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Design and Micro Environment Analysis of Wet Curtain Air Conditioning System for Citrus Storage

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Abstract

Ventilation storage is one of the main ways to store citrus in China. In order to overcome the influence of large temperature fluctuation in storage due to the high temperature outside, a wet curtain air conditioning system for citrus ventilation storage was proposed in this paper. The cooling and humidifying numerical models for wet curtain air conditioning system were established by using the method of computational fluid dynamics, and the micro environment test in storage had been employed for verification. The results of the numerical analysis show that: in condition of outdoor ambient temperature 20°C and relative humidity 60%, the wet curtain air conditioning system can reduce the temperature in storage by 5°C, increase the relative humidity to 82%, and decrease the average airflow velocity to 0.2 m/s. The distribution of temperature, relative humidity and airflow velocity in the storage is well distributed.

Keywords: citrus storage, wet curtain, air conditioning system, numerical simulation

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INTRODUCTION

As a low-cost citrus storage building, ventilation storage has been widely used in the main producing areas of citrus in China. The temperature in storage is mainly regulated through natural ventilation and heat insulation. At present, the main storage period of Citrus in China is from November to April of next year. During December to February of next year, the outdoor temperature is low, the temperature in storage is suitable for citrus, but in the early and late storage period, the outdoor temperature is higher, just ventilation is difficult to ensure suitable temperature in storage.

In order to solve this problem, it is necessary to optimize the design of ventilation storage. Hu et al, made some improvement design and improved ventilation effect (Hu et al. 2001). Wang et al. (2010) added refrigeration and humidification systems to it, designed a wet-cold citrus ventilation storage. He et al. (2016) put forward some improvement design in the perspective of agricultural storage buildings. Li et al. (2016) redesigned the ventilation system which improved the ventilation performance. These designs and optimization measures do not solve problems well. In the case of higher outdoor temperature, the optimization designs of ventilation can't effectively reduce the temperature in the storage, while, the refrigeration methods will consume more energy.

Therefore, a wet curtain air conditioning system for citrus ventilation storage was proposed in this paper. The cooling and humidifying numerical models were established by using the method of computational fluid dynamics, and the micro environment in storage had been analyzed. The results of the numerical analysis show that the distribution of temperature, relative humidity and airflow velocity in the storage is well distributed.

MATERIALS AND METHODS

Scheme of Wet Curtain Air Conditioning System

The wet curtain air conditioning system is composed of three parts: cold water supply system, wet curtain air conditioning system and monitoring and control system. The cold water supply system includes outdoor water tank, indoor water tank, water tank connection pipeline, filters, pumps and other devices. Outdoor water tank absorbs radiation cold at night, so that water temperature decreases. Then, the cold water is pumped into the indoor water tank for wet curtain air conditioning system. Wet curtain air conditioning system includes surface air cooler, wet curtain system, air inlet and exhaust pipe. When the outdoor

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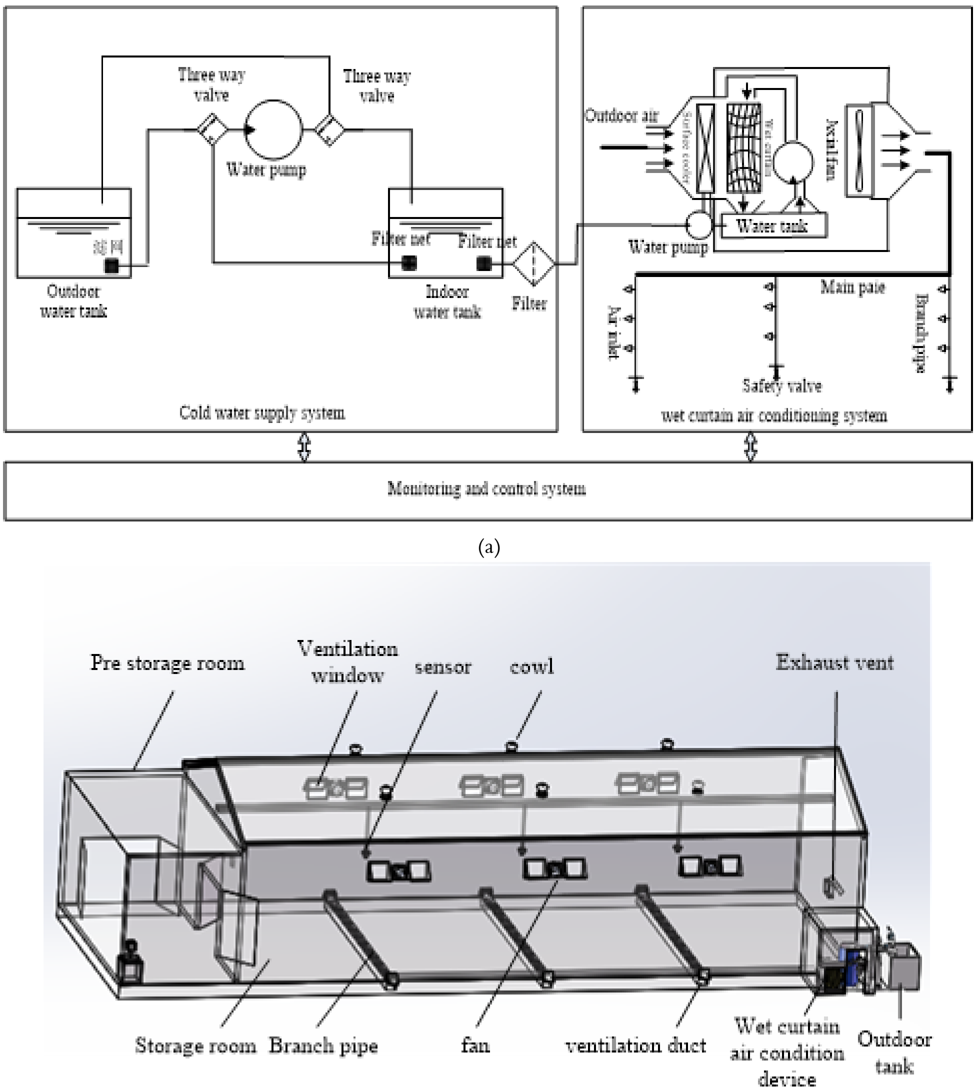


Fig. 1. (a) Scheme of wet curtain air conditioning system; (b) Layout of wet curtain air conditioning system in storage

temperature is high in daytime, the wet curtain air conditioning system is turned on automatically. Cold water is pumped to the surface cooler. The outdoor air is pre cooled by the surface cooler under the action of negative pressure fan, and then it is cooled and humidified by the wet curtain humidifying and cooling device. After that, the wet and cold air is blown in through the branch pipe evenly arranged at the bottom of the storage. The monitoring and control system is composed of control circuits. The control switches, temperature and humidity sensors are controlled by this system. The scheme of wet curtain air conditioning system and layout in the storage are shown in **Fig. 1**.

Computational Domain and Meshing

This paper is based on an improved ventilation storage of citrus with 12 m long, 7 m wide, 4 m eaves height and 6 m roof ridge height. The stacking is 3.2 m×5.8 m×2.5 m and three stacking are rowed with the gap 0.6 m in storage. The gap between stacking and wall are also 0.6 m. In order to ensure uniform air inlet, the branch pipes are installed in the ventilation duct between the stacking and stacking. There are seven circular air inlet holes with a diameter of 0.18 m on each branch pipe at equal intervals. The exhaust vent is located in the middle of the wall, with a height of 1m, width of 0.6 and length of 0.9m, as shown in **Fig. 2**. The 3D model of computational domain was built and meshed by using the software ICEM CFD. Moreover, the unstructured meshing method was adopted, and the local mesh refinement approach was using on air inlet, exhaust vent and stacking areas. The total number of the grids is 5999529.

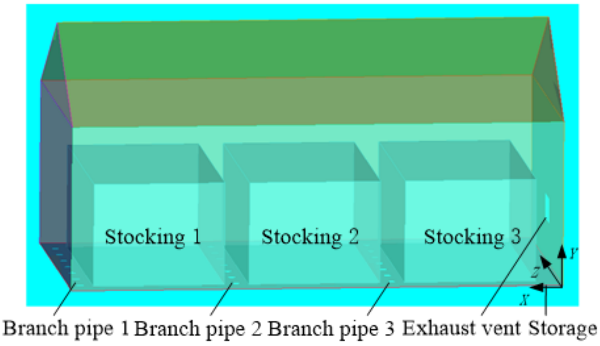


Fig. 2. The computational domain of citrus ventilation storage

Control Model

Model hypothesis

In order to simplify the calculation, the model was assumed as follows (Chourasia et al. 2005, Chourasia and Goswami 2007a, Delele et al. 2009, Moureh and Flick 2004, Sadi and Hellickson 2001, Yu et al. 2008):

Air was assumed to be a continuous and incompressible ideal fluid and follow the Boussinesq hypothesis (Liu et al. 2013); the citrus stacking was assumed to be porous medium, and it was isotropic with constant respiration heat; Water vapor in the air was assumed not to condense into water.

The basic control equations

The value of fluid Reynolds coefficient is about 105 based on the calculation, and the type of fluid motion in the storage is turbulent. The calculation formula of Reynolds number of air flow in the storage is as follow:

$$R_e = \frac{\bar{u}d}{\nu} \tag{1}$$

In this equation, ū is the average airflow velocity in the storage, m/s; d is the hydraulic radius d=x·y/[(x+y)/2], x, y are the length of both sides of the flow section, m; ν is the dynamic viscosity of air, Pa·s.

The flow field in the storage should follow the continuity equation, momentum conservation equation, energy conservation equation, component transport equation and k-ε model equation. Since it is a steady flow, the control equation is as follow:

$$div(\rho \boldsymbol{u} \phi) = div(\Gamma \boldsymbol{grad} \phi) + S \tag{2}$$

In the equation, ρ is the density, kg/m^3; **u** is the velocity vector, m/s; φ is generalized variables; Γ is the generalized diffusion coefficient corresponding to φ; S is the generalized source term. The calculation formula of each parameter in the equation can be gotten as in the reference (He et al. 2013).

Stacking model equation

1. Resistance model of porous media

Citrus stacking in the storage was considered as a porous medium. When the air seeps into the stacking, it would be resisted by the citrus, and this part of resistances should be considered as the source term of fluid momentum in calculation, which are made of viscous resistance term and inertial resistance term. For isotropic porous media, the flow resistance equation is as follow:

$$S_i = -\left(\frac{\mu}{\alpha} u_i + C_2 \frac{1}{2} \rho |\boldsymbol{u}| u_i\right) \tag{3}$$

In the equation, μ is the dynamic viscosity of a fluid, Pa·s; α is the permeability of porous media, m2; C_2 is the inertial resistance coefficient, 1/m; u_i is the component of velocity in the X, Y, and Z directions, m/s; **u** is magnitude of fluid velocity, m/s.

The viscous resistance and inertial resistance coefficient can be calculated by Ergun Equation (Ergun and Orning 1949). Viscosity drag coefficient:

$$\frac{1}{\alpha} = \frac{150(1-\varepsilon)^2 \cdot \lambda^2}{D_p^2 \cdot \varepsilon^3} \tag{4}$$

Inertial drag coefficient:

$$C_2 = \frac{3.5}{D_p} \cdot \frac{(1-\varepsilon) \cdot \lambda}{\varepsilon^3} \tag{5}$$

In the equation, D_p is the equivalent diameter of porous media particles, which can be calculated by the volume of solid particles as $D_p = (6V/\pi)^{1/3}$; ε is the porosity of porous media, which is the ratio of the void space volume V_v the total volume subtracts the solid volume) to the total volume V_b; λ is the shape coefficient, which is calculated by the surface area and equivalent diameter of solid particles as $\lambda = A_p/(\pi D_p^2)$.

2. The heat transfer model of porous media

The heat balance model is widely applied to the convective heat transfer process of porous media, which assumes that the temperature of solid skeleton is equal to that of the fluid nearby. This model is applicable to the condition that the temperature difference of the solid skeleton and fluid nearby is not obvious (Chourasia and Goswami 2006, 2007b, Smale et al. 2006). For the heat transfer process of citrus stacking, the heat balance model control equations are as follows:

$$div(\rho_f c_{pf} \varepsilon \boldsymbol{u} T) = div(k_{eff} \boldsymbol{grad} T) + S \tag{6}$$
$$k_{eff} = \varepsilon k_f + (1-\varepsilon) k_s \tag{7}$$

$$S = \varepsilon S_f + (1-\varepsilon) S_s \quad (8)$$

The fluid and solid phases of porous media are respectively represented in the equation as f and s; k_{eff} is the effective thermal conductivity of porous media, which is the average of fluid thermal conductivity and solid thermal conductivity; k_f and k_s are thermal conductivity of fluid and solid respectively; S_f and S_s are internal heat source terms of the fluid and the solid respectively.

The respiration of citrus has being during the period of store. According to the respiratory reaction equation, when 1mol hexoses is consumed, 6 mol (264 g) CO_2 would be produced along with 2817.3 kJ of the energy released. Thereby for every 1 mg CO_2 being produced, there shall be 10.676J of heat released simultaneously (Feng and Sun 1990). The respiratory heat can be calculated by measuring the respiratory strength of citrus, and it would be considered as the source term of the energy equation. The equation is as follow:

$$q_h = 2.7778 \times 10^{-4} \times (m_h \times 10.676) \quad (9)$$

In the equation, q_h is mass respiration heat, w/kg; m_h is respiration intensity, mg/(kg·h).

Boundary Conditions

The wet and cold air is blown into the storage from air inlets. So they were set as velocity inlet with the wind speed 5 m/s, the temperature 14℃, and relative humidity 90% (The mass fraction of water vapor is 0.008877, which can be calculated by Formulas 10-12).

$$R_H = \frac{p_w}{p_{sat}} \times 100\% \quad (10)$$

$$m_w = \frac{p_w V}{R_w T}, m_a = \frac{p_a V}{R_a T} \quad (11)$$

$$C_h = \frac{m_a}{m_a + m_w} \quad (12)$$

In the equation, R_H is relative humidity, %; p_{sat} is water vapor partial pressure in saturated moist air at standard atmospheric pressure (Yan et al. 2006), Pa; p_w, p_a are dry air partial pressure and water vapor partial pressure respectively at standard atmospheric pressure, Pa; m_a, m_w are quality of dry air and water vapor respectively at standard atmospheric pressure, kg; V is the volume of air, m^3; T is the temperature of air, K; R_a, R_w are gas constants of dry air and water vapor respectively, J/(kg·k), C_h is the mass fraction of water vapor in moist air, %.

The turbulence intensity parameters I and hydraulic diameter D_H were calculated by Equation 13 and Equation 14.

$$I = 0.16 R_e^{-1/8} \quad (13)$$

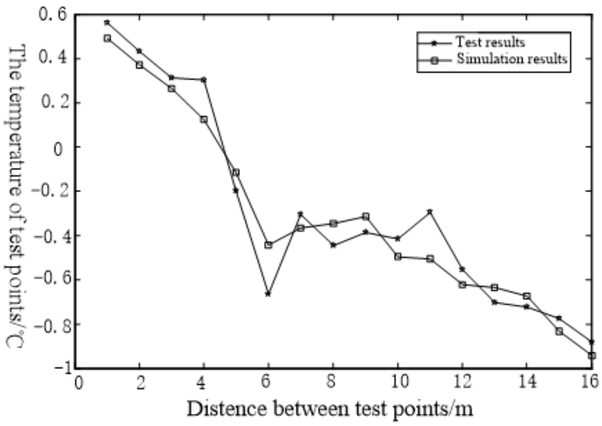
$$D_H = 4\frac{A}{\chi} \quad (14)$$

In the equation, A is the effective cross-sectional area, m^2; χ is wet perimeter, m.

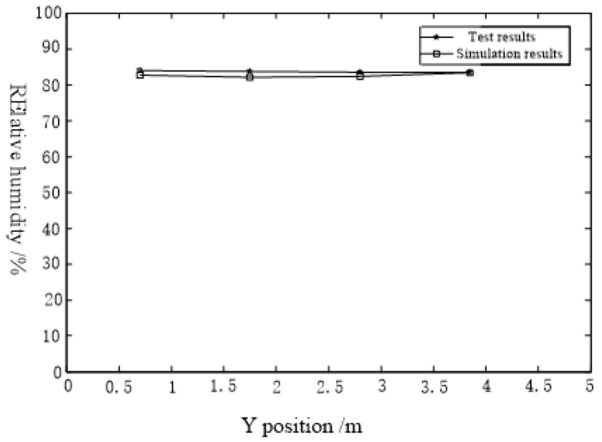
The exhaust vent was set as free outflow. The wall surface was set as the third boundary condition, and the thermal convection coefficient was 23 W/m^2·K, the temperature outside was 20℃, wall thickness was 0.26 m, the thermal conductivity was 0.93 W/m·K. The roof of the storage is usually heat insulation, so the influence of solar radiation is neglected. The roof was set as the third boundary condition, and the thermal convection coefficient was 23 W/m^2·K, roof thickness was 0.2 m. The ground was set as the second boundary condition, and the heat flux density was 3 W/m^2. Initially, the temperature of air and citrus were 20℃, relative humidity of air was 60% (the mass fraction of water vapor was 0.008657).

Model Verification

The temperature distribution test in references (Liu and Nan 2016) and the humidity distribution test in references (Serap and Thomas 2015) had been employed for verification. **Fig. 3(a)** is temperature distribution comparison between numerical calculation and test results in references (Liu and Nan 2016). It indicates that the two curves are basically the same and the maximum error is 0.24℃. **Fig. 3(b)** is humidity distribution comparison between numerical calculation and test results in references (Serap and Thomas 2015). It indicates that the simulated value is basically the same as the test value and the maximum error is less than 2%. The two comparison results verified the correctness of the CFD models.

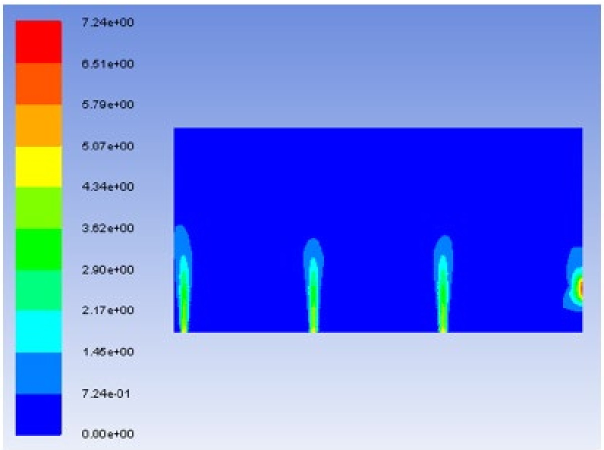


(a)

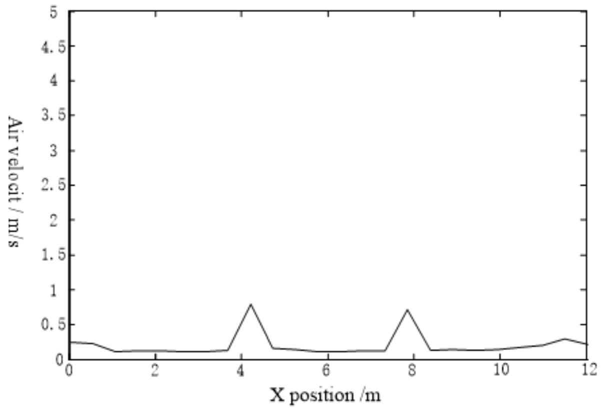


(b)

Fig. 3. (a) Validation of temperature distribution; (b) Validation of relative humidity distribution



(a)



(b)

Fig. 4. (a) Velocity contour of Y=3.5m section; (b) Air velocity curve of X section.

RESULTS AND DISCUSSION

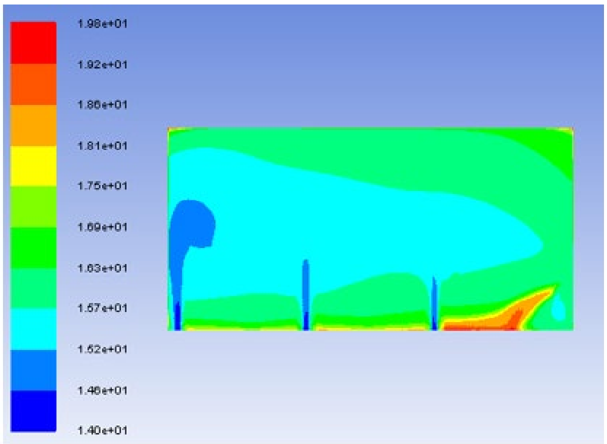
The air velocity, temperature and humidity distribution in the citrus ventilation storage under the action of wet curtain air conditioning system were obtained by numerical simulation. In order to get the distribution of air velocity, temperature and humidity in the storage, nine points in X section were selected with the coordinate of Y=0.5 m, 3.5 m, 6.5 m, Z=0.5 m, 2 m, 4 m, and the average value at these nine points are taken as result in this section. The results are shown in **Figs. 4-6**.

Results and Discussion of Airflow Field in the Storage

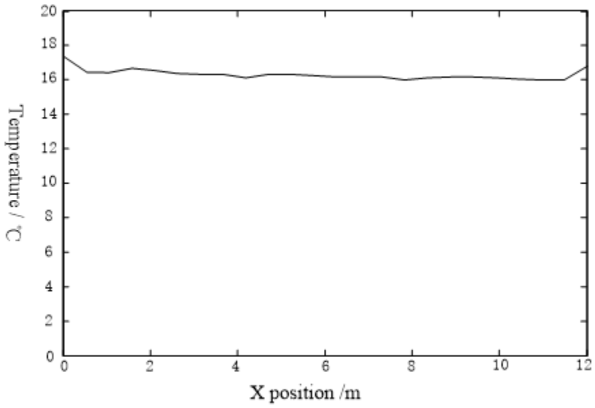
Fig. 4(a) is velocity contour of Y=3.5 m section in the storage. It indicates that the velocity of air flow at the inlet and exhaust vent is larger, about 5 m/s, while in other places, the velocity of air flow is smaller, about 0.2 m/s. **Fig. 4(b)** is the velocity curve of airflow in the X section. It indicates that the average air velocity of the section between stacking and stacking is larger, reaching 0.9 m/s, while at the stacking site, due to the influence of porous media, the average air velocity is smaller, below 0.2 m/s. So, the air velocity in the storage is small and well distributed, which meets the air velocity requirement of citrus storage.

Results and Discussion of Temperature Field in the Storage

Fig. 5(a) is temperature contour of Y=3.5 m section in the storage. It indicates that the nearer the exhaust vent in storage, the higher the temperature is. The temperature of left stacking area is about 15°C, and the temperature of right stacking area is higher, about 18°C. This is because the wet and cold air enters into the storage and flows out after convective heat transfer. **Fig. 5(b)** is the temperature curve in the X section. It indicates that the curve is smooth, about 15°C, near the exhaust vent (X = 0), the temperature rises slowly to 17°C. The simulation results show that under the cooling of wet curtain air conditioning system, the temperature in storage can be reduced from 20°C to 15.5°C, and the temperature in the storage changes slightly and distributes evenly.

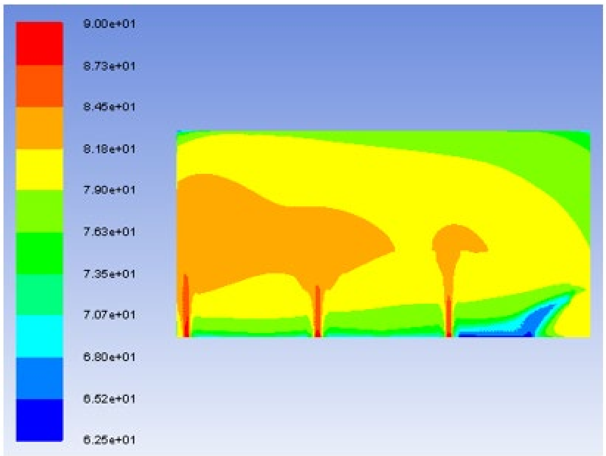


(a)

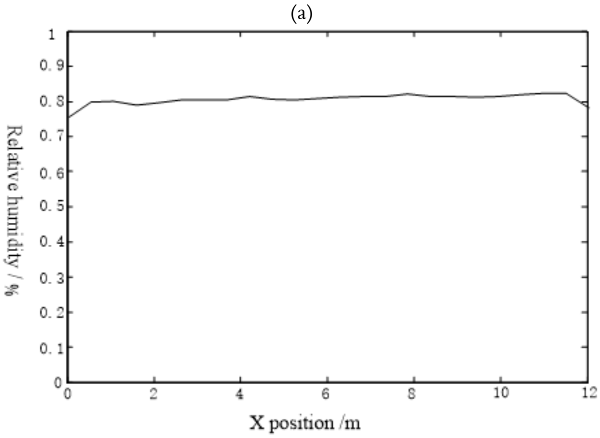


(b)

Fig. 5. (a) Temperature contour of Y=3.5 m section; (b) Temperature curve of X section



(a)



(b)

Fig. 6. (a) Relative humidity contour of Y=3.5 m section; (b) Relative humidity curve of X section

Results and Discussion of Humidity Field in the Storage

Fig. 6(a) is relative humidity contour of Y=3.5 m section in the storage. It indicates that the nearer the exhaust vent in storage, the lower the relative humidity is. The relative humidity of left stacking area is the highest, about 85%, and the relative humidity of right stacking area is lower, about 65% (the mass fraction of water vapor in the air in storage is basically the same). **Fig. 6(b)** is the relative humidity curve in the X section. It indicates that the relative humidity curve is smooth and rising slowly. This is because the nearer the exhaust vent, the higher the temperature is, the lower the relative humidity is when the mass fraction of water vapor in the air is the same. The simulation results show that the average relative humidity is about 82%, and the distribution is uniform.

CONCLUSIONS

In order to solve the problem of large temperature fluctuation in storage due to the high temperature outside, a wet curtain air conditioning system for citrus ventilation storage was proposed in this paper. The micro environment controlled by wet curtain air conditioning system in the storage were simulated by using the method of computational fluid dynamics. The results of the numerical analysis show that:

The average air velocity in the storage controlled by wet curtain air conditioning system is small and well distributed, about 0.2 m/s, which meets the air velocity requirement of citrus storage.

The wet curtain air conditioning system can reduce the temperature in the storage by 5℃ and increase relative humidity to 82% in the condition of outdoor ambient temperature 20℃, relative humidity 60%. The distribution of temperature, relative humidity in the storage is well distributed.

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