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Ventilation optimization of solar greenhouse with removable back walls based on CFD

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ABSTRACT

Ventilation is important for crop production and quality in greenhouse cultivation, and vent dimension and position are the basis of greenhouse design. In this study, the effect of the back wall vent dimension on solar greenhouse cooling was investigated by CFD (Computer Fluid Dynamics). The results showed that the average air temperature in a solar greenhouse with removable back walls (RG) was reduced by approximately 1.7 °C and the highest temperature dropped by approximately 5.8 °C compared with the traditional solar greenhouse with a brick back wall (TG). A 2-D CFD transient simulation model was developed to simulate the indoor temperature and airflow distributions in RGs with different back wall vent sizes. The results suggest that a back wall vent of 1.4 m increased inside the ventilation efficiency in a solar greenhouse with removable back walls.

1. Introduction

Solar greenhouses are unique types of greenhouses in China characterized by low cost, good thermal insulation and high energy efficiency (Meng et al., 2009; Liang et al., 2013). In recent years, there has been much research on the regulation of environmental factors in greenhouses. Various cooling measures, such as natural ventilation and shading, combined with wet pads and spray cooling, have been studied for their effects on greenhouse cooling in summer (Arbel et al., 1999; Li et al., 2002; Wang and Zhang, 2006). Natural ventilation plays an important role in indoor climate control, as it directly affects heat exchange between the outside and inside of the greenhouse, it can also reduce the humidity of greenhouses. In addition, outdoor air is essential to replenish the CO_2 consumed by plants for the photosynthesis process (Liu et al., 2003; Molina-Aiz et al., 2009; Sun et al., 2014). Ventilation is an important issue in greenhouse technology, and vent dimensions and position are key elements in natural ventilation design.

The structure of the ventilation vent used in a greenhouse has a significant impact on the ventilation of the greenhouse. A large number of studies have shown that a good structure of vent is conducive to guiding the flow of external air into the interior and forming a good greenhouse airflow field, which will be effective in cooling the greenhouse. There are three categories of greenhouse ventilation: side window ventilation, roof ventilation and combined ventilation. Many scholars have concluded that the side vent and roof vent combined ventilation have the best cooling effect in both the greenhouses and the glasshouses. Wang et al. (2007), Inbok et al. (2000), Bournet et al. 2007a, 2007b agreed with this conclusion.

The most notable structural feature of a solar greenhouse is the back wall, which is one of the main factors that leads to differences of microclimate inside the greenhouse (Tong et al., 2013). For a solar greenhouse, heat is stored in the back wall by receiving solar radiation during daytime and released indoors at night (Zhang et al., 2015; Li et al., 2011; Li et al., 2010; Wang et al., 2012). However, in summer, the back wall of a traditional greenhouse becomes a heat source that easily leads to heat accumulation, and high indoor temperature, seriously interfering with the greenhouse climate achieved by ventilation and cooling (Wang et al., 2016). To improve the cooling efficiency, a solar greenhouse with removable back walls (RG) was designed for the control of indoor environment. The removable back walls are made of jute fiber boards and installed in winter for heat preservation and removed in summer for ventilation (Wei et al., 2016).

Computational fluid dynamics (CFD) has been proven to serve as an effective simulation tool to predict microclimate in greenhouses with reliable results and low cost (Lee et al., 2013; Fidaros et al., 2010; Piscia et al., 2012; Nebbali et al., 2012; Teitel and Wenger, 2014). Kacira et al. (1998) and Cheng et al. (2011) studied natural ventilation rates and airflow patterns in a multi-span saw-tooth greenhouse and a glass greenhouse, respectively. A good balance between air flow and air speed can be designed by means of proper CFD analyses. Bartzanas et al. (2004) and Benni et al. (2016) compared different vent opening configurations (side and/or roof openings) by CFD simulations in order

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Nomenclature

Γ_ψ	generalized diffusion coefficient ($m^2\,s^{-1}$)
I	radiation intensity ($W\,m^{-2}$)
n	refractive index
$\vec{s}$	direction vector
S_ψ	source terms ($W\,m^{-3}$)
V^v	velocity vector ($m\,s^{-1}$)
x_{mi}	measured temperature (°C)
Ψ	universal variable
σ	Stefan-Boltzmann constant ($W\,m^{-2}\,°C^{-4}$)
Ω'	solid angle
a	absorption coefficient
m	parameters' number
$\vec{r}$	position vector
$\vec{s}'$	scattering direction vector
T	temperature (°C)
x_{pi}	simulated temperature (°C)
ρ	fluid density ($kg\,m^{-3}$)
σ_s	scattering coefficient
Φ	phase function

Subscripts

pi	simulation
s	stroke length (m)
xi	measurement

to optimize ventilation in the tunnel greenhouse and Venlo greenhouse. A CFD tool was also used by Hong et al. (2008) to determine ventilation efficiencies of naturally ventilated multi-span greenhouses in Korea; that study indicated that the ventilation rate could be calculated by the sum of the mean air velocity at each opening and the area of the opening. However, there are has been little research on natural ventilation in a solar greenhouse (Nebbali et al., 2012; Wang et al., 2013).

In this paper, a 2-D computer simulation model was developed with the finite-volume based commercial software, Fluent®, to simulate the temperature and airflow distributions caused by the natural ventilation in RGs. The objectives of this study were (1) to explore the environment in RGs with different back wall vents using CFD unsteady simulation, (2) to validate the CFD model by comparison with the measured data, (3) to predict the different temperature and air flow distributions with different back wall vents, and (4) to optimize the back wall vent size of RGs based on CFD simulations.

2. Materials and methods

2.1. Description of the greenhouses

The experimental greenhouse with removable back walls (RG) and the traditional greenhouse (TG) which is used as a control (Fig. 1) are located in the Facility Horticulture Research Institute of Nanjing Agricultural University, Suqian (34.03° N, 118.28° E) Jiangsu, China. The removable back wall greenhouse (RG) has the same structure as a traditional greenhouse (TG) and is orientated in the east-west direction. The greenhouse structures are shown in Fig. 2, including the back wall, the back roof constructed of polystyrene board and the south roof covered with 0.12 mm thick polyvinyl chloride (PVC) film. The greenhouse is 70 m long, 9 m wide and 3.8 m high. The back wall of greenhouse has 2.8 m height and 0.5 m thickness. The back wall of the RG has two parts: the upper part is a 1.4 m removable wall and the lower part is a 1.4 m fixed wall. The removable back walls are assembled using jute fiber boards with dimensions of 1.4 × 1.4 × 0.08 m and which are wrapped with polyethylene film to form waterproof blocks. The removable back walls are composed of 0.08 m thick jute fiber boards, 0.34 m thick air space, and 0.08 m thick jute fiber boards from inside to outside. The fixed wall was built with hollow concrete bricks. The jute fiber boards were installed in winter and removed in summer. During the experiment, both greenhouses had no crops, and the vents were open all day except on rainy days.

2.2. Measurement and data collection system

During the experiment, a meteorological station (TYD-ZS2 type environmental data recorder, with instrument temperature measurement accuracy ± 0.1 °C, measuring range −40 to 80 °C, wind speed

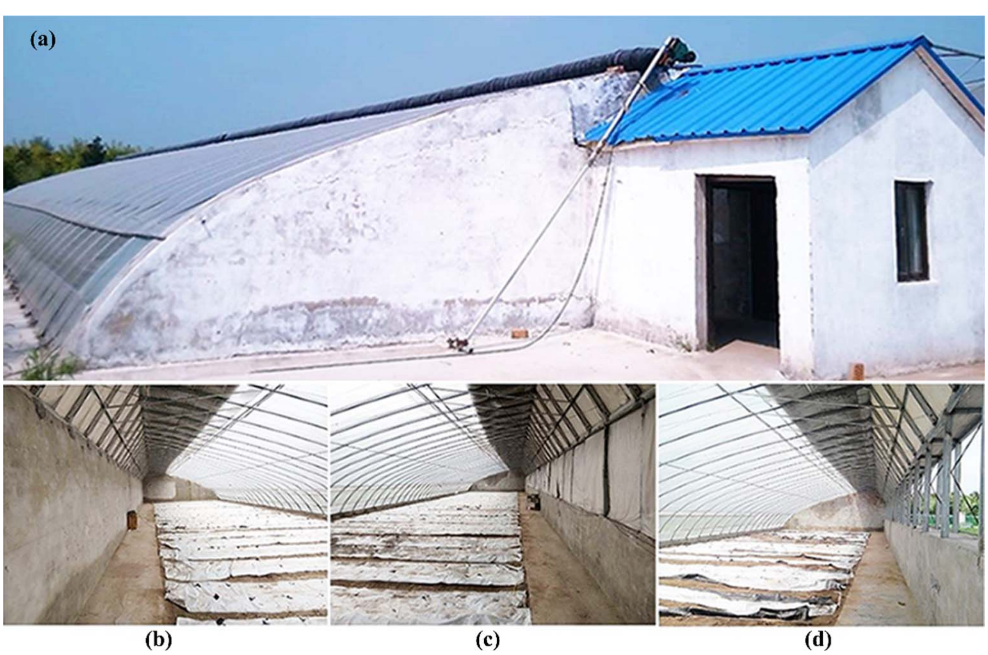

Fig. 1. Photographs of the experimental greenhouses. a: Outdoor view of RG and TG; b: Indoor view of TG; c: Indoor view of RG during winter months; d: Indoor view of RG during summer months.