Numerical Simulation of Humidity Distribution in Solar Greenhouse

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Abstract. In the winter and spring when the temperature is relatively low, in order to achieve the purpose of thermal insulation, solar greenhouses usually adopt closed measures, resulting in a very high humidity inside the greenhouse. Crop growth requires a suitable environment. Too high humidity is likely to limit the progress of plant transpiration, which will lead to physiological disorders of the crop and increase the probability of crop disease. Therefore, we must grasp the law of humidity change in sunlight greenhouses, and then rationally regulate the humidity. It is of great significance. In this paper, the numerical simulation of the greenhouse environment using computational fluid dynamics (CFD) method, and the CFD numerical simulation results and experimental test results are fitted and verified, and finally the humidity distribution of the greenhouse in a certain period of time under winter irrigation conditions. In order to comprehensively understand the law of humidity change in the sunlight wet room during this period, take reasonable methods and measures to carry out artificial control to provide a suitable growth environment for crops and prevent disease from occurring. The numerical simulation results of the solar greenhouses under no-plant conditions were fitted with experimental test results. The average error between the simulated value of indoor air temperature and the actual measured value was 2.5\%, and the average error between the simulated value of indoor air humidity and the actual measured value was 3.3\%. The numerical simulation results and experimental test results have a higher degree of fit, which proves that the established CFD numerical model can basically reflect the internal conditions of the greenhouse.

Keywords: Solar Greenhouse, Computational Fluid Dynamics, Humidity Field, Numerical Simulation

1. Introduction
As a closed or semi closed system, solar greenhouse is affected by solar radiation intensity, internal temperature, humidity, carbon dioxide concentration and other environmental factors, which directly
affect the growth and development of crops. At the same time, the transpiration, photosynthesis and respiration of crops, as well as the reaction of the characteristics of porous media of crops to the air flow, temperature and humidity, solar radiation and so on in the greenhouse, which in turn affect the environment in the greenhouse. The properties of porous media of crop canopy cause the low temperature and high humidity environment inside the canopy, and affect the normal physiological activities of crop transpiration and respiration. It can inhibit the absorption of nitrogen, phosphorus, potassium and other minerals by crops and easily cause diseases and insect pests. Therefore, it is of great significance to study the internal environmental factors of greenhouse and the coupling effect between greenhouse air and crops for guiding greenhouse planting, improving greenhouse structure and preventing diseases and insect pests.

Through changing the natural light and temperature conditions, facility agriculture creates environmental factors suitable for the growth of plants. It is an important part of modern agriculture in China, and has the advantages of good heat preservation, low investment and energy saving. It plays an important role in facility agriculture in China, brings huge economic benefits to the rural areas and farmers, and solves the problem of vegetable production in winter in the northern region, Therefore, it has been widely used in the north of China[1-2]. Since the beginning of the 21st century, solar greenhouse has entered a rapid development stage, and is developing towards automation, mechanization, standardization, harmlessness and standardization [3-4]. Solar energy is the main heat source of solar greenhouse. Through the heat storage and insulation function of enclosure structure, the environment suitable for crop growth is created to meet the production needs of crops in cold period, and the labor force in winter idle period is reasonably utilized [5]. Therefore, it is of great significance to develop solar greenhouse and study the internal environment of solar greenhouse for crop growth [6-7]. The suitable temperature and humidity environment in solar greenhouse plays an important role in the growth and development of crops. The prediction of temperature and humidity inside the greenhouse is the premise of controlling the temperature and indoor environment, and it can also reduce the time and quantity of sensor measurement. It is of great significance to study the environment inside the greenhouse. Through literature review, many scholars have conducted in-depth research on the prediction of temperature and humidity inside the greenhouse, but there is little research on the prediction of crop canopy temperature and humidity [8].

This paper studies the distribution of humidity in a greenhouse under the irrigation method by CFD numerical simulation, and understands the change law of the humidity in the greenhouse at a certain period of time. Therefore, reasonable measures are taken to regulate the humidity, so that the crop growth is in a suitable humidity and control the incidence of crop diseases and insect pests guarantees high yield of greenhouse crops.

2. Method

2.1 Application Status of Solar Greenhouse
Solar greenhouse is a new type of solar greenhouse with inner and outer double-layer covering film. Compared with other types of greenhouse, its heat preservation performance is better, which is very suitable for the cold and dry areas in North China. The air vent is arranged on the top cover of the greenhouse, so that when the cold air entering from the outside passes through the inner and outer double-layer film, the heat exchange will make the air temperature rise and then blow to the crops. Because of the double-layer film structure, most of the floating heat flow in the greenhouse will rise to the inner layer film and be blocked, so that the heat flow will form a circulation in a smaller area. At night, the heat preservation and insulation effect of double covering layer makes the temperature inside the greenhouse higher than that of other traditional greenhouse types [9].

The crop canopy is arranged vertically up, down, and about 5 cm above the canopy and horizontally. A total of 12 air temperature and humidity sensors are arranged according to the south, middle, and north of the crop canopy, which is used to observe the temperature and humidity distribution of the crop canopy. And the law of change and adjust the height of the sensor according to
the height of the crop. The soil surface layer arranges three soil temperature and humidity sensors in the north-south direction for setting the boundary conditions and observing the relationship between the soil surface layer temperature and moisture content and the crop canopy temperature and humidity. Two solar radiation sensors are arranged in the air 2.2m above the ground and in the canopy 0.4m above the ground to observe the setting of solar radiation and boundary conditions inside the greenhouse; about 1.9m above the ground and 0.4m above the ground Four carbon dioxide sensors are arranged at about 1.9m in the middle of the canopy, which are used to observe the changes of carbon dioxide concentration in the air above the crop canopy and canopy; regularly test the canopy leaf area of crops at different locations in the greenhouse, and observe the changes and distribution of leaf area [10- 11].

The common heating methods of greenhouse include furnace heating, radiation heating, hot air heating, steam heating, etc. According to the scale of the wet room and the variety of cultivated crops, combined with the principle of reliability and economy, the appropriate heating mode is selected. Hot air heating is applicable to all kinds of wet rooms, with short preheating time, fast temperature rise, easy operation and low cost, but the heat preservation performance is not good and the temperature is unstable after shutdown; stove heating is applicable to earth greenhouse or greenhouse requiring short-term heating, with low cost and certain heat preservation after shutdown, but the preheating needs a long time and ventilation [12].

2.2 Mathematical Model for Simulation of Greenhouse Humidity

Based on the physical model of the experimental greenhouse, the three-dimensional unsteady mathematical model of the greenhouse was established after appropriate simplification, and then the humidity distribution was simulated by using FLUENT software and the finite volume method. The finite volume method is mainly solved by the method of subdomain plus discretization, which divides the calculation domain into grids and ensures that there is a non overlapping control volume on each grid point. Then, the differential equation to be solved is integrated for each control volume to obtain a set of discrete equations. The unknown is the dependent variable on the grid node.

The Reynolds number of greenhouse gas flow is generally greater than $10^{10}$, so the standard $k - \varepsilon$ turbulence model is used to analyze the distribution of greenhouse humidity, the wall function method is used to treat the area near the wall. The basic control equation of greenhouse fluid is as follows:

1) Conservation equation of mass

$$\frac{\partial \rho}{\partial t} + \frac{\partial}{\partial x_j}(\rho u_j) = S_m$$  \hspace{1cm} (1)

In the formula: $S_m$ is the mass (kg) added to the continuous phase from the dispersed secondary phase; $\rho$ is the fluid density (kg.m$^{-3}$); $u_i$ is the average mass velocity (m / s) in the i direction; It is the length (m) of the microbody in the i direction.

2) Momentum conservation equation

$$\frac{\partial}{\partial t}(\rho u_i) + \frac{\partial}{\partial x_j}(\rho u_i u_j) = -\frac{\partial \tau_{ij}}{\partial x_j} + \rho g_i + F_i$$  \hspace{1cm} (2)

In the formula: $p$ is the static pressure (Pa); $\tau_{ij}$ is the stress tensor; $g_i$ is the gravitational volume force (N / m$^3$) in the i direction; $F_i$ is the external volume force (N / m) in the i direction.

3) Energy conservation equation

$$\frac{\partial (\rho T)}{\partial t} + \text{div}(\rho u T) = \text{div} \left( \frac{k}{c_p} \text{grad} T \right) + S_r$$  \hspace{1cm} (3)

Where: $c_p$ is the specific heat capacity (J / (kg K)); $T$ is the thermodynamic temperature (K); $k$ is
the heat transfer coefficient of the fluid; $u$ is the velocity term (m/s); $S_T$ is the internal heat source of the fluid and due to viscosity, the part that converts fluid mechanical energy into thermal energy.

3. Experiment

3.1 Actual Measurement of Environmental Data
The measured outdoor meteorological parameters include temperature, relative humidity of atmosphere, solar radiation, wind speed and wind direction, which are automatically collected by the data acquisition instrument set outside the greenhouse, once every 15 minutes, and finally processed after downloading by computer; Indoor meteorological parameters include indoor air temperature and humidity, indoor soil temperature and moisture content, indoor surrounding enclosure temperature, etc., which are measured by HOBOProv2 series temperature and humidity recorder and infrared thermometer. In this experiment, the indoor meteorological parameters of the temperature were collected by the method of point distribution measurement. A total of 27 measuring points were arranged on the three levels of 0.5, 1.3 and 2.0m above the ground.

3.2 Test Content and Method
(1) Measurement of outdoor meteorological parameters
Outdoor meteorological parameters include: temperature, relative humidity of atmosphere, solar radiation, wind speed and wind direction. Send some data to be collected automatically by the weather station data acquisition instrument set outside the greenhouse, which collects data every 15 minutes, and finally processes the data through computer download.

(2) Measurement of indoor temperature and humidity
HOBOProv2 series temperature and humidity recorders are used to measure the temperature and humidity inside the greenhouse. The instrument model selected in this paper is u23-002. The features of the instrument are: rain proof design, can also be used in outdoor or condensation environment; high precision; fast response; Optical USB communication port. The sampling rate is 1 second to 18 hours. The user can customize the sampling rate. In this experiment, sampling is carried out every 15 minutes. The temperature measurement range is -40-70°C, the resolution is 0.02°C, and the accuracy is ±0.2°C; the humidity measurement range is 0-100%, the resolution is 0.03%, and the accuracy is ±2.5%. In this experiment, 27 measuring points are arranged on three horizontal planes 0.5m, 1.3m and 2.0m away from the ground.

4. Discuss

4.1 Analysis of Experimental Results
The whole greenhouse structure is selected as the computational domain for environmental data numerical simulation. Through ICEMCFD software, the greenhouse space is divided into 616068 grids using structured grid. The actual measurement of the environmental conditions in the greenhouse is carried out in a week of a certain month in a certain year, during which the weather is basically sunny. Select the representative test data of a certain day, as shown in Table 1. Take the average value of the data of all the measuring points every hour in 24 hours as the boundary condition input of numerical simulation. At the same time, in order to ensure the reliability of the established model, select part of the data of other days for simulation.

| Parameter | Wind speed/(m·s⁻¹) | Sun radiation/(mwh/cm²) | Outdoor air temperature/°C | Relative humidity of outdoor air/% | Indoor soil temperature/°C |
|-----------|--------------------|------------------------|-----------------------------|-----------------------------------|---------------------------|
| Average value | 3.64               | 338                    | 8.3                         | 16.2                              | 15                        |
In solar greenhouse, solar radiation is very important in the environmental factors that affect the growth of crops. On the one hand, it affects the temperature and humidity environment of the greenhouse, on the other hand, it affects the growth of crops, and has an important impact on the output of the whole greenhouse. It can be seen from the experiment that, in general, the solar radiation curve is similar to parabola shape, which starts to strengthen at about 7:00 in the morning, reaches the maximum value at 11:00-13:00 in the noon, and then gradually weakens. The range of change in sunny days is relatively large, while that in cloudy days is relatively small. The average humidity of the air inside the humidity is higher than the average humidity outside the greenhouse. With the gradual increase of solar radiation, the temperature increases, and the humidity decreases, the same change trend appears both inside and outside the chamber. At about 14:00, the temperature and humidity reach the maximum value and the minimum value respectively. Then, with the decrease of solar radiation, the temperature gradually decreases, and the humidity gradually rises. The temperature distribution at different heights in the room is shown in Figure 1.

![Figure 1. Temperature change at different heights in a room](image)

At the beginning, the solar radiation is strong, the closer to the ground, the less blessing radiation is received, the lower the temperature is, and the higher the humidity is. After that, the solar radiation gradually decreases, and the humidity gradually rises.

4.2 CFD Numerical Simulation Analysis of Greenhouse Humidity

At present, the humidity regulation of the wet room is divided into two aspects, one is to reduce the indoor humidity, the other is to humidify. There are several kinds of measures to reduce the indoor humidity: (1) ventilation and air exchange. When the outdoor humidity is low, ventilation and air exchange can effectively reduce the indoor humidity, but at the same time, ventilation will exhaust the indoor heat, which is not conducive to the heat preservation of greenhouse, so it is necessary to control the size of ventilation or adopt intermittent ventilation; (2) humidification and humidity reduction, there is a negative correlation between the change of temperature and the change of humidity. In winter, heating measures can be taken to reduce the indoor humidity; (3) the mulching of plastic film, the control of irrigation amount and irrigation mode, the mulching of plastic film on the greenhouse ground soil, the reduction of water evaporation, the use of modern water-saving irrigation technology can effectively reduce the ground evaporation; (4) prevent wall condensation, with the evaporation of indoor water vapor, It will condense liquid drops inside the greenhouse covering materials, which will cause the ground to be wet. The covering materials with anti dripping function or spraying anti dripping agent can be used; (5) other cooling technologies and equipment can use special dehumidifiers, hygroscopic agents, etc. In addition, in some cases, the environment in the greenhouse
may be dry. When the indoor relative humidity is less than 40%, it needs to be humidified. Generally, humidification measures include increasing irrigation and spraying.

5. Conclusion
In this paper, the solar greenhouse is taken as the research object, and the relevant data measured by the experiment are analyzed to provide reliable boundary conditions for the numerical simulation; the three-dimensional CFD numerical model of the solar greenhouse under the natural ventilation condition is established by the CFD method, the whole greenhouse structure is determined as the calculation domain, the grid is divided, and the grid quality is checked; the standard k - ε end flow model is adopted. The standard wall function method is used to encrypt the near wall area; the DO radiation model is used to process the solar radiation; the component transfer model is used to describe the indoor relative humidity; the finite volume method is used to solve the flow field differential equation discretely.

Acknowledgements
This work was supported by 2018 Shouguang Facility Agriculture Center Open Scientific Research Project (2018SG-S-01) and Liaoning Province Doctoral Research Startup Fund Project (2019-BS-138) fund.

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