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Evaporation performance of moisture-conducting fiber-type evaporative cooler#

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ABSTRACT

Moisture-conducting fibers have the potential to be used as an evaporative medium in evaporative cooling systems. The performance of indirect evaporative coolers depends on the evaporation of the water film in the wet channel, while traditional core materials face issues such as poor wetting (low wetting rate, uneven water film, etc.). This study experimentally investigated the evaporation performance of a novel wet surface material (moisture-conducting fibers) when applied to an indirect evaporative cooler, constructing a single-channel evaporative cooling test bench equipped with a micro-pressure water distribution system. Under different inlet air temperatures (25°C–35°C), relative humidity (40%–80%), and air velocity (2 m/s–4 m/s) conditions, the surface dynamic wetting characteristics, including changes in moisture content and evaporation rate, were investigated. A sensitivity analysis was conducted using Pearson correlation analysis to assess the importance of the three influencing factors. The effects of various factors on the performance of the evaporative cooler were analyzed, providing guidance for the development, design, and efficient operation of moisture-conducting fiber-type evaporative coolers.

Keywords: Moisture-conducting fibers; Evaporative cooling; Material properties; Dynamic wetting; Evaporation rate

1. INTRODUCTION

Under the dual challenges of continuous growth of global energy demand and climate change, the demand for energy-efficient cooling technologies in the building and industrial sectors is becoming more and more urgent. Indirect evaporative cooling technology has become a popular research direction to partially replace the traditional compression refrigeration system due to its natural energy-saving feature of utilizing the latent heat of water evaporation to achieve cooling.

Since the indirect evaporative cooler (IEC) relies on the evaporation of water in the wet channel to absorb heat to cool the primary air in the adjacent dry channel, the hydrophilicity of the wet channel of the cooler and its evaporation rate have important impact on the cooling performance of the device. In recent years, there is a large amount of related research reporting solutions to enhance the hydrophilicity and evaporation of the wet surfaces mainly from the material perspectives. Bruno et al.[1] constructed a flat-plate staggered-flow heat and mass exchanger, using a special medium to improve the hydrophilicity of the wet channel, while the water can not permeate into the dry channel. Wang et al.[2] further used numerical simulations to reveal the porous structure of moisture-conducting fibers contributes to the evaporation rate. Xu P et al.[3] mentioned that the thickness of the COOLMAX fiber layer is very thin, which can effectively reduce the thermal resistance and increase the heat transfer rate of the primary air. In the study of material moisture transfer performance, most of the studies conduct a series of comparative tests on the wicking height test, diffusion capacity, evaporation capacity, water retention, durability and so on among various fiber materials (including different types of textiles[4], kraft paper[5], synthetic fibers[6], plant fibers[7]) in order to obtain the optimal one. The selected materials with optimal performance including fiber fabrics (tight straight weave), polypropylene geotextiles[8], cellulose, polyester and COOLMAX fabrics[9].

As reported, current studies focus on the wet surface material characteristics evaluation under a standard test environment or limited operating environments. The dynamic moisture transport capacity of the wetted material and the evaporation rate under a wide range of operating conditions are seldom reported, including the ambient temperature, humidity and air velocity. To explore the unique performance characteristics of the evaporative cooler brought by the novel wet surface material, and optimize the operating parameters, a comprehensive parameter analysis and sensitivity analysis is essential.

This paper takes the moisture-conducting fiber-type IEC as the research object. Firstly, a single-channel

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evaporative cooling experimental bench is constructed to study the dynamic evaporation performance of the moisture-conducting fiber composite plate under different air temperature, relative humidity and air velocity. Secondly, a sensitivity analysis was carried out to determine the rank of significance of all factors.

2. EXPERIMENT

2.1 Material properties

IECs are thermal mass exchangers consisting of multiple wet and dry channel pairs in a stacked configuration. IEC systems typically consist of alternating wet and dry channels, with the dry channels conveying the air to be cooled and the wet channels absorbing heat by evaporation through a water film, with both exchanging sensible heat through the conductive heat transfer spacer. Fig. 1 shows a schematic diagram of a single unit channel counter-current IEC. The high porosity COOLMAX moisture-conducting fiber and polypropylene composite plate is used as the wall surface of the wet channel. Water is uniformly transported through capillary action to enhance the wettability of the evaporation interface. Table 1 shows the specific thermophysical information of the selected COOLMAX moisture-conducting fibers and polypropylene composite panels.

Table 1 Physical properties of moisture-conducting fiber polypropylene composite panels

Material Properties	Fiber composition	Wicking height	Horizontal wet diffusion velocity
Composite Sheet	63%Polyester 37% polypropylene	24cm	2.87 cm^2/s
	Porosity	**Thermal conductivity**	**Moisture content**
	79%	0.5 W/(m·K)	380g/m^2

2.2 Evaporation test bench

The evaporative cooler experimental bench is constructed by transparent acrylic shell wrapped by a layer of insulation cotton. There are 20 parallel slit-type grooves on two opposite sides of the shell to allow the tested plates to be inserted and extracted. The heat and mass exchanger consists of 20 composite plates (Coolmax fiber + polypropylene) extractable for weighting during the experiment. The other components in the test rig include solid cone nozzle, water distribution system, fans, water baffle and measuring instruments. The schematic diagram and physical diagram are shown in Figure 2. A nozzle is installed above the heat and mass exchanger and placed in the center for

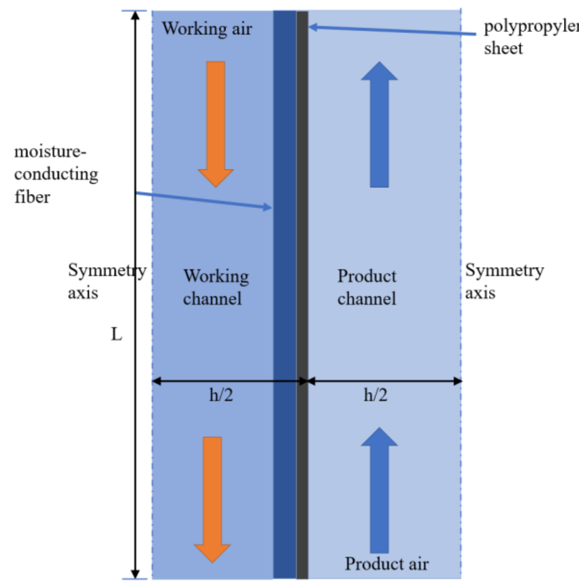

Fig. 1 Schematic of a single-unit channel of an indirect evaporative cooler

evenly water distribution. The experimental bench is located in the environmental chamber with controllable air temperature and humidity. Table 2 lists the dimensional specifications of the experimental bench as well as the main equipment list. The composite plate is made by attaching a layer of moisture-conducting fiber to a 3mm-thick polypropylene board by thermally-conductive glue and hot-melt pressure-sensitive adhesive. A fan is positioned at the top of the unit and the air is extracted and passed through the unit from bottom to top. The air velocity is measured with a hot-film anemometer in the center of the shell cross-section. The model of the anemometer is testo405-V1, with a measuring range of 0~10m/s and an accuracy of ±(0.3m/s+5% of the measured value). The temperature was measured by a K-type thermocouple with a range of -200°C to 260°C and an accuracy of ±0.5°C. A multifactorial approach was adopted to study the effects of air temperature, relative humidity, and air velocity on the evaporative performance of wet surface.

By setting different inlet air temperature, humidity and air velocity, as listed in Table 3, the dynamic wetting characteristics of the wet channel can be obtained, including the fiber moisture content and evaporation rate. Between them, the evaporation rate can be obtained by weighting the sample plate with precision electronic scale over a continuous period of time. The weighing accuracy of the precision electronic scale is 0.01g. The water content of the wet material is the ratio of the weight of the water in the material to the total weight of the board. Due to measurement errors and fluctuations in air temperature and humidity, the data obtained has an error margin of 5%.

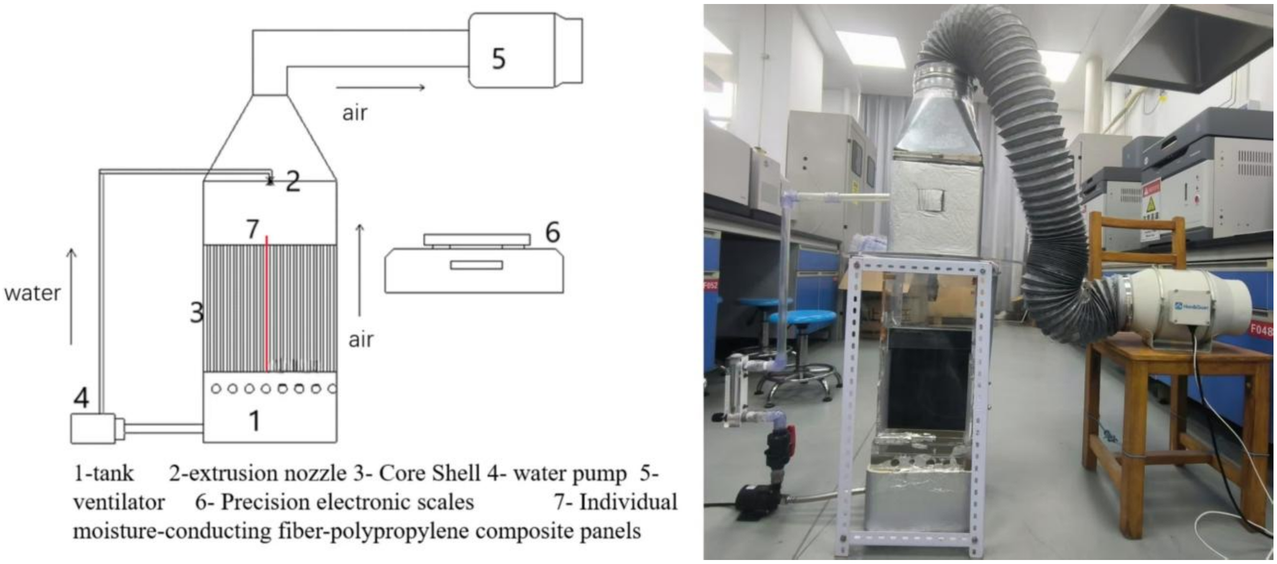

Fig. 2 Schematic diagram and photo of evaporation test bench

Table 2 Main component and materials of the test bench

Serial number	Component	Specification or material
1	Water storage	Acrylic material (thickness: 10mm)
2	Extrusion nozzle	Solid Cone Nozzles
3	Core body	Moisture-conducting fiber + pp board（240mm×200mm×1.5mm）
4	Water pump	Century DC55E-2160VR DC booster submersible pump (flow: 40L/min head: 16m)
5	Ventilator	HF-150P Pilot Flow Pressurized Duct Fans
6	Precision electronic scales	Weighing accuracy 0.01g

Table 3 Parameter settings in the experiment

Parameter	Temperature (°C)	Relative humidity (%)	Air velocity (m/s)
Temperature (°C)	[25，30，35]	40	2
Relative humidity (%)	30	[40，60，80]	3
Air velocity (m/s)	35	80	[2，3，4]

3. RESULTS AND DISCUSSION

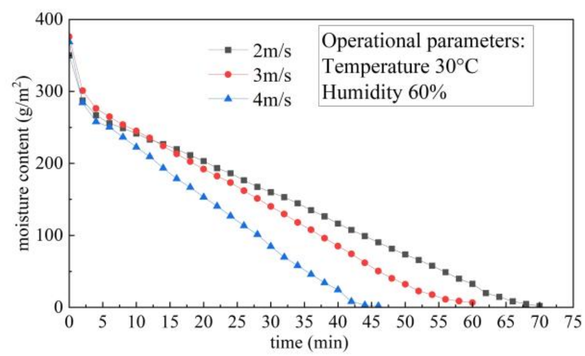

Fig. 3 Moisture content variation of wet surface material with time

Figure 3 shows the moisture content variation of the wet surface material over time under temperature of 25°C, relative humidity of 60%, and air velocity of 2 m/s, 3 m/s, and 4 m/s flowing through the surface of the board. The results show that the moisture content decreases rapidly from 370 g/m^2 to about 270 g/m^2 during the first 4 minutes when the water content of the board has reached saturation. The rapid water loss is resulted from direct outflow of the saturated water due to gravity. After the excess water flows out, the water content of the board surface decreases at a fixed rate due to evaporation, and the rate of evaporation is the slope of the water content decrease. After that, when the water is reduced to a certain level, the rate of reduction of water content begins to slow down until the water in the board is completely evaporated. It can be concluded that the water in the core material decreases at a constant rate of evaporation after stabilization.

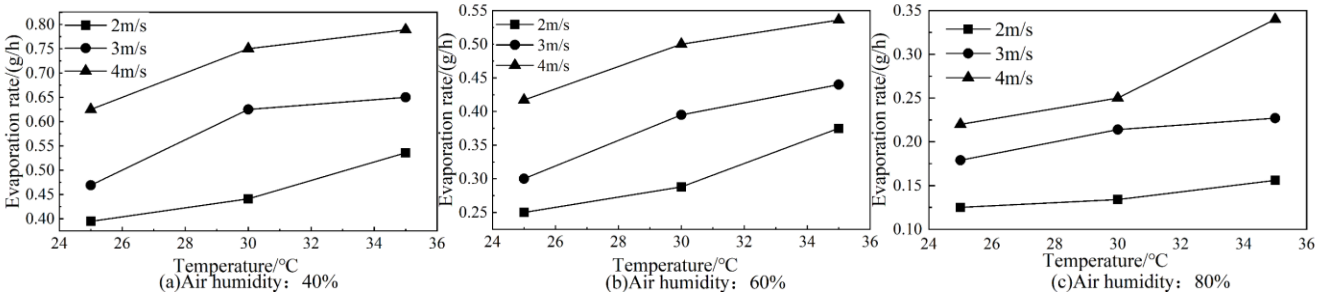

Fig. 4 Evaporation rate under different operating conditions

The evaporation process on the wet surface can be divided into three stages, and the physical properties of each stage are as follows:

(1) Initial stage: the fiber surface water film is complete and there is excess flowing water, moisture-conducting fibers to absorb excess water, excess water with the natural loss of gravity, resulting in a rapid decrease in moisture content of moisture-conducting fibers.

(2) Stabilization stage: the fiber surface water film is complete, wet diffusion and evaporation coupling, capillary water transfer rate and evaporation rate to reach a dynamic equilibrium, the water supply is sufficient, the evaporation rate remains stable. Evaporation rate remains stable.

(3) Drying stage: uneven distribution of moisture in the fiber pores, the local area began to appear insufficient water supply, the effective evaporation area is sharply reduced, the evaporation rate declined precipitously until the moisture in the moisture-conducting fiber evaporation is complete.

The evaporation rate of wet material under different air temperature, relative humidity and air velocity was obtained after three repetitive experiment as shown in Figure 4. The evaporation rate was calculated according to the standard in the relevant textile industry with a material surface area of 10 cm^2. Figure 4 (a) shows that under air humidity of 40% and a temperature of 30°C, the evaporation rate of the fiber material increases from 0.441 g/h to 0.75 g/h when air velocity increases from 2 m/s to 4 m/s flowing through the boards. When temperature increases from 25°C to 35°C under air velocity of 3 m/s, the evaporation rate of the fiber material increases from 0.469 g/h to 0.65 g/h. The evaporation rate of the composite fiber material decreases as the relative humidity increases. The evaporation rate of the fiber material decreases from 0.625 g/h to 0.214 g/h as air relative humidity increases from 40% to 80% under temperature of 30°C and air velocity of 3 m/s.

Table 3 Pearson correlation analysis of evaporation rate by three different factors: temperature, humidity and wind speed

Influencing factors	Statistical measure	number
Air velocity flowing between the plates	Correlation coefficient	0.425*
	p-value	0.027
	sample size	27
Air humidity	correlation coefficient	-0.846**
	p-value	0.005
	sample size	27
Temperature	correlation coefficient	0.263*
	p-value	0.014
	sample size	27

Based on the tested results, a sensitivity analysis was carried out to determine the rank of significance among the three influential factors by Pearson correlation analysis. From Table 3, the correlation coefficient between evaporation rate and wind speed is 0.425 and shows significance at 0.05 level, thus indicating a significant positive correlation between evaporation rate and air velocity. The correlation coefficient between evaporation rate and humidity is -0.846 and shows significance at 0.01 level, thus indicating a significant negative correlation between evaporation rate and humidity. The correlation coefficient value between evaporation rate and temperature is 0.263 and shows significance at 0.05 level, thus indicating a significant positive correlation between evaporation rate and humidity. In sum, in terms of the evaporation rate, the significance rank is relative humidity > air velocity > air temperature.

4. CONCLUSIONS

In this paper, the evaporation performance of moisture-conducting fiber-type indirect evaporative cooler under different operating parameters is systematically investigated by experiment. The specific conclusions are as follows:

(1) The evaporation process of moisture on the surface of moisture-conducting fibers can be divided into three stages: the initial stage, the excess water is lost naturally with gravity, and the moisture content of moisture-conducting fibers decreases rapidly; the stabilization stage, the water film on the surface of the fibers is complete, and the rate of capillary water transport and the rate of evaporation reaches a dynamic equilibrium and the rate of evaporation is kept stable; and the drying stage: there is insufficient supply of water in the pores of the fibers, and the rate of evaporation decreases off a cliff.

(2) Changes in air intake parameters affect the heat and moisture transfer characteristics of fibers. By increasing the air temperature, reducing the relative humidity, and increasing the air flow velocity, the evaporative cooling efficiency of moisture is greatly improved.

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