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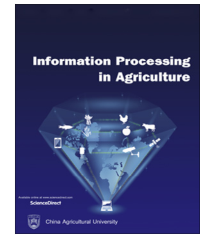

A quasi-steady state model for predicting the heating requirements of conventional greenhouses in cold regions

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A B S T R A C T

A time-dependent, quasi-steady state thermal model (GREENHEAT) based on the lumped estimation of heat transfer parameters of greenhouses has been developed to predict the hourly heating requirements of conventional greenhouses. The model was designed to predict the hourly heating requirements based on the input of greenhouse indoor environmental control parameters, physical and thermal properties of crops and construction materials, and hourly weather data including temperature, relative humidity, wind speed, and cloud cover. The model includes all of the heat transfer parameters in greenhouses including the heat loss for plant evapotranspiration, and the heat gain from environmental control systems. Results show that the predicted solar radiation data from the solar radiation sub-model are a reasonable fit with the data from the National Solar Radiation Database (NSRDB). Thermal analysis indicates environmental control systems could reduce 13–56% of the total heating requirements over the course of a year in the study greenhouse. During the winter season, the highest amount of greenhouse heat is lost due to conduction and convection, and the heat used for evapotranspiration is dominant in the summer. Finally, the model was validated with actual heating data collected from a commercial greenhouse located in Saskatoon, and the results show that the model satisfactorily predicts the greenhouse heating requirements.

1. Introduction

Greenhouse production of vegetables can enable people living in cold regions to enjoy fresh healthy food during the winter season. The harvested area of greenhouse production in Canada has been increasing steadily despite high heating costs [1]. At high northern latitudes, heating of a greenhouse for about eight months of the year is essential to ensure the growth and development of crops grown therein. In Canada, heating accounts for 10–35% of the total greenhouse production costs; the amount of heat necessary depends on the building envelope, the location of the greenhouse, and the kind of crops grown [2]. Different types of thermal models are available that can be used for studying the greenhouse

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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 non-transparent and transparent surfaces, m^2
CF	cloud cover factor, Octas
C_{pa}	specific heat of air, $J\,kg^{-1}\,K^{-1}$
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
G_r	Grashof number, dimensionless
g	acceleration of gravity, $m\,s^{-2}$
H	depth of underground soil for constant temperature, m
h_a	thermal air conductance, $W\,m^{-2}\,K^{-1}$
h_i, h_o	convection coefficient for indoor and outdoor surfaces, $W\,m^{-2}\,K^{-1}$
I_b, I_d	direct beam radiation, and diffuse radiation on horizontal surfaces, $W\,m^{-2}$
I_{bc}, I_{dc}	clear sky direct beam radiation and diffuse radiation, $W\,m^{-2}$
I_g	global solar radiation on horizontal surface, $W\,m^{-2}$
I_{gc}	clear sky global solar radiation on horizontal surface, $W\,m^{-2}$
I_{ex}, I_N, I_{sc}	extraterrestrial solar radiation, sky beam normal radiation, and solar constant ($W\,m^{-2}$)
k_a, k_c, k_s	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	characteristic length of convective surfaces and plant leaves, m
L_v	latent heat of water vaporization, $J\,kg^{-1}$
MFR	carbon dioxide supply rate in greenhouse, $kg\,m^{-2}\,h^{-1}$
M_T	moisture transfer rate, $kg\,s^{-1}$
n	day of the year, n = 1, for January 1st
N	number of air exchange per hour
N_c	number of layer in covering
N_f	number of re-circulation fans
Nu	Nusselt number, dimensionless
NHV	net heating value of fuel, $MJ\,kg^{-1}$
P	perimeter of greenhouse, m
P_m	motor power rating, W
P_r	Prandtl number, dimensionless
PR	CO_2 production rate, kg/kg fuel
p	atmospheric pressure, kPa
p_w	partial pressure of the water vapor, kPa
p_{ws}	partial pressure at saturation, kPa
Q	heat transfer rate, W
R_a, R_s	aerodynamic resistance and stomatal resistance, $s\,m^{-1}$
R_e	Reynold number, dimensionless
S	total solar radiation entering the greenhouse, W
T_c, T_i, T_o	cover temperature, indoor temperature, and outdoor temperature, K
T_s, T_{sk}	underground soil temperature and sky temperature, K
T_R	turbidity Factor, dimensionless
U_t, U_n	heat transfer coefficient for transparent and non-transparent surfaces, $W\,m^{-1}\,K^{-1}$
V	volume of greenhouse, m^3
v_i, v_o	indoor airspeed, and outdoor airspeed, $m\,s^{-1}$
W	installed power of lamp, $W\,m^{-2}$
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_s	factor for estimation of effective solar radiation, dimensionless
β	angle of inclined surface with horizontal, °
γ	surface azimuth angle, °
δ	declination angle of sun, °
ε_c, ε_i	emissivity of cover and indoor components, dimensionless
ε_{sky}, ε_{clear}	cloud cover sky emissivity and clear sky emissivity, dimensionless
θ	angle between two radiative surfaces, °
θ_z	zenith angle of sun, °
θ_i	angle of incidence of surfaces, °
ρ	air density, $kg\,m^{-3}$
ρ_r	reflectivity of outdoor ground, dimensionless
τ	transmissivity of cover, dimensionless
τ_l	transmissivity of cover to long-wave radiation, dimensionless
μ	dynamic viscosity of air, $kg\,m^{-1}\,s^{-1}$
φ	local latitudes, °
∂	volumetric thermal expansion coefficient, K^{-1}
σ	Stefan-Boltzmann Constant, $W\,m^{-2}\,K^{-4}$
ω	hour angle, °
Δx	thickness of ith section in composite wall, m
ΔT	temperature difference, °C

Subscripts

sr, sw	south roof and south wall
nr, nw	north roof and north wall
er, ew	east roof and east wall
wr, ww	west roof and west wall

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