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NUMERICAL INVESTIGATION ON THE HOLLOW FIBER MEMBRANE-BASED EVAPORATIVE COOLING SYSTEM

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ABSTRACT

A mathematical model has been developed to theoretically investigate the heat and moisture transfer between water and air in a hollow fiber membrane-based evaporative cooling module. We validated the model by comparing its outlet air dry bulb temperature and relative humidity against experimental data acquired from literature sources. The numerical model showed good agreement with the experimental findings with maximum discrepancy of 7%. The validated model was employed to investigate the influences of the inlet air velocity, inlet air dry-bulb temperature, inlet air relative humidity and geometric parameters on the cooling effect of the evaporative cooling module. The simulation results have been employed to propose optimization suggestions for the design of the hollow fiber membrane-based evaporative cooling module.

Keywords: Evaporative cooling, Hollow fiber membrane, Heat and mass transfer, Numerical simulation

NONMENCLATURE

Abbreviations	
RH	Relative Humidity
Symbols	
T	temperature (°C)
ω	humidity ratio of the air (g/kg)
u	incoming air velocity (m/s)
Re	Reynolds number
ε	effectiveness

1. INTRODUCTION

In the past few decades, energy demand worldwide for buildings cooling has increased dramatically, which has raised concerns over resources depletion and global warming[1]. Instead of the current widely-used vapour compression system, the evaporative cooling system arouses great attentions among the researchers due to the fact that it is more environmentally friendly (use of the water as working fluids), simple in structure configuration, and less consumption in primary energy[2]. Evaporative cooling systems are generally divided into two types, namely, the direct evaporative cooling and the indirect evaporative cooling. The direct evaporative cooling system works under the following principle: the incoming hot and dry air gets direct contact with the circulating water, causing the evaporation of the water and the air temperature will be reduced accordingly. Consequently, the evaporated water vapour leads to the humidity increase of the outlet air.

Direct evaporative cooling systems usually involve the process of spraying water, which may form the drift of water droplets. In addition, the use of circulating water can also lead to the growth of bacteria and mold on the surface of the packing material, affecting the indoor air quality. In order to solve these problems, this paper intends to propose an evaporative cooling method incorporated with hollow fiber membranes. The selective permeation membrane technology allows the membrane module to isolate air from water, which selectively allows only water vapor to pass through, preventing the droplets from entraining bacteria into the air.

Zhang et al.[3]introduced the currently selective moisture permeable membrane materials, and analyzed the heat and mass transfer process of flat membrane total heat exchangers, plate-finned membrane heat exchangers, cross-triangular corrugated plate heat exchangers, and hollow fiber membrane modules. They took into account of the natural boundary conditions of the thermal-wet coupling on both sides of the membrane, the non-uniformity of fluid flow in the module, the random distribution of tube bundles and other practical operational factors on the heat and mass transfer. These studies provided a theoretical basis for the design of membrane modules and the optimization of membrane systems. Zhang[4] studied the evaporative cooling system using hollow fiber membranes by experimental and numerical methods. They used the fractal model to establish the relationship between the Sherwood number obtained by experiments and the Reynolds number. Chen et al.[2] proposed a hollow fiber membrane evaporative cooling system using a spindle configuration. In order to avoid the shielding effect of adjacent fibers on the airflow, the fibers in each bundle are made into a spindle shape to maximize the contact between the airflow and fibers. They studied the outlet air dry bulb temperature, wet-bulb efficiency, dew-point efficiency and cooling capacity under different inlet air dry bulb temperatures through simulation and experiments. Franco et al. [5] simulated direct evaporative coolers using porous paper materials. By comparing the cooling performance of five different porous materials, they found that plastic grid blocks provided the highest efficiency (82.6%) resulting in a lower unit water consumption rate.

The present study develops a computational model to theoretically investigate the influences of the inlet air velocity, inlet air dry-bulb temperature, inlet air relative humidity and geometric parameters on the cooling effect of the evaporative cooling module with a countercurrent arrangement for a single hollow fiber tube. The design of this evaporative cooling module can be optimized based on the simulation results.

2. THEORY

The hollow fiber membrane module exhibits a structure similar to a shell-and-tube heat exchanger in which the circulating water flows inside the tube and the air flows across the tube. The water vapor is transferred through the membrane material. As water evaporates between the pores of the hollow fiber membrane, it will absorb heat from the incoming dry hot air, causing the air temperature to drop. In the hollow fiber membrane module, assuming that the moist air is steady and incompressible, the general governing equations of the air stream can be given as follows:

$$\frac{\partial u_a}{\partial x}+\frac{\partial v_a}{\partial y}=0 \quad (1)$$

$$u_a\frac{\partial u_a}{\partial x}+v_a\frac{\partial u_a}{\partial y}=-\frac{1}{\rho_a}\frac{dp}{dx}+v_a\frac{\partial^2 u_a}{\partial y^2} \quad (2)$$

$$\frac{\partial}{\partial x}(u_aT_a)+\frac{\partial}{\partial y}(v_aT_a)=\alpha_a\frac{\partial^2 T_a}{\partial y^2} \quad (3)$$

$$u_a\frac{\partial c_a}{\partial x}+v_a\frac{\partial c_a}{\partial y}=D_a\frac{\partial^2 c_a}{\partial y^2} \quad (4)$$

The basic heat and mass transfer equation:

$$q=m_aC_{pa}(T_1-T_2)+m_a[\omega_1(h_{v1}-h_{wb})-\omega_2(h_{v2}-h_{wb})]\times 10^{-3} \quad (5)$$

$$m_e=m_a(\omega_2-\omega_1)\times 10^{-3} \quad (6)$$

where q is the flow of transferred heat (W);

m_e is the flow of evaporated water(kg/h);

C_{pa} is the specific heat of dry air (kJ/kg K);

T_1 is the dry bulb temperature of the incoming air (°C);

T_2 is the dry bulb temperature of the outgoing air (°C);

h_{v1} and h_{v2} are the enthalpy of saturated water vapour at the entrance and exit of the hollow fiber manifold (kJ/kg);

h_{wb} is the enthalpy of saturated water vapour at the wet bulb temperature of the incoming air (kJ/kg);

m_a is the mass flow rate of the incoming air (kg/h);

ω_1 is the humidity ratio of the incoming air(g/kg);

ω_2 is the humidity ratio of the outgoing air(g/kg).

Reynolds number can be calculated by:

$$Re=\frac{u\cdot d_h}{v} \quad (7)$$

where u is the incoming air velocity, m/s;

d_h is the hydraulic diameter of the hollow fiber manifold, m;

v is the viscosity of the incoming air, m^2/s.

The wet bulb effectiveness (ε_{wb}) is an important expression used to characterize the air saturation capacity of the hollow fiber membrane module. This is defined as the ratio between the actual temperature change of the air passing through the hollow fiber membrane module (T_1-T_2) and the maximum temperature change when the air were fully saturated (T_1 -T_{wb}):

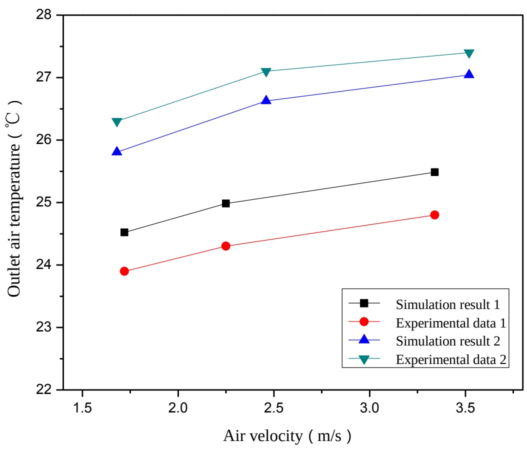
$$\varepsilon_{wb}=\frac{T_1-T_2}{T_1-T_{wb}} \quad (8)$$

3. RESULTS

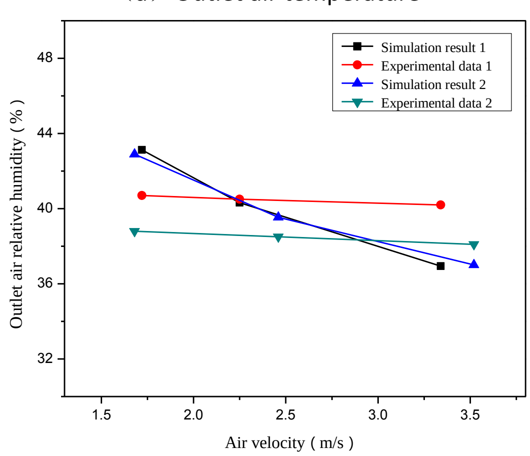
The validated computational model is employed to examine the influences of the inlet air velocity, inlet air dry-bulb temperature, inlet air relative humidity and geometric parameters on the cooling effect of the evaporative cooling module, where air is in a countercurrent through a single hollow fiber tube.

3.1 Validation

The mathematical model is validated with experimental data acquired from previous literature[6]. The experimental condition was replicated in the simulation. Fig. 1 compares the simulated outlet air temperature and relative humidity with the experimental data. It can be inferred from the figure that the numerical model is able to predict accurately with a maximum discrepancy about 2.7% and 7%, respectively.



（a） Outlet air temperature



（b） Outlet air relative humidity

Fig 1 Comparison between modeled results and experimental data.

3.2 Effect of inlet air temperature and relative humidity on outlet air temperature

Fig. 2 shows the variation of the outlet air temperature under various simulated conditions. It can be observed that the outlet air temperature is greatly affected by the relative humidity of the inlet air under constant inlet air temperature conditions. A higher inlet air relative humidity will result in a higher outlet air dry bulb temperature. The reason is that the inlet air with a low relative humidity has a lower partial pressure of water vapor, which results in a large difference between the saturated vapor pressure of the water surface in the hollow fiber tube and the partial pressure of the main air stream. Therefore, a larger driving force of the mass transfer can be achieved. On the other hand, the figure shows that under the same inlet air relative humidity, the outlet air dry bulb temperature exhibits a linear relationship with the inlet air dry bulb temperature. When the inlet air temperature increases by 10 °C, the outlet air temperature will only increase by 5.1-5.4 °C.

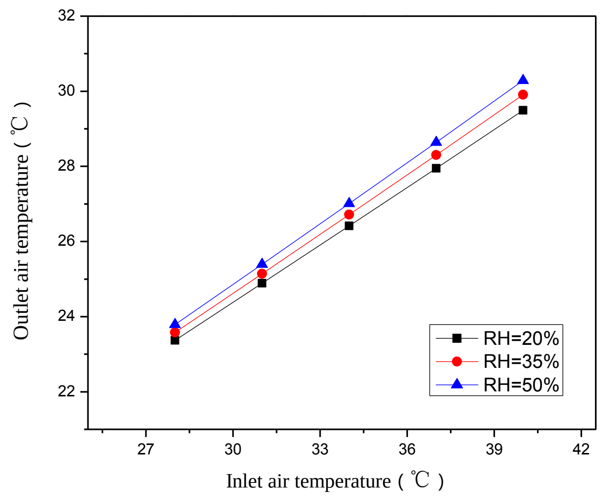
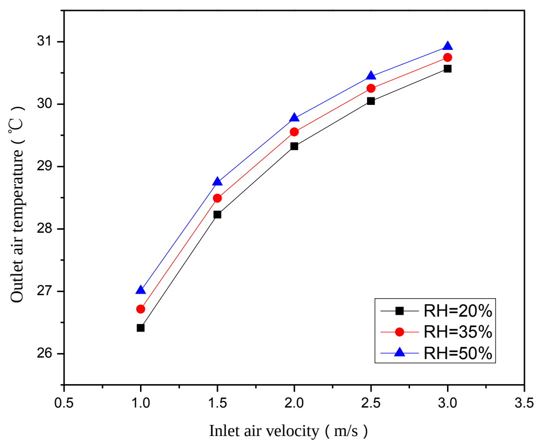


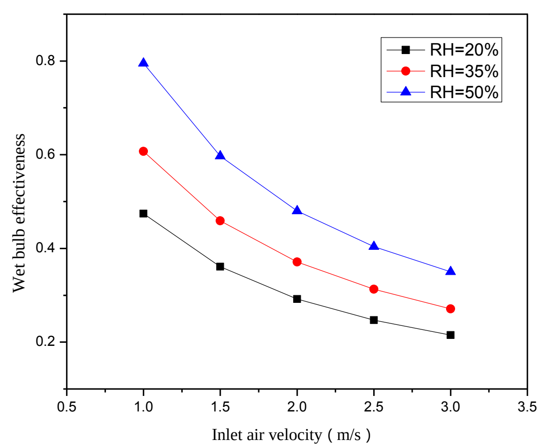
Fig 2 Effect of inlet air temperature and relative humidity on outlet air temperature.

3.3 Effect of inlet air velocity on outlet air temperature and wet bulb effectiveness

Fig. 3 illustrates the variations of outlet air temperature and wet bulb effectiveness with respect to different inlet air velocities. The overall trend from the figure shows that the air velocity is an important factor influencing the outlet air temperature and wet bulb effectiveness. As can be seen from Fig. 3(a), the larger the inlet air velocity, the higher the outlet air dry bulb temperature, while keeping other simulation parameters constant. The reason is that by increasing the air velocity, the contact time between the air and the hollow fiber is reduced. A similar variation trend can be observed from Fig. 3(b). As the air velocity increases, the wet bulb effectiveness of the hollow fiber membrane module decreases, which is also caused by a decrease in contact time between the two streams. Therefore, in practical applications, on the basis of being able to ensure sufficient air volume, in order to achieve a higher cooling effectiveness, the inlet air velocity should not be set too high.



（a）Outlet air temperature



（b）Wet bulb effectiveness

Fig 3 Effect of inlet air velocity on outlet air temperature and wet bulb effectiveness.

3.4 Effect of length of hollow fiber tube on outlet air temperature

The variation of the outlet air temperature with the length of the hollow fiber tube is shown in Fig. 4. It can be seen from the figure that as the length of the hollow fiber tube increases, the temperature of the outlet air gradually decreases. It can be attributed to the fact that the contact time and contact area of the air and water flow increase by increasing the length of the hollow fiber tube. The heat and mass transfer process is carried out more fully, thereby enhancing the cooling effect. It is worth mentioning that blindly increasing the length of the hollow fiber tube does not always reduce the temperature of the outlet air. It can be seen from the trend in the figure that when the length of the fiber tube increases to a certain extent, the outlet air temperature tends to a certain constant value. Therefore, in the geometric design of the hollow fiber membrane module, it is necessary to comprehensively consider the cooling effect and economic factors, and select an optimal hollow fiber tube length for different working conditions .

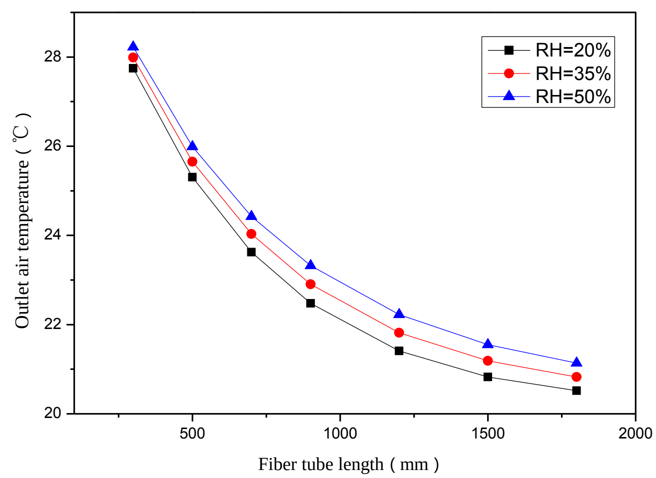


Fig 4 Effect of length of hollow fiber tube on outlet air temperature.

4. CONCLUSIONS

A mathematical model has been developed to theoretically investigate the heat and moisture transfer between water and air in a hollow fiber membrane-based evaporative cooling module. The validated model was employed to investigate the influences of the inlet air velocity, inlet air dry-bulb temperature, inlet air relative humidity and geometric parameters on the cooling effect of the evaporative cooling module. The simulation results have been used to propose optimization suggestions for the design of the hollow fiber membrane-based evaporative cooling module.

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