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Research Paper

Visualized experimental investigation on cross-flow indirect evaporative cooler with condensation

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HIGHLIGHTS

- A visualized cross-flow IEC is constructed.
- Two turning points are determined.
- Five performance is analysed under three states.
- The thermal resistance is non-ignorable due to condensation.

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ABSTRACT

In hot and humid regions, condensation will easily occur in the dry channels of indirect evaporative cooler (IEC) due to high dew point temperature of primary air. However, the visualized investigation on cross-flow IEC with condensation has seldom been reported by previous studies. Therefore, a visualized cross-flow IEC was constructed with a transparent cover plate for observing the condensation in a primary air channels. A series of experiment had been carried out to investigate the comprehensive performance of IEC under different inlet primary air temperature and humidity. The outlet primary air temperature, wb-effectiveness, water consumption rate, heat transfer rate and condensation rate were analysed in detail under non-condensation, partial condensation and total condensation cases. The experimental results showed that the turning point from non-condensation to partial condensation was 33.0 °C under relative humidity of 50%, 29.0 °C under relative humidity of 60% and partial condensation to total condensation was 35.0 °C under relative humidity of 70%, 30.0 °C under relative humidity of 80%, respectively. Condensation improved the outlet primary air temperature, total heat transfer, water consumption rate and condensation rate but lowered the wb-effectiveness. Furthermore, the thermal resistance of condensate film was non-ignorable because of thick water film.

1. Introduction

Growing air-conditioned buildings worldwide lead to rapid increase of electricity demand [1]. As an energy efficiency and environmental friendly technology, indirect evaporative cooler (IEC) uses water evaporation to produce cooling air rather than conventional vapor compression system [2–5]. Therefore, it is drawing more and more attention in the field of building energy conservation for its high efficient, good comfort, pollution-free and easy maintenance features in recent years [6–8].

In hot and dry regions, the primary air is sensibly cooled without any change in the humidity. The cooling capacity is satisfactory due to a larger evaporation driving force of lower humidity air [9–11]. In recent years, extensive numerical studies [12–17] considering non-condensation in the primary air channels have been fundamentally investigated. Ren and Yang [14] presented an analytical model considering the spray water evaporation, spray water temperature variation and spray water enthalpy change along the heat exchanger surface to study the the performances of IEC and its analytical solution was obtained by rearranging the differential equations. To numerically study the performance of two-stage evaporative coolers, a mathematical model was developed by Gilani and Poshtiri [15] taking account of the variation of water film temperature and mass simultaneously. The results showed that it can provide the thermal comfort condition in hot and dry regions (temperature 34–54 °C and relative humidity 10–60%). To take full account of the heat and mass transfer process of the secondary air, Chua

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Nomenclature

c_p	specific heat of air (kJ/(kg °C))
d	moisture content of air (g/kg)
i	enthalpy of air (kJ/kg)
m	mass flow rate (g/s)
V	volume flow rate (m^3/h)
η	effectiveness
ρ	density (kg/m^3)
A	superficial area of plate (m^2)
n	the number of surface
Q	heat transfer rate (kW/m^2)
δ	the average growth rate of condensate film thickness (um/s)
λ	thermal conductivity (W/(m °C))

Subscripts

p	primary air (dry channel)
s	secondary air (wet channel)
pl	plate
pw	condensate water of primary air
w	water film
wb	wet bulb
in	inlet
out	outlet

et al. [16] developed a two-dimensional theoretical model considering heat transfer between secondary air and plate due to incomplete wetted surface, which displayed a deviation within ± 5% comparing the simulation results with available experimental data from literature. Hettiarachchi et al. [17] firstly considered the effect of the longitudinal heat conduction (LHC) in the exchanger walls with cross-flow configuration and developped a set of coupled four Ordinary and Partial Differential Equations under assumption of neglecting the variation of water film temperature.

It can be observed that the theoretical analysis of IEC considering condensation of primary air has seldom been reported by previous studies. In hot and humid regions, condensation will probably occur in the dry channels due to a higher dew point temperature of primary air. Therefore, the IEC is developed to pre-cool the fresh air and considered to be heat recovery device. Chen et al. [11] developed a new numerical model neglecting the variation of the evaporating water film under condensation state. The results showed that the condensation is beneficial to the total heat transfer rate due to dehumidification but lowered the wet-bulb efficiency of indirect evaporative coolers. Moreover, Chen et al. [18] proposed a method for judging three states of non-condensation, partial condensation and total condensation by establishing a simplified analytical model for indirect evaporative coolers.

In terms of experimental study, various configurations [19–24] have been tested to evaluate the performance of IEC over the last few decades. Lee and Lee [22] fabricated a counter flow fin-inserted regenerative evaporative cooler applying the thin porous layer coating on the internal surface of the wet channel to improve surface wettability to investigate the cooling performance. The results showed that the supply air of 22.0 °C is obtained when the intake air condition is 32.0 °C, 50% RH (23.7 °C wet bulb temperature) and the pressure drop in the wet channel stays invariant whether the evaporation water is supplied or not. In addition, Duan et al. [23] experimentally investigated the operational performance and impact factors of a counter-flow polygonal-sheets-stacked plate regenerative evaporative cooler (REC). Compared to conventional IEC, the presented cooler showed 31% increase in wet-bulb effectiveness which ranged from 0.55 to 1.06. Kim [24] experimentally investigated two types of IECs under general operation and regenerative cooling modes to evaluate the sensible cooling performance. The experimental results revealed that they have the similar thermal performances. However it shows higher sensible cooling performances in terms of cooling rate, wet-bulb effectiveness, and supply air temperature in the general operation mode. Furthermore, 112 experiments have been carried out in different working conditions (variation of water flow rate, humidification nozzles setup and secondary air temperature, humidity and flow rate) by Antonellis et al. [25] to evaluate performance of indirect evaporative air cooling system in data centers. Results put in evidence that the performance is greatly influenced by water flow rate and slightly affected nozzles number and size. The maximum wet bulb effectiveness reaches 85% depending on working conditions and equipment setup. In hot and humid regions, Chen et al. [26] conducted an experimental study to evaluate the plate type air cooler performance under condensation condition. The results show that condensation improves latent and total heat transfer and the highest COP can reach 9.0 under condensation condition. However, the condensation cannot observed intuitively.

It can be observed that previous experimental works focused on performance evaluation by a novel configuration of IEC. However, the effect of operation parameters on condensation area in the dry channels and performance under non-condensation, partial condensation and total condensation has seldom been reported by previous studies. Compared with method proposed by Chen et al. [11,18] indirectly estimated the turning point from non-condensation to partial

Table 1
The comparison between some experimental study of IEC and present study.

Study	IEC type	Particular study points	Working condition	The experimental results
[12]	counter flow	The material novel of dew point evaporative cooling system was a thin-film cotton sheet coated evenly by polyurethane material (PU) (total thickness 0.5 mm).	Non-condensation	The wb-effectiveness ranged between 92 and 114% and the dew point effectiveness between 58 and 84%.
[22]	counter flow	Multiple pairs of finned channels were arranged and thin porous layer coating was applied.	Non-condensation	The cooling performance was found greatly influenced by the evaporative water flow rate.
[23]	counter-flow	The polygonal sheets stacked plate was applied.	Non-condensation	The wet-bulb effectiveness ranged from 0.55 to 1.06.
[24]	cross-flow	The cooling performances of two different types of cross-flow IEC were evaluated.	Non-condensation	The general IEC had higher wb-effectiveness than REC in a 100% outdoor air system application.
[25]	cross-flow	The effects of variation of water flow rate, humidification nozzles setup and secondary air temperature, humidity and flow rate on performance of IEC for data centers.	Non-condensation	The performance was greatly influenced by water flow rate and slightly affected nozzles number and size.
[26]	counter-flow	An experimental study was conducted under four operating modes.	Condensation	The wet operating improved the sensible and latent cooling capacities significantly.
Present study	cross-flow	A visualized cross-flow IEC is constructed and five performance are analysed under three states	Condensation	