The UGT is not affected by fluctuations of air temperatures from the ground surface (Kurevija et al., 2011). By using the UGT and some initial guess for the exterior soil temperature and the soil temperature at some discrete points, the exterior soil temperatures could be obtained.

The depth at which the layer has stable temperature (UGT) of 13℃ over the whole year, was 2.5m based on the outcomes of Radioti et al. (2017). Therefore, by assuming the heat transfer of ground was under the transient state, the ground layer was divided into two layers: layer 1 (0m to -1.25m), layer 2 (-1.25 to -2.5m), After that, the heat balance of the soil at -1.25 m was:

$$Q_{m.1.25}= Q_{cc(m2.5\rightarrow m1.25)}-Q_{cc(m1.25\rightarrow m0)} \quad (33)$$

These two conductive heat loss from indoor air to the ground can be calculated as:

$$Q_{cc(m2.5\rightarrow m1.25)}=\frac{k_sA_f}{h}(T_{m2.5}-T_{m1.25}) \quad (34)$$

$$Q_{cc(m1.25\rightarrow m0)}=\frac{k_sA_f}{h}(T_{m1.25}-T_{m0}) \quad (35)$$

After the temperature in the layer with depth of 1.25m was determined, the temperature of the exterior ground surface could be calculated as:

$$Q_{m0}= Q_{ground}= Q_{cc(m1.25\rightarrow m0)}+Q_{s.absorb.ground}- Q_{r(ground\rightarrow ceil.int)}- Q_{r(ground\rightarrow plant)}+Q_{sl.absorb.ground}-Q_{cc(ground\rightarrow air.int)} \quad (36)$$

$$Q_{s.absorb.ground} = Q_{s.transmitted}\alpha_{ground} \quad (37)$$

$$Q_{sl.absorb.ground} = Q_{sl}\alpha_{ground} \quad (38)$$

Where,

α_g= absorption of the ground

Simulation setting

The weather data used in the model was the exterior temperatures of a typical day (Figure 3) of Edmonton, Canada. The date was January 1st, 2002. This day was selected because it is a clear day, and it had the extremely low temperature for the whole day. The mean temperatures was -23℃. Steady periodic weather conditions, and lighting and ventilation operations were used for the simulation. The time step was set to be 6 seconds. The iteration stopped when the difference between two outcomes was fewer than 0.01 K.

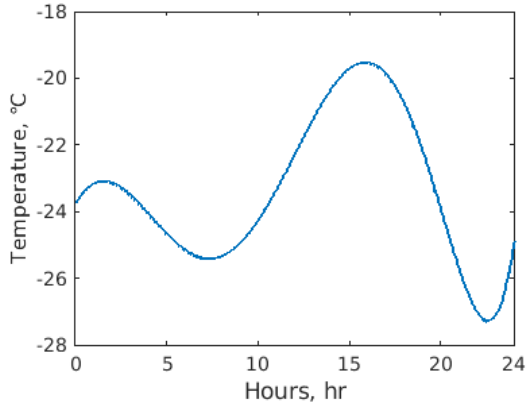

Figure 3 Temperature of the exterior environment on Jan 1st, 2002

In order to use the hourly weather data which was 24 discrete points in the loop, the interpolation was carried out to make the weather data become continuously. The weather data used were the exterior temperature, dew point temperature and relative humidity, which were provided by Environment Canada (2019).

The table summarized all the used parameters as follows.

Table 1 Summarized information for parameters used in the model

Parameters	Symbols	Units	Values
Ground reflectance	ρ_g	Dimensionless	0.3
Indoor wind speed	u	m/s	0.5
Characteristic length of leaves	d	m	0.04
Leaf area index	LAI	m^2/m^2	1.6
Specific heat of air	C_{air}	J/kg.K	1000
Air density	ρ_{air}	kg/m^3	1.29
Specific heat of plants	C_{plant}	J/kg.K	3253 (Chen et al., 2014)
Density of plants	ρ_{plant}	kg/m^3	700 (Taki et al., 2017)
Specific heat of cover	C_{ceil}	J/kg.K	1250
Density of cover	ρ_{ceil}	kg/m^3	1220
Density of ground(sand y loam soil)	ρ_{soil}	kg/m^3	2215 (Song et al., 2017)
Specific heat of ground(sandy loam soil)	C_{soil}	J/kg.K	850 (Song et al., 2017)
Latent heat of vaporization	L_v	kJ/kg	2450
Emissivity of plants	ε_{plant}	Dimensionless	0.7
Emissivity of cover	ε_{ceil}	Dimensionless	0.17
Emissivity of ground	ε_{ground}	Dimensionless	0.8
Shortwave absorption coefficient of plants	α_{plant}	Dimensionless	0.7
Shortwave absorption coefficient of cover	α_{cover}	Dimensionless	0.015
Shortwave absorption coefficient of ground	α_{ground}	Dimensionless	0.8
Heat conversion factor	F_{hc}	Dimensionless	0.65 (LED), 0.85(HPS)
Light allowance factor	F_a	Dimensionless	1(LED), 1.2(HPS)
Thermal conductivity of soil	k_s	W/m.K	1.6 (Ekwue et al., 2011)
Thermal conductance of the double layer polycarbonate (PC)	U_{trans}	$W/m^2{\cdot}K$	3.3 (ASAE, 2003)
Thermal conductance of single layer PC	$U_{singlePC}$	$W/m^2{\cdot}K$	6.3 (ASAE, 2003)
Thickness of single layer PC	l_{pc}	m	6×10^{-3}
Thickness of the air layer of ceiling	l_{air}	m	10×10^{-3}
Total power of lamps (W/m^2)	W	W/m^2	100(HPS),10(LED)

Stefan-Boltzmann constant	σ	W/m^2K^4	5.67×10^{-8}
Depth of each discrete soil layer	h	m	1.25 (Radioti et al., 2017)
View factor	F	Dimensionless	Ground→Ceiling: 0.2
			Ceiling →Plants: 0.74
			Ground→Plants: 0.77
			Plants→Ceiling: 0.23
			Ceiling→Sky: 1
			Ceil.int→Ceil.ext: 1

Results and Discussion

The surface temperatures of the central unit area are given as follows.

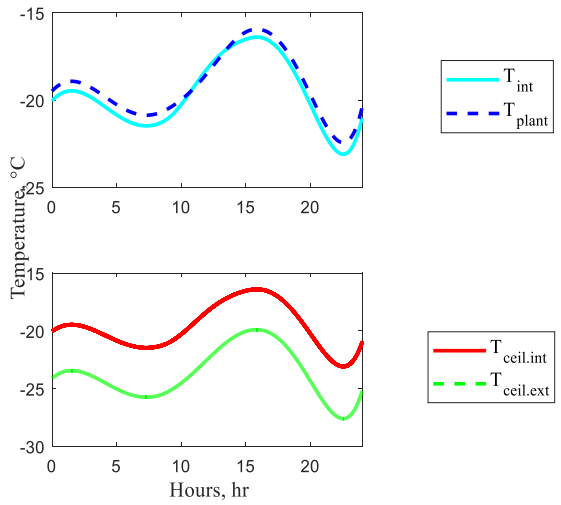

Figure 4 Surface temperatures for central unit areas

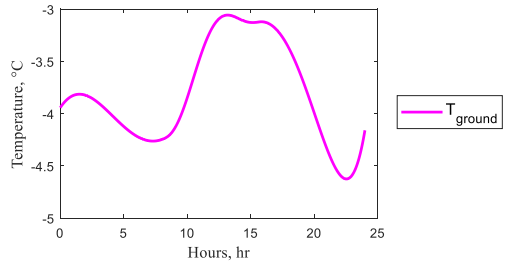

Figure 5 Ground temperature for central unit areas

Since no spacing heating is considered in the current models, the temperatures of the greenhouse components are floating freely. Based on the trend shown in the two figures, the indoor air temperature and the plant temperature were similar. The maximum difference was around 1℃. Both these two surface temperatures were almost 2.2℃ higher than the exterior temperature. The possible reason was the extra heat gain from the hybrid lighting system. The plant temperature was slightly higher than the indoor air because of the solar radiation, and the longwave radiation from the ground. The temperature difference between the interior and exterior surfaces of the ceiling was approximately 3 ℃. The ground had significantly higher temperature than other surfaces for the whole day, since the nether surface had UGT, which was 13 ℃ constantly for the whole year.

Overall, all the results were normal, which indicated that the model worked good for the conceptual greenhouse design. The indoor temperature, the plant temperature, the exterior and interior ceiling temperatures were all followed the same trend as the outdoor temperature. The exterior ceiling temperature was close to the outdoor temperature. In the future, spacing heating will be added to the model. Some energy-saving strategies such as thermal screen, north concrete wall would be added.

This model is not only simplified in the dimension of thermal network, but also increased in its accuracy. The difficulty of the modelling work is diminished by dividing a complex greenhouse thermal network into simpler subnetworks (from 3-D to 2-D and 1-D). For central unit areas, the model is built based on a 1-D thermal network; for edge areas, the model is created based on a 2-D thermal network. The corner unit areas are still modelled based on a 3-D thermal network, but they only occupy a small area of a greenhouse and can be neglected in most cases. The subnetworks can be combined to form a complete network of a whole greenhouse. In addition, the accuracy of new modelling method is also higher. The plants were incorporated into the greenhouse model, hence. Both the sensible heat and latent heat transfer were considered. The interior air is modelled in more than one control volumes in middle and edge areas within a greenhouse, and the air node is separated from the plant node.

Conclusion

In this paper, a general modelling method was applied in a conceptual greenhouse design to determine the heat transfer and heating requirement. The key points are listed as follows.

•The greenhouse was divided into three kinds of unit areas, and only the areas located in the centre of the greenhouse were modelled.

•The heat balance equations were built for all the surfaces, including the interior and exterior surfaces of the ceiling, the indoor air, the plant and the ground.

•The changes in the temperatures of all greenhouse surfaces were assumed to be under the transient state.

•The heat balance equation of the plant layer was more complex than other surfaces inside the greenhouse. It contained both biotic and abiotic factors, and the heat exchange of it involved both latent heat and sensible heat. The convective sensible heat exchange between the greenhouse air and the plant layer was related to the boundary layer resistance. The process which lost the latent heat was the evapotranspiration.

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