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Performance Enhancement of Indirect Evaporative Cooler Treated by Hydrophobic Coating under Dehumidifying Conditions

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ABSTRACT

Potential energy savings of the central air-conditioning systems can be induced by the indirect evaporative cooler (IEC) through energy recovery from exhaust air to the fresh air. However, the condensation in the dry channels can pose significant influences on cooling performance, especially for the IEC used in hot and humid areas. In this paper, a novel IEC heat exchanger was fabricated by depositing the hydrophobic nanoparticles on the surfaces of primary air channels, and experiments were conducted to compare its performance with the traditional uncoated IEC. The droplet behaviors on the plate surfaces with and without hydrophobic coating were compared under both dynamic and steady states. Results show that, the hydrophobic coating produces a higher contact angle for the plate surface, causing a reduced size of falling-off droplets and frequent droplets removal. The dropwise condensation on the hydrophobic surface has less deterioration effect on the convective heat transfer of primary air flowing over the heat exchange plates. Under dehumidifying conditions, the hydrophobic coating treatment on the primary air channel surfaces of the IEC could enhance the heat and mass transfer and improve the energy-saving rate by 8.5-17.2%, promising a great application potential for upgrading the evaporative cooling technologies in humid regions.

Keywords: Indirect evaporative cooler, Condensation flow, Heat transfer, Hydrophobic surface

NONMENCLATURE

Abbreviations	
AC	Air-conditioning
IEC	Indirect evaporative cooler
COP	Coefficient of performance
Symbols	
η_{wb}	Wet-bulb effectiveness
η_{ω}	*Dehumidification effectiveness*
$E_{recovery}$	Energy recovery rate, kW/kg
f_d	Droplet falling frequency, Hz
D_d	Droplet departure diameter, mm
M_d	Falling droplet mass, mg
t_p	Primary air temperature, °C
ω_p	Primary air humidity ratio, kg/kg
RH_p	Primary air relative humidity, %
c_{pa}	Specific heat of moist air, J/(kg·°C)
h_{fg}	latent heat of water vapor, J/kg

1. INTRODUCTION

As a passive cooling solution, the indirect evaporative cooler (IEC) makes use of the water evaporation to cool the air by running only a small pump and fans [1]. In hot and humid areas, the IEC integrated with the central AC system can pre-handle the fresh air by recovering the cooling capacity of exhaust air. Compared with current commonly adopted exhaust air energy recovery technologies, the IEC owns advantages such as low cost, energy-efficient, and free from cross-contamination [2].

There are two distinct passages in the IEC, respectively designed for the primary air to be cooled and the secondary air that vaporizes the spraying water. Many research studies have focused on the surface wettability of secondary air channels in the IEC to improve the heat exchange efficiency that is dominated by the water film evaporation. Zhao et al. [3] compared the thermal conductivity and water-retaining capacity of different heat and mass exchanging materials of IEC, among which the heat transfer rate ranges between 392-399 W/m^2. Guilizzoni et al. [4] evaluated the static contact angle and water retention of the IEC heat exchanger with two different surface coatings. According to the experimental results, the novel hydrophilic coating could improve the wet-bulb effectiveness of IEC by up to 10% than the conventional epoxy coating. Wang [5] studied the effects of water-retention capacity on the cooling performance of IEC by measuring the receding contact angles of different aluminum surfaces. Results showed that the high wicking surfaces with reduced dynamic contact angles could dramatically increase the cooling effectiveness of the IEC, especially at a lower water flow rate. Xu et al. [6] investigated the properties of seven different wet channel surface mediums in an IEC. It is found that the wicking ability, diffusion ability, and evaporation ability of the textile fabrics were more than 171%, 298%, 77% respectively higher than the Kraft paper. Joohyun and Dae-Young [7] fabricated and tested a novel regenerative IEC with hydrophilic coating on the internal surface of wet channels. Due to the improved surface wettability, the evenly distributed water film and higher cooling effectiveness can be obtained at a minimized water flow rate.

In hot and humid areas, the IEC operates under partial or total condensation states for about half of the annual operation time, and the achieved latent cooling accounts for 41.3% of annual total cooling capacity [8, 9]. Although the dehumidifying process contributes to the total heat transfer rate of the IEC, it degrades the sensible efficiency due to the condensate retention on the heat exchanger plates [10]. The aluminum sheets widely used for fabricating the IEC heat exchangers are naturally hydrophilic [11], which is not favorable for the condensate water drainage and therefore increases the heat transfer resistances. However, existing research on the surface modification of IEC has only focused on the surface wettability of wet channels for achieving higher evaporation rate, the heat transfer enhancement of IEC in terms of the dry channels for condensate water drainage was rarely addressed.

In view of the above, this paper investigated the enhanced heat transfer performance of an IEC with hydrophobic coating for fresh air pre-handling through experimental study. The influence of operating conditions on the sensible cooling and dehumidifying performance subject to the surface properties have been thoroughly analyzed. The results of this study contribute to the IEC upgrading with more innovative surface treatments for offering better condensate drainage and improving the energy efficiency of AC systems.

2. EXPERIMENTAL SETUP

2.1 Fabrication of IEC with hydrophobic coating

Comparative experiments were conducted on both the conventional plate-type aluminum IEC and the one treated with silicon nanomaterials. After cleaning the IEC heat exchanger, the blocking materials were applied to the secondary air inlet and outlet to prevent the wet channel surfaces from contacting the coating. And the hydrophobicity of primary air channels was rendered by immersing the heat exchanger in an aqueous solution of nanoparticles for 30 min to form a molecular structure consisting of $(R_2SiO)_x$ on the plate surfaces. To measure the static and dynamic contact angles of the aluminum heat exchange plate, a contact angle meter (JCY20-13) was used. The contact angles of un-coated and hydrophobic sample plates were compared in Fig. 1.

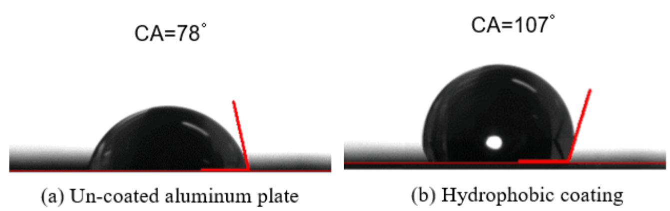


Fig. 1 Contact angles of plate surfaces

For the static contact angle measured on the horizontal sample plate, a remarkable increase from 78° to 106° was observed on the plate surface after performing the hydrophobic coating. It is indicating that surfaces with a high contact angle generally have low surface energy and low interfacial tension. As a result, the hydrophobic surface has high drainage capabilities to remove the condensate water droplets to slide off from the heat exchanger plate more promptly.

2.2 IEC test rig

Visual experiments were carried out on both the IEC heat exchangers with and without hydrophobic coating to investigate the effect of surface modification on the heat transfer under dehumidifying conditions. Fig. 2 shows the schematic diagram of a cross-flow IEC test rig. After the primary air being adjusted to the required temperature and relative humidity conditions, it was provided to the heat exchanger for cooling and dehumidifying. To capture the dynamic condensation behaviors, a high-speed CCD camera (Phantom, M-110 with Nikon, AF Micro Nikkor 60 mm lens) was placed in front of the chamber. The falling frequency of the droplets detached from the plate surface was measured using a stopwatch. Besides, the primary airflow rate, temperature, and relative humidity at inlet and outlet were measured by the sensors listed in Table 1. The data collection interval of the sensors was set at 2s.

Table 1 Specification of different measuring instruments

Parameters	Device	Range	Accuracy
Dry bulb temperature	Pt1000 Model: EE160	-15 - 60 °C	±0.3 °C
Relative humidity	Pt1000 Model: EE160	10-95% RH	±2.5% RH
Air velocity	Hot film anemometer Model: EE65	0-10 m/s	±0.2 m/s
Data logger	GRAPHTEC GL820, 12 channels		

2.3 Performance indicators

To evaluate the cooling and dehumidifying performance of the IEC with coated and uncoated plate surfaces, two performance indexes, namely the wet-bulb efficiency (η_{wb}) and dehumidification efficiency were proposed. The wet-bulb effectiveness (η_{ω}) evaluates the sensible cooling performance of IEC by describing the extent of the approach of outlet air temperature to the wet-bulb temperature of inlet secondary air ($t_{wb,s}$). The dehumidification efficiency is a ratio of the removed moisture to the moisture difference between the inlet primary air and saturated air at the wet-bulb temperature of inlet secondary air ($\omega_{t_{wb}}$). The energy recovery rate ($E_{recovery}$, kW/kg) represents the energy-saving per unit time of an IEC unit in handling the fresh air.

$$\eta_{wb} = \frac{t_{p,in} - t_{p,out}}{t_{p,in} - t_{wb,s}} \quad (1)$$

$$\eta_{\omega} = \frac{\omega_{p,in} - \omega_{p,out}}{\omega_{p,in} - \omega_{t_{wb}}} \quad (2)$$

$$E_{recovery} \frac{\eta_{wb} c_{pa}(t_{p,in} - t_{wb,s}) + \eta_{\omega} h_{fg}(\omega_{p,in} - \omega_{t_{wb}})}{COP} \quad (3)$$

The falling droplet mass and falling frequency are the two key indicators to evaluate the surface properties for condensate formation and drainage. In this study, the observed droplet departure diameter (D_d) during the experiments were processed by an image processing method [10]. Meanwhile, the real-time droplet falling frequency (f_d) for the steady-state conditions of IEC was measured using a stopwatch.

2.4 Uncertainty analysis

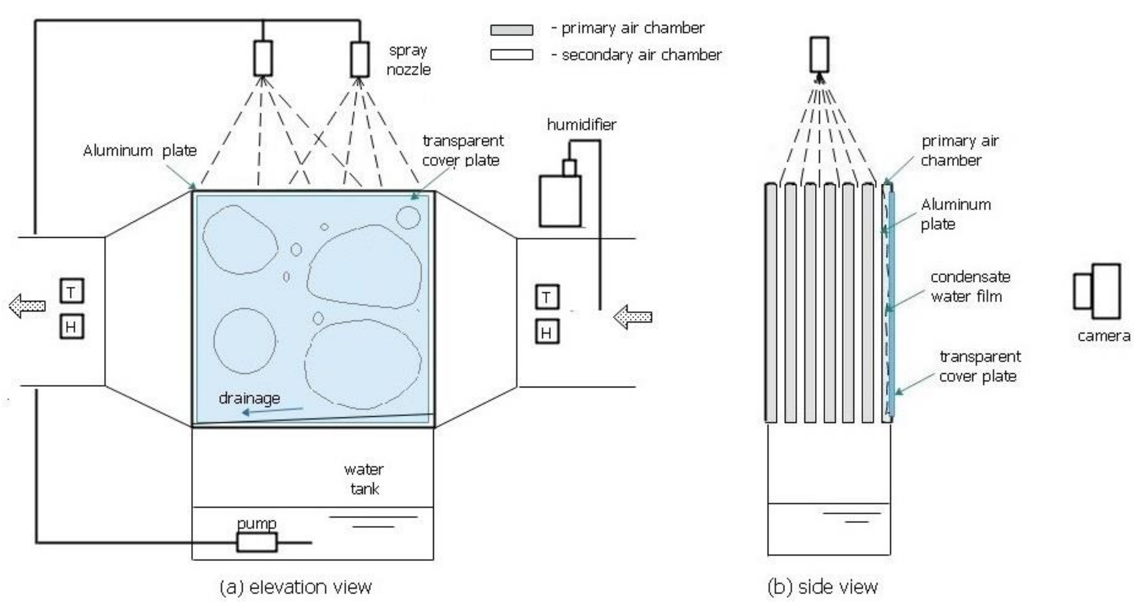


Fig 2 Schematic of experimental apparatus.

The uncertainty analysis results of the performance indicators under steady-state conditions are listed in Table 2. As the experimental conditions and apparatus are unchanged for controlled experiments on both the IECs with and without hydrophobic coating, the relatively high uncertainties of the test variables under dynamic conditions could not invalidate the performance comparison results.

Table 2 Uncertainty analysis results

Parameter	Nominal value		Uncertainty	
	Coated	Uncoated	Coated	Uncoated
$t_{p,out}$	23.2	23.6	±1.4%	±1.7%
$RH_{p,out}$	17.0	17.6	±2.8%	±3.1%
M_d	38.7	57.2	±13.8%	±16.0%
f_d	0.40	0.24	±16.4%	±19.0%
η_{wb}	0.63	0.57	±4.6%	±5.1%
η_{ω}	0.57	0.48	±5.9%	±7.5%
$E_{recovery}$	7.79	6.89	±8.9%	±10.7%

3. CONDENSATION MODE

The condensate evolution on the bare and hydrophobic plate surfaces and its effects on the dynamic operating performance of the IEC was studied through experimental analysis of a case study ($t_p = 30℃, RH_p = 82\%, u_p = 2m/s, t_s = 24℃, RH_s = 65\%, u_s = 2m/s$).

3.1 Dynamic performance

Fig. 3 presents the outlet primary air temperature and humidity variations after starting up the systems for coated and uncoated IECs.

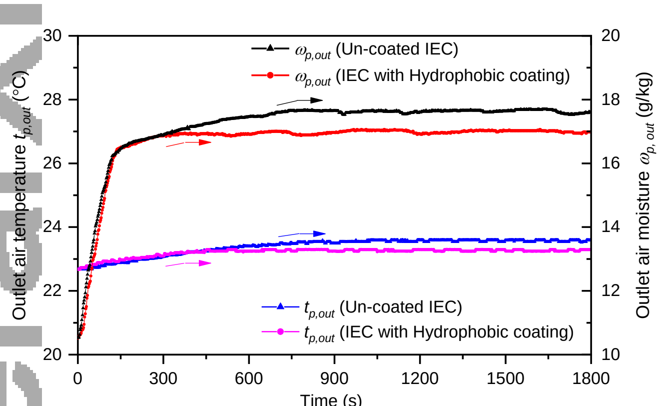


Fig. 3 Outlet air variation process of coated and un-coated IEC

The two IECs differed in the time durations for condensation evolution as well as the steady-state outlet air statuses. For the IEC with hydrophobic coating, the steady state with stable dropwise condensation can be reached shortly after 400s. Compared to the un-coated IEC, the heat transfer degradation resulting from the condensation evolution is slighter on the coated surfaces, and the outlet primary air can be processed to a lower temperature of 23.2ºC with less moisture content of 17.0 g/kg.

3.2 Condensation growth

Four stages from initial nucleation (I), growth (II), coalescence (III) and eventual departure (IV) were identified for the condensation growth on each surface. The different condensation mechanisms on the plate surfaces of IEC with and without hydrophobic coating were demonstrated in Fig. 4.

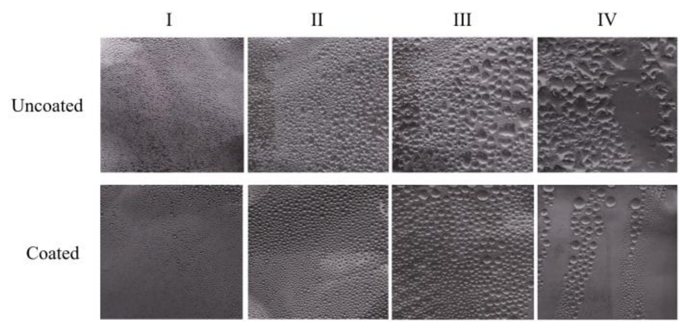


Fig. 4 Images of condensation on the plate surfaces of coated and uncoated IEC

After the steady state is attained for the system's operation, the average falling droplet mass and frequency on the two kinds of plate surfaces of IEC were collected. The observed departure diameter of droplets adhered to the plate surfaces is 2-3 mm for the hydrophobic one and 4-6 mm for the bare-aluminum one, respectively. As the small droplets transfer heat more efficiently than the large ones, the hydrophobic surface of IEC can provide enhanced condensate heat transfer performance by enabling the droplet departure to happen at a smaller size. Furthermore, the higher falling frequency on the hydrophobic surface (0.40 Hz) than on the uncoated surface (0.24 Hz) indicates more frequent periodical surface refreshment for contacting with air directly and allowing new drops to grow. The average falling droplet mass derived from experimental results are 38.7 mg for coated surface and 58.2 mg for uncoated plates, which are conformed to the calculated values based on theoretical maximum diameters.

4. PERFORMANCE ENHANCEMENT

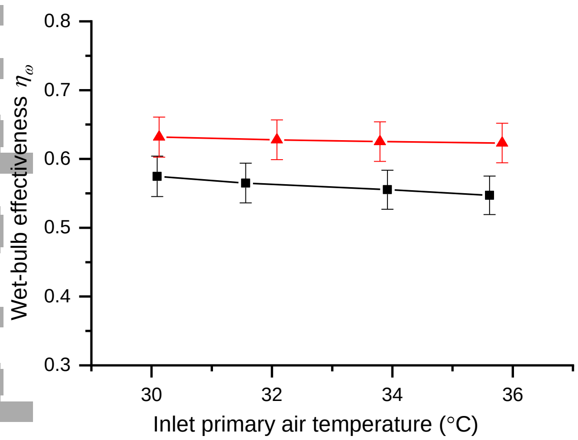
Several test conditions have been conducted to evaluate the performance of coated and un-coated heat exchangers for the IEC under different dehumidifying conditions, as listed in Table 3. The steady state is defined as the outlet air temperature and relative humidity variations are within 0.1^o C and 2% for 5 min.

Table 3 Settings of controllable parameters

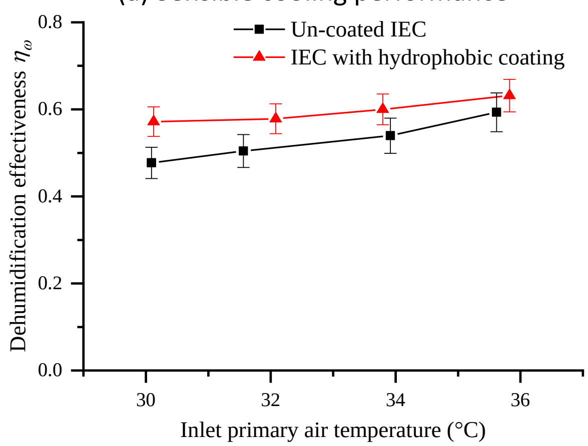
Parameters	$t_{p,in}$ (^{o} C)	$RH_{p,in}$ (%)
$t_{p,in}$	[30, 32, 34, 36]	80
$RH_{p,in}$	30	[60, 70, 80, 90]

4.1 Sensible cooling and dehumidifying performance

As the degree of sub-cooling increases with the rising inlet air temperature, a greater mass flow of condensate occurred on the plate surfaces, resulting in a decrease of η_{wb} and an increase of η_ω for both of the two IECs.



(a) Sensible cooling performance



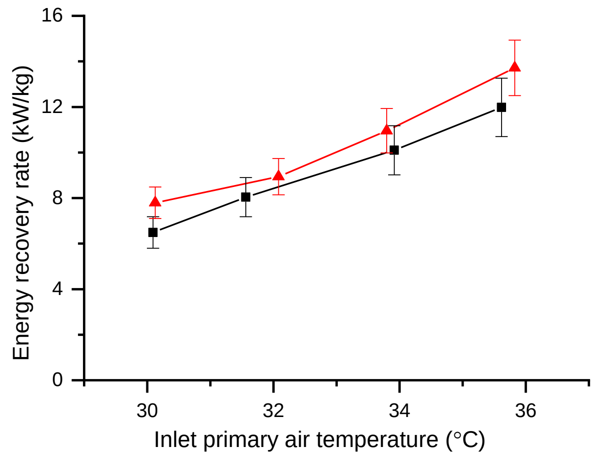
(b) dehumidifying performance

Fig.5 Performance of uncoated and coated IEC under different inlet air temperatures

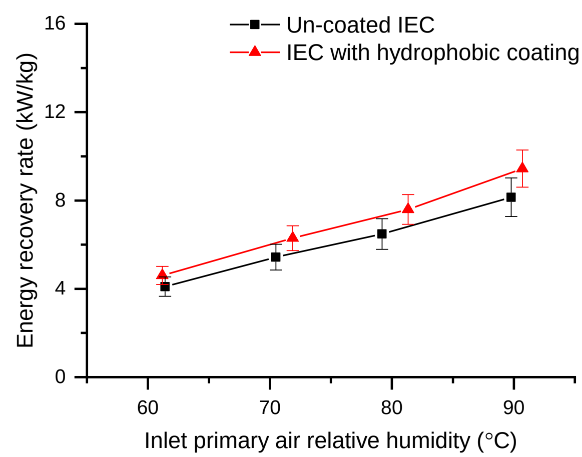
In Fig. 5, it is shown that the coated IEC provides higher η_{wb} by 11.8% and higher η_ω by 13.1% on average than the un-coated one. With the inlet air temperature increases from 30 ^{o} C to 36 ^{o} C, the degradation on η_{wb} of un-coated IEC is more than twice of the coated IEC due to the enlarged condensation area on the plate surfaces covered by liquid film.

4.2 Energy-saving potential

To further estimate the effect of hydrophobic coating on energy saving potential, both the sensible and latent cooling performance was considered to compare the total energy recovery rates of IECs with coated and uncoated heat exchange plates.



(a) Under different inlet air temperatures



(b) Under different inlet air relative humidity

Fig.6 Energy recovery rate of uncoated and coated IEC

Fig. 6 shows the $E_{recovery}$ based on experimental results of two IECs under different inlet air conditions. It is found that the increases of inlet air temperature and relative humidity both result in approximately linear growths of the energy recovery rates for the two IECs, while the IEC with hydrophobic coating performs better than the uncoated one. Under all the tested conditions, the energy recovery rate of coated IEC is at an average of 14.1% higher than that of uncoated IEC. As the difference in condensation mechanisms subjected to surface properties becomes more pronounced with the rise of inlet air temperature and humidity, the coated IEC shows an increasing improvement on $E_{recovery}$ which varies from 8.5% to 17.2%.

5. CONCLUSION

In this paper, comparative experiments were carried out to estimate the effect of hydrophobic coating on the cooling performance and energy-saving potential of IEC under dehumidifying conditions. Such observations suggested that using hydrophobic coating materials on primary air channel surfaces of the IEC can potentially improve the energy recovery of AC systems in hot and humid areas. Main conclusions can be drawn as follows:

(1) The hydrophobic surface promotes dropwise condensation with a smaller droplet departure diameter of 2-3 mm, differed from the irregular droplets (4-6 mm) stuck on the bare-aluminum plate and drained off as filmwise.

(2) After starting the experiments, the condensation on coated plate surfaces grows more quickly (400 seconds) than the uncoated surfaces (750 seconds) to attain a balance between the condensate deposition and shedding.

(3) The IEC with hydrophobic coating on dry channels provides higher wet-bulb effectiveness by 11.8% and higher dehumidification effectiveness by 13.1% on average than the un-coated one. The energy recovery rate of coated IEC can be enhanced by 8.5-17.2% under various inlet air conditions.

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