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Indirect evaporative cooler considering condensation from primary air: Model development and parameter analysis

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ABSTRACT

The indirect evaporative cooler (IEC), regarded as a low-carbon cooling device, was proposed as fresh air pre-cooling and heat recovery device in the air-conditioning system to break the region limitation of application in hot and humid areas. In this hybrid system, the exhausted air with low temperature and humidity from air-conditioned space is used as secondary air to cool the inlet fresh air. As the dew point temperature of the fresh air is high, condensation may occur in the dry channels. However, the modeling of IEC with condensation has been seldom studied and corresponding parameter study is also lacking. So the paper established a new numerical model taking the condensation from primary air into consideration. The model was validated by the published data from literature with good agreement. Nine parameters were analyzed in detail under three operation states (non-condensation, partial condensation and total condensation) using four evaluation indexes: condensation ratio, wet-bulb efficiency, enlargement coefficient and total heat transfer rate. The results show that the condensation lowers the wet-bulb efficiency of IEC but improves the total heat transfer rate due to dehumidification.

1. Introduction

Indirect evaporative cooler (IEC) is an energy efficient and environmental friendly cooling device which uses water evaporation to produce cooling air. It receives increasingly attention in the field of building energy conservation for its high efficient, good comfort, pollution-free and easy maintenance features [1–5]. The most commonly used plate-type IEC consists of alternative wet and dry channels which are separated by thin plates [6]. In the wet channels, the spraying water drops form a thin water film on the plate surface and consistently evaporates into the main stream of the secondary air. The primary air in the adjacent dry channels is cooled down by the low temperature wall without adding moisture. In normal practice, the outdoor fresh air is used for both primary air and secondary air.

Because the air with lower humidity can provide larger evaporation driving force and cooling capacity, the IEC has been widely adopted in hot and dry regions for directly supplying the cooled primary air [7–9]. Its thermal performances influenced by various operation conditions were investigated [10]. Under such weather conditions, the primary air is only sensibly cooled. The IEC's performances under diverse climate regions were also investigated and proved that its ability to diminish annual cooling degree-days is practically ubiquitous in all territory [11]. However, in hot and humid regions, the supply air temperature of the IEC is limited to the high ambient wet-bulb temperature [12], so the device can't be used independently. Correspondingly, the modeling of IEC with only sensible heat transfer in the primary air channels has been fundamentally investigated.

In general, the modeling methods can be classified into analytical approach and numerical approach. For analytical approach, Maclaine-cross and Banks [13] proposed a linear approximate model of wet surface heat exchangers by analogizing with dry surface heat exchangers. Erens and Dreyer [14] made a comparison among Poppe model, Merkel model and simplified model. Alonso [15] developed a more user-friendly simplified model by introducing an equivalent water temperature. Ren [16] developed an analytical model for IEC with parallel/counter flow configurations considering variable Lewis factor and surface wettability. The modified ε-NTU method is a simplified method for IEC modeling by redefining some parameters and assuming a linear saturation temperature-enthalpy relation of air [17–19]. Kim

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Nomenclatures

A	heat transfer area, m^2
B	barometric pressure, Pa
H	cooler height, m
L	cooler length, m
P	water vapor pressure, Pa
R	condensation ratio
T	thermodynamic temperature, K
Pr	Prandtl number
NTU	number of heat transfer unit
c_{pa}	specific heat of air, J/kg °C
c_{pw}	specific heat of water, J/kg °C
d_e	hydraulic diameter of channel, m
h	heat transfer coefficient, W/m^2 °C
h_m	mass transfer coefficient, kg/m^2 s
h_{fg}	latent heat of vaporization of water, J/kg
i	enthalpy of air, J/kg
m	mass flow rate, kg/s
n	number of channels
q	total heat transfer rate per unit mass, kW/kg
s	channel gap, m
t	celsius temperature, °C
u	air velocity, m/s

Greek symbols

ω	moisture content of air, kg/kg
σ	wettability
η	wet-bulb effectiveness
ε	enlargement coefficient
μ	dynamic viscosity, Pa·s
υ	kinematic viscosity, m^2/s
λ	thermal conductivity, W/m °C

Subscripts

c	condensation
e	evaporation
p	primary/fresh air
s	secondary air
w	wall
cw	condensate water
ew	evaporation water
ew	evaporation water
qb	saturation vapor pressure
wb	wet-bulb temperature
sat	saturated humidity

developed a practical correlation for IEC based on ε-NTU method [20]. The analysis of the heat and mass transfer process of IEC based on exergy theory was also conducted [21].

For numerical approach, the thermal performances of IEC under a wide variety of inlet air conditions, construction type and flow patterns have been investigated by laying different focuses on the evaporation water loss, water film temperature variation, wall longitudinal heat conduction and variable Lewis factor [22–28]. For experimental research, five kinds of heat and mass exchanging materials were selected for comparative experimental study in IEC systems [29]. A two-stage evaporative cooling system with higher cooling ability was tested and evaluated [30,31]. The performances of IEC and heat exchanger in summer and winter operation were theoretical analysis and measured [32].

In recent years, some novel hybrid evaporative cooling systems were proposed for promoting the 'green cooling technology' to more regions [33–37], of which a hybrid air-conditioning system consisting of an IEC and mechanical cooling came into being for using in hot and humid regions. The IEC, installed before an air handling unit (AHU), is used to pre-cool the incoming fresh air for energy conservation of the air-conditioning system [38]. In this system, the cool and dry exhaust air with much lower wet-bulb temperature from air-conditioned space is used as secondary air for enhancing the cooling effect. However, owing to the high dew point temperature of the fresh air in humid areas, condensation probably occurs, which results in not only sensible cooling but also dehumidification effect. The simultaneous heat and mass transfer process in the primary air channel is much more complicated and will greatly affect the IEC performance.

In respect of research on hybrid evaporative cooling system, an experimental study was conducted to investigate the energy saving potential of IEC as a pre-cooling unit combined with PUA (packaged unit air-condition) in Iran [39]. Numerical analysis was conducted to the IEC combined with a cooling/reheating unit [40]. Financial feasibility of a hybrid-mode operation of a direct evaporative cooler (DEC) with an air conditioning unit was studied [41]. These studies prove that the energy saving and economic benefit are optimistic and attractive for the hybrid cooling system, but condensation case has not been taken into consideration.

It can be observed that the modeling of IEC with condensation from primary air has seldom been reported by previous studies. Besides, a comprehensive parameter study of IEC under condensation state is also lacking. Therefore, an IEC model considering condensation and a comprehensive parameter study are needed for better predicting the performance and optimization of the hybrid cooling system. The comparison between some representative IEC parameter studies and present study is listed in Table 1.

To make up the research gap, a novel numerical model considering condensation from primary air was established. The model was validated by the published data from the literature. Then, a comprehensive parameter study was conducted with the established numerical model. The effect of nine parameters (including temperature and humidity of primary air and secondary air, channel gap, wettability and cooler height) were analyzed in detail under three operation states (non-condensation, partial condensation and total condensation) by four proposed evaluation indexes (condensation ratio, wet-bulb efficiency, enlargement coefficient and total heat transfer rate). The study results can provide references for evaluation of the hybrid cooling system and optimization of the IEC applied in hot and humid regions.

2. Three condensation states of IEC

When an IEC hybrid cooling system is applied in hot and humid regions, the humidity of the primary air is high and the wet-bulb temperature of the secondary air from air-conditioned space is low. So condensation will occur at the place where the plate surface temperature is lower than the dew point temperature of the primary air. According to different inlet air conditions, three possible operation states of IEC can be identified, which are total condensation, partial condensation and non-condensation, as shown in Fig. 1. Non-condensation state occurs when the inlet primary air is dry and the dew point temperature is always lower than the plate surface temperature. Total condensation state occurs when the