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Development of a thermal model for simulation of supplemental heating requirements in Chinese-style solar greenhouses

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ABSTRACT

The simulation model CSGHEAT has been developed to estimate the hourly heating requirements in a Chinese-style solar greenhouse. The heating model was developed based on the heat balance of greenhouse air. With the set indoor temperatures, the surface temperatures of the floor and north wall were estimated by solving ordinary differential heat balance equations. The model is relatively easy to use because the model does not need to input measured data such as solar radiation like other models, and most of the heat sources and sinks in the Chinese-style solar greenhouse are included in the model. The model was validated with experimental data, and the predicted result was found to be in good agreement with the measured data. The mean difference between the measured and the estimated ground temperature is about 1.4 °C, and 1.8 °C for the north wall. The average percent error and relative root means square error (rRMSE) value for hourly heating prediction are 8.7%, and 11.5%, respectively. Therefore, the CSGHEAT model is considered to be sufficiently accurate and a reliable tool for researchers and others in the greenhouse industry to assist in designing and analyzing supplemental heating requirements in Chinese-style solar greenhouses.

1. Introduction

A high amount of supplemental heat is needed during the long winter months for greenhouses located in northern latitudes. The heating cost in northern greenhouses such as Canada can be from 75 to 85% of the total operating cost, excluding costs associated with labor (Rorabaugh et al., 2002). Hence, reducing heating cost by improving greenhouse covering materials and optimizing greenhouse design has been an important research topic for cold regions. Chinese-style solar greenhouse (CSG), a mono-slope greenhouse, has great potential to serve as a model of an energy-efficient horticultural facility in northern latitudes because this type of greenhouse significantly reduce supplemental heating demands as compared to the conventional greenhouses. It uses non-transparent north wall, north roof, ground, etc. to store excessive heat during the daytime and release the heat at night when heating is needed. CSGs have been used to produce warm season vegetables at latitudes of 40°N in China with little or no supplemental heating during the winter season (Zhang et al., 2008). Beshada et al. (2006) studied the thermal performance of a CSG in Manitoba (49.9°N) and reported the greenhouse could maintain an indoor temperature above 10 °C about 19% of the time when the outdoor temperature fluctuated between −29.2 and 4.5 °C; however, supplemental heating was required at up to 17.0 W m^{-2} for 19 h per day to maintain an indoor temperature of 10 °C in February. As the high heating cost is one of the crucial factors for determination of CSG feasibility in the cold region, accurate prediction on heating requirement is needed before the greenhouse growers can make decision on establishing such greenhouses. Hence, simulation of supplemental heating requirements in CSGs is essential for predicting heating needs in greenhouses at higher northern latitudes; furthermore, the heating simulation model can also be used to analyze heat gain and loss through each component of the CGS so the design of the CGSs can be improved to minimize heating loads.

A few thermal models (Du et al., 2012; Guo et al., 1994; Ma et al., 2010; Meng et al., 2009; Taki et al., 2016; Tong et al., 2009, 2008; Yu et al., 2016; Zhou et al., 2017; Zou et al., 2017) have been developed for simulation of microclimates in the CSGs. Most of these dynamic models (Ma et al., 2010; Meng et al., 2009; Taki et al., 2016; Zhou et al., 2017) have been developed for prediction of temperature variations of different interactive components in CSGs including indoor air, cover, plant, soil, north wall, and sidewalls. These types of dynamic models have a high degree of complexity with numerous parameters that have

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Nomenclature

A_c, A_f ,A_p	area of cover, floor, and plant, m^2
A_n, A_t	area of the non-transparent, and transparent surface, m^2
C_p	specific heat capacity, $J\,kg^{-1}\,K^{-1}$
E_m	motor efficiency, %
F_c, F_{sk}	cover view factor, and sky view factor, dimensionless
F_p	perimeter heat loss factor, $W\,m^{-1}\,K^{-1}$
F_{hc}, F_a	heat conversion factor, and lighting allowance factor, dimensionless
F_{um}, F_{ul}	motor load factor, and motor use factor, dimensionless
H_{cs}	depth of underground soil for constant temperature, m
h_a	air thermal conductance, $W\,m^{-2}\,K^{-1}$
h_i, h_o	convection coefficient for indoor, and outdoor surface, $W\,m^{-2}\,K^{-1}$
I_b, I_d	direct beam radiation, and diffuse radiation on horizontal surface, $W\,m^{-2}$
k_a, k_c, k_{cs}	thermal conductivity of air, cover, and soil, $W\,m^{-1}\,K^{-1}$
k	thermal conductivity of ith section in composite wall, $W\,m^{-1}\,K^{-1}$
L_c, L_f	characteristics length of convective surfaces, and plant leaves, m
L_v	latent heat of water vaporization, $J\,kg^{-1}$
MFR	carbon dioxide supply rate, $kg\,m^{-2}\,h^{-1}$
M_T	moisture transfer rate, $kg\,s^{-1}$
n	day of the year, n = 1, for 1st January
N_c	number of layers in cover, dimensionless
N_r	number of re-circulation fans, dimensionless
NHV	net heating value of fuel, $MJ\,kg^{-1}$
P	perimeter of greenhouse, m
P_m	motor power rating, W
PR	production rate of CO_2 from fuel combustion, kg/kg fuel
Q	heat transfer rate, W
R_a, R_s	aerodynamic resistance, and stomatal resistance, $s\,m^{-1}$
S	total solar radiation entering the greenhouse, W
T_c, T_i, T_o	cover temperature, indoor temperature, and outdoor temperature, K
T_{cs}, T_{sk}	underground constant soil temperature, and sky temperature, K
T_R	turbidity factor, dimensionless
U_t, U_n	heat transfer coefficient for transparent, and non-transparent surface, $W\,m^{-1}\,K^{-1}$
V	greenhouse volume, m^3
v_i, v_o	indoor airspeed, and outdoor airspeed, $m\,s^{-1}$
W	installed power of lighting, $W\,m^{-2}$
w_{ps}	saturated humidity ratio of air at plant temperature, $kg\,kg^{-1}$
w_i	humidity ratio of air at indoor temperature, $kg\,kg^{-1}$
Greek letters	
α	solar absorptivity, dimensionless
β	angle of inclined surface with horizontal, degrees
γ	surface azimuth angle, degrees
ε_c, ε_i	emissivity of cover, and indoor component, dimensionless
θ	angle between two radiative surfaces, degrees
θ_z	zenith angle of the sun, degrees
θ_i	angle of incidence of surfaces, degrees
ρ	volumetric density, $kg\,m^{-3}$
ρ_r	reflectivity of outdoor ground, dimensionless
τ	solar transmissivity of cover, dimensionless
τ_l	transmissivity of cover to long-wave radiation, dimensionless

Subscripts

a	air
nw	north wall
f	floor

to be determined due to the difference of greenhouse locations, shape, orientation, cover materials, crop, and weather conditions (Chen et al., 2015; Sethi et al., 2013), therefore, they are not readily available for use by other researchers and greenhouse industries. Computation fluid dynamics (CFD) is a powerful method to analyze the spatial and temporal distribution of temperature for various interactive components in greenhouses. Tong et al. (2009) have used CFD for simulation of time and space dependent temperature distributions in a CSG. However, CFD model is difficult for simulation of a large greenhouse due to long computation time; it could be very complicated for heating simulation over a long period such as a month or a year (Taki et al., 2016). It also needs specialty CFD skill, each model is for a specific greenhouse and cannot be easily applied to other greenhouses. Also, variety 'black box' methods have been used very recently for simulation of greenhouse thermal environment such as the artificial neural network (ANN), least squares support vector machine (LSSVM), convex bidirectional extreme learning machine (CB-ELM) (Yu et al., 2016; Zou et al., 2017). Yu et al. (2016) have developed the temperature prediction model based on the least squares support vector machine (LSSVM) model. Zou et al. (Zou et al., 2017) present a novel temperature and humidity prediction model based on convex bidirectional extreme learning machine (CB-ELM). The black-box modeling methods need large amounts of data, otherwise, the model's reliability could be unacceptable (Chen et al., 2015). Several studies (Ahamed et al., 2017; Du et al., 2012; Jolliet et al., 1991) indicate that the lumped estimation models based on the energy balance of greenhouse as a whole could be a simple and reliable tool for time-dependent simulation of the heating requirement in greenhouses. Du et al. (2012) developed a simulation heat transfer model to estimate heating demands in a CSG, however, this model did not consider heat addition from the north wall. This model also neglected the heat contributions from environmental control systems, including lighting and CO_2 generators, which are very important components for maintaining the optimum environment for plants in greenhouses at high northern latitudes. The previous studies (Du et al., 2012; Tong et al., 2009) did not consider the variation of solar radiation fraction available on the north wall and soil surface in the presence of plants in greenhouses. Also, most of the previous models (Du et al., 2012; Ma et al., 2010; Taki et al., 2016) either neglected the heat transfer from the canopy transpiration (Du et al., 2012) or used coefficients for estimation of evapotranspiration (Ma et al., 2010; Taki et al., 2016), but the canopy transpiration varies significantly depending on solar radiation available in greenhouses. Furthermore, most of the studies were conducted in China, and these models are not applicable for Canadian greenhouse practice because the greenhouses in China are basically passive greenhouses without automatic control of temperature by heating and ventilation systems. This environment management method cannot be accepted by different regions especially western modern commercial greenhouses which require indoor temperature well controlled by environment control systems. Therefore, the existing lumped estimation models would result in high uncertainty if used in CSGs located at high northern latitudes. Besides, new materials for cover, insulation, heat storage, etc. have been developed continuously, and methods for estimating heat and moisture transfer in the greenhouses have been modified continuously, therefore, the thermal model should reflect these new technologies.

Conversely, the building simulation programs (TRNSYS, EnergyPlus) could not be used to accurately predict the heating requirement of greenhouses because the microclimate in greenhouses is