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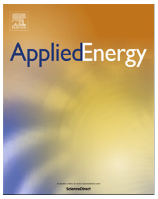

A control method for agricultural greenhouses heating based on computational fluid dynamics and energy prediction model

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HIGHLIGHTS

- A novel control method for the heating greenhouse with SWSHPS is proposed.
- CFD is employed to predict the priorities of FCU loops for thermal performance.
- EPM is act as an on-line tool to predict the total energy demand of greenhouse.
- The CFD–EPM-based method can save energy and improve control accuracy.
- The energy savings potential is between 8.7% and 15.1%.

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ABSTRACT

As energy heating is one of the main production costs, many efforts have been made to reduce the energy consumption of agricultural greenhouses. Herein, a novel control method of greenhouse heating using computational fluid dynamics (CFD) and energy prediction model (EPM) is proposed for energy savings and system performance. Based on the low-Reynolds number k–ε turbulence principle, a CFD model of heating greenhouse is developed, applying the discrete ordinates model for the radiative heat transfers and porous medium approach for plants considering plants sensible and latent heat exchanges. The CFD simulations have been validated, and used to analyze the greenhouse thermal performance and the priority of fan coil units (FCU) loops under the various heating conditions. According to the heating efficiency and temperature uniformity, the priorities of each FCU loop can be predicted to generate a database with priorities for control system. EPM is built up based on the thermal balance, and used to predict and optimize the energy demand of the greenhouse online. Combined with the priorities of FCU loops from CFD simulations offline, we have developed the CFD–EPM-based heating control system of greenhouse with surface water source heat pumps system (SWSHPS). Compared with conventional multi-zone independent control (CMIC) method, the energy savings potential is between 8.7% and 15.1%, and the control temperature deviation is decreased to between 0.1 °C and 0.6 °C in the investigated greenhouse. These results show the CFD–EPM-based method can improve system performance with more accurate temperature, more rapid responses and lower energy consumption.

1. Introduction

Agricultural greenhouses need input energy to maintain a satisfactory temperature for the plant growth, especially in winter, and the energy savings is an important issue of greenhouse control [1,2]. Over the last decades, many efforts have been made to replace energy sources of fossil fuels with renewable energy or to improve energy efficiency for greenhouse heating [3,4]. Chou et al. [5], Tong et al. [6], Nayak and Tiwari [7], Ozgener and Hepbasli [8] and Benli and Durmus [9] used renewable energy to control the temperature in the greenhouse to decrease the fossil fuels consumption, such as ground or air source heat pump, photovoltaic/thermal system and biomass energy. The combination of energy savings and application of renewable energy is necessary for greenhouse heating. To improve heating efficiency in the greenhouse with energy sources of renewable energy, it is essential to investigate the control method integrated with heat transfer mechanism.

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Nomenclature

a	permeability of the porous medium (m^2)
a_λ	absorption coefficient (m^{-1})
A_g	ground area of the greenhouse (m^2)
A_s	surface area of greenhouse cover material (m^2)
c_a	the air specific heat ($J\ kg^{-1}\ K^{-1}$)
c_w	the water specific heat ($J\ kg^{-1}\ K^{-1}$)
C_1, C_2, C_μ	constants in the turbulence model
d	characteristic length of leaf (m)
D_i	pressure difference of saturated water vapor (p_a)
e_s	saturated water vapor pressure (p_a)
e_a	actual air vapor pressure (p_a)
e_0	actual air water vapor pressure outside (p_a)
f_1, f_2, f_μ	damping functions in the transport equation
g	gravity acceleration ($m\ s^{-2}$)
G_B	turbulence kinetic energy production
I_a	outdoor global radiation ($W\ m^{-2}$)
I_λ	radiation intensity depends on position ($\vec{r}$) and direction ($\vec{s}$) ($W\ m^{-2}\ sr^{-1}\ Hz^{-1}$)
L	characteristic length of the greenhouse (m)
L_{ai}	the leaf area index ($m^2\ m^{-2}$)
k	turbulence kinetic energy ($m^2\ m^{-2}$)
k_s	sky clearness index
K_g	heat transfer coefficient ($W\ m^{-2}\ K^{-1}$)
K_c	correct coefficient of internal thermal curtain and infiltration
n	time step
n_λ	refractive index
q	output energy of FCU.
q_{sen}	the sensible heat caused by heat exchange between leaves and ambient air ($W\ m^{-2}$)
q_{lat}	latent heat caused by plant transpiration ($W\ m^{-2}$)
q_t	net solar radiation into the greenhouse (W)
q_s	energy input from FCU (W)
q_w	heat flux from ventilation (W)
q_c	heat flux through the cover (W)
q_l	energy flux due to the long wave thermal radiation (W)
q_{min}	lower limit of input energy (W)
q_{max}	upper limit of input energy (W)
$\vec{r}$	position vector (m)
r_a	plant canopy aerodynamic resistance ($s\ m^{-1}$)
r_s	plant canopy stomatal resistance ($s\ m^{-1}$)
R_a	Rayleigh number
Re_t	Reynolds number of turbulent quantities
Re_k	Reynolds number of turbulent distances from the wall
R_n	net radiation of plant canopy ($W\ m^{-2}$)
$\vec{s}$	direction vector
$\vec{s}'$	scattering direction vector
S_φ	source term
$S_{\varphi 1}$	source term in the momentum equation
$S_{\varphi 2}$	source term in the energy equation
t	time (s)
T_i	indoor air temperature (K or °C)
T_{leaf}	plant leaf temperature (K)
T_0	outside temperature of greenhouse (K)
T_{ref}	FCU outlet temperature (K)
T_{sky}	sky temperature (K)
x_j	coordinate in the jth direction (m)
y	generalized normal distance from a solid boundary (m)
Y	nonlinear momentum loss coefficient (m^{-1})
u	air velocity ($m\ s^{-1}$)
u_j	velocity component in the jth direction ($m\ s^{-1}$)
V	air volume of the greenhouse (m^3)
V_w	flux of supply hot water ($m^3\ s^{-1}$)

Greek symbols

α	air thermal diffusivity ($m^2\ s^{-1}$)
β	thermal expansion coefficient (K^{-1})
γ	psychrometric constant (0.0646 kPa °C^{-1})
Δ	curve slope of saturated water vapor pressure (kPa °C^{-1})
Δq_{max}	maximum change rate of input energy (W)
ΔT	temperature variation (°C)
ΔT_p	temperature difference between the plants and the cold roof of the greenhouse (°C)
ΔT_w	difference of supply water and return water temperature (°C)
Γ	diffusion coefficient ($m^2\ s^{-1}$)
ε	dissipation rate of the turbulent kinetic energy ($m^2\ s^{-3}$)
ε_1	cover emissivity
ε_2	sky emissivity
ε_{12}	emissivity between the cover and sky
η	FCU loop heating efficiency (°C kW^{-1})
μ	dynamic viscosity ($kg\ m^{-1}\ s^{-1}$)
μ_t	turbulent viscosity ($kg\ m^{-1}\ s^{-1}$)
ρ	air density ($kg\ m^{-3}$)
ρ_w	water density ($kg\ m^{-3}$)
σ	Stefan–Boltzmann constant ($5.67 \times 10^{-8}\ W\ m^{-2}\ K^{-4}$)
σ_k	Prandtl number of the turbulence kinetic energy
σ_s	scatter coefficient (m^{-1})
σ_ε	Prandtl number of the dissipation rate
τ_a	cover transmissivity
φ	transportation concentration
Φ	phase function
Ω	radiation solid angle (radians)
∇	divergence operator

Abbreviations

CFD	computational fluid dynamics
CMIC	conventional multi-zone independent control
EPM	energy prediction model
FCU	fan coil units
PAR	photosynthetic active radiation
SWSHPS	surface water source heat pumps system

Computational fluid dynamics (CFD) is an effective method to analyze the spatial and temporal distribution of flow velocity and temperature, and can be used for modeling fluid flow situations, heat, mass and momentum transfer and optimal design in agriculture [10,11]. CFD has been mainly used for simulation and optimum design of the greenhouse construction and configuration to save energy in the last decades. Lee and Short [12] verified the temperature simulations of CFD in a full-scale naturally ventilated greenhouse with plant, and found that the CFD numerical model was a good tool for evaluating the ventilation rates of the natural ventilation system. Campen and Bot [13] studied the ventilation of a greenhouse using three-dimensional CFD, and the CFD calculations were verified by experimental results from tracer gas measurements. Mistriotis and Briassoulis [14] numerically calculated the external and internal aerodynamic coefficients on a tunnel structure with openings in the case of a transverse wind using CFD method. Kittas and Bartzanas [15] and Bourneta and Boulard [16] used CFD simulations to analyze the effect of ventilation openings on the greenhouse microclimate and compare the ventilation efficiency according to vent configurations. The impact of plant