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Parameter sensitivity analysis of indirect evaporative cooler (IEC) with condensation from primary air

Yi Chen[a], Hongxing Yang[a,*], Yimo Luo[b]

[a]*Renewable Energy Research Group (RERG), Department of Building Services Engineering, The Hong Kong Polytechnic University, Hong Kong*
[b]*Faculty of Science and Technology, Technological and Higher Education of Hong Kong, Hong Kong*

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 sensitivity analysis is also lacking. So the paper established a new numerical model taking the condensation from primary air into consideration. Two evaluation indexes (wet-bulb efficiency and enlargement coefficient) were proposed to investigate the thermal performance of IEC with condensation. Sensitivity analysis was conducted among seven parameters by orthogonal test and variance analysis.

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Keywords: indirect evaporative cooler, numerical model, condensation, orthogonal test, variance analysis

1. Introduction

Indirect evaporative cooler (IEC) is an energy efficient and environmental friendly cooling device which uses water evaporation to produce cooling air [1]. It receives increasingly attention in the field of building energy conservation for its high efficient, pollution-free and easy maintenance features. The most commonly used plate-type IEC consists of alternative wet and dry channels which are separated by

* Corresponding author. Tel.: +852 2766 5816
E-mail address: hong-xing.yang@polyu.edu.hk

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thin plates. 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.

Because the air with lower humidity can provide larger cooling capacity, the IEC has been widely adopted in hot and dry regions for directly supplying the cooled primary air[2]. Under such weather conditions, the primary air is only sensibly cooled. But in hot and humid regions, the supply air temperature of the IEC is limited to the high ambient wet-bulb temperature.

Recently, a new hybrid air-conditioning system consisting of IEC and mechanical cooling has been proposed for IEC application in hot and humid regions. The IEC, installed before an AHU, is used to pre-cool the incoming fresh air for energy conservation of the air-conditioning system. In this system, the cool and dry exhaust air from air-conditioned space is used as secondary air. However, due to the high humidity of the fresh air in humid areas, condensation probably occurs, which results in not only sensible cooling but also dehumidification effect. The IEC modeling with condensation from primary air has seldom been reported by previous studies. Besides, a sensitivity parameter study under IEC condensation state is also lacking.

In order to predict the performance and optimize the configuration of IEC under condensation operation state, a novel numerical model considering condensation from primary air was established in this paper. Three evaluation indexes (wet-bulb efficiency, enlargement coefficient and total heat transfer rate) were proposed to investigate its thermal performance. To find out the most influential parameters, sensitivity analysis was conducted among seven parameters (temperature and RH of primary air and secondary air, air flow ratio, channel gap, cooler height) by orthogonal test and variance analysis.

Nomenclature

Abbreviation

IEC	Indirect Evaporative Cooler
RH	Relative Humidity
AC	Air-conditioning
AHU	Air Handling Unit
FDM	Finite Difference Method

Symbols

c_{pa}	specific heat of air, J/kg·℃
c_{pw}	specific heat of water, J/kg·℃
h	heat transfer coefficient, W/m2·℃
h_m	mass transfer coefficient, kg/m2·s
h_{fg}	heat capacity of vaporization, J/kg
i	enthalpy of air, J/kg
m	mass flow rate, kg/s
s	channel gap, m
t	celsius temperature, ℃
u	air velocity, m/s
ω	moisture content of air, kg/kg

Subscript

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

2. Modelling of IEC

2.1. Numerical modelling

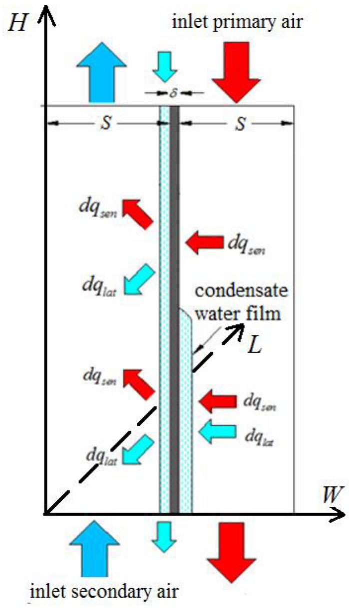

Figure 1 IEC with partially condensation

The diagram of IEC under partially condensation state is shown in Fig.1. The new model of IEC considering the condensation from primary air is based on the following assumptions: 1) Thermal properties of the air and water are constant; 2) The unit is adiabatic 3) The thermal resistances of water film and wall are negligible; 4) Heat and mass are only transferred vertically across the separated plate; 5) The water film is continuously replenished at the same temperature 6) Lewis number is unity.

The heat balance of the secondary air is calculated as:

$$h_s(t_w - t_s)dA = c_{pa}m_s dt_s \quad (1)$$

The mass balance of the secondary air is calculated as:

$$h_{ms}(\omega_{t_w} - \omega_s)dA = m_s d\omega_s \quad (2)$$

If the local plate surface temperature is higher than dew point temperature of primary air, only sensible heat exchange will take place in the primary air channels. The heat balance equation of the primary air, mass balance of evaporation water film and energy balance equation of the control volume are calculated as Equation (3) to (5), respectively.

$$h_p(t_p - t_w)dA = c_{pa}m_p dt_p \quad (3)$$

$$dm_e = m_s d\omega_s \quad (4)$$

$$m_s di_s - c_{pa}m_p dt_p = d(c_{pw}t_{ew}m_e) \quad (5)$$

If the local plate surface temperature is lower than dew point temperature of primary air, the condensation will take place and the moisture is released from the primary air to the plate surface. The heat and mass balance equation of the primary air, mass balance of evaporation water film and condensate water film, as well as the energy balance equation of the control volume are calculated as Equation (6) to (10), respectively.

$$h_p(t_p - t_w)dA = c_{pa}m_p dt_p \quad (6)$$

$$h_{mp}(\omega_p - \omega_{t_w})dA = m_p d\omega_p \quad (7)$$

$$dm_e = m_s d\omega_s \quad (8)$$

$$dm_c = -m_p d\omega_p \quad (9)$$

$$m_s di_s - m_p di_p = d(c_{pw}t_{ew}m_e) + d(c_{pw}t_{cw}m_c) \quad (10)$$

In sum, the Equation (1) ~ (5) form the enclosed governing equations of IEC without considering condensation from primary air; while the Equation (1) ~ (2) and Equation (6) ~ (10) form the enclosed governing equations of IEC with condensation from primary air. The boundary conditions are: $x=H$, $t_p=t_{p,in}$,; $x=H$, $\omega_p=\omega_{p,in}$, $x=0$, $t_s=t_{s,in}$; $x=0$, $\omega_s=\omega_{s,in}$; $x=H$, $m_c=0$; $x=H$, $m_e=m_{e,in}$.

The above governing equations can be written in standard ordinary differential equations. Then, the differential term is discretized into algebraic form by finite difference method (FDM) and numerical simulation results at each discretize node can be obtained by solving a set of algebraic equations simultaneously.

2.2. Orthogonal experiment

The orthogonal experiment is a high efficient, fast and economical design method for studying the multiple factors with multiple levels. In this paper, seven parameters (primary air temperature t_p, primary air relatively humidity RH_p, secondary air temperature t_s, secondary air relatively humidity RH_s, air flow ratio of primary air to secondary air u_p/u_s, channel gap s and cooler height H) were selected for sensitivity study in order to determine the most influential parameters of IEC performance under condensation state. Three indexes (wet-bulb efficiency η_{wb},, enlargement coefficient ε and total heat transfer rate Q_{tot}) are proposed for evaluating IEC performance with condensation from primary air, which expressed as:

$$\eta_{wb} = \frac{t_{p,in} - t_{p,out}}{t_{p,in} - t_{wb,s}}$$

$$\varepsilon = \frac{Q_{tot}}{Q_{sen}} = \frac{c_{pa} \cdot m_p \cdot (t_{p,in} - t_{p,out}) + h_{fg} \cdot m_p \cdot (\omega_{p,in} - \omega_{p,out})}{c_{pa} \cdot m_p \cdot (t_{p,in} - t_{p,out})}$$

$$Q_{tot} = c_{pa} \cdot m_p \cdot (t_{p,in} - t_{p,out}) + h_{fg} \cdot m_p \cdot (\omega_{p,in} - \omega_{p,out})$$

Seven-parameter and three-level orthogonal experiment table $L_{18}(3^7)$ was selected. The values of each parameter are listed out in Table 1. The simulation was conducted according to the arrangement of orthogonal test table $L_{18}(3^7)$ and the total number of experiment is 18 times. Two methods were adopted in analyzing the results of orthogonal experiment, called range analysis method and variance components method. In this research, only the main effect of the parameter was considered and interaction effect was neglected.

Table 1 values of parameters

No.	Parameter	Level 1	Level 2	Level 3
1	tp (℃)	30	35	40
2	RHp (%)	70	80	90
3	ts (℃)	22	24	26
4	RHs (%)	40	50	60
5	up/ us	0.5	1	2
6	S (mm)	2	6	10
7	H (m)	0.1	1	2

The influence of one parameter can be evaluated by R_j in the range analysis method, which is calculated as Equation (11). The larger the R_j , the more influential the parameter is.

$$R_j = \max[\bar{y}_{j1}, \bar{y}_{j2}, ...] - \min[\bar{y}_{j1}, \bar{y}_{j2}, ...] \quad (11)$$

The influence of one parameter can be evaluated by S in the variance components method, which is calculated as Equation (12). The significant of a certain parameter can be investigated by F-test method.

$$S = \sum_{i=1}^{a} (y_i - \bar{y})^2 = \sum_{i=1}^{a} y_i^2 - \frac{1}{a} (\sum_{i=1}^{a} y_i)^2 \quad (12)$$

3. Results and discussion

The sensitivity analysis results of seven parameters of IEC under condensation state are shown in Fig.2. By the range analysis method and variance components method, the influence of each parameter on the wet-bulb efficiency is: $H > S > u_p/ u_s > t_s = t_p > RH_s > RH_p$; for the enlargement coefficient is: $RH_p > t_p > RH_s > u_p/ u_s > t_s > H > S$; for total heat transfer rate is: $H > S = u_p/ u_s > RH_p > t_p > RH_s > > t_s$.

By adopting F-test method for evaluating the influential significant of each parameter on the index, air flow ratio, channel gap and cooler height were found to be have significant effect on the wet-bulb efficiency as the F values are 40.0, 52.2 and 174.8, respectively, higher than the F critical value of 4.46 (α=0.05).

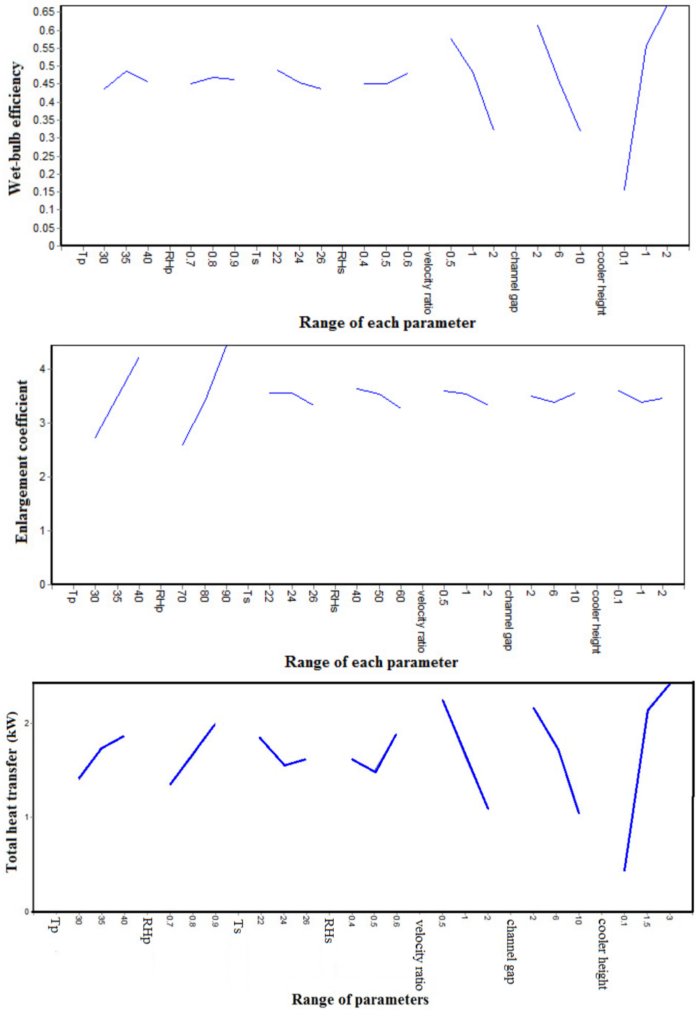

Figure 2 sensitivity analysis results

4. Conclusions

A new numerical model of indirect evaporative cooler (IEC) was established, taking condensation from primary air into consideration. Parameter sensitivity analysis of IEC under condensation state was conducted using orthogonal experiment and variance analysis. The results show that the most influential parameter on the wet-bulb efficiency is: cooler height > channel gap > air flow ratio; for the enlargement coefficient is: primary air RH > primary air temperature > secondary air RH; for total heat transfer rate is: cooler height> channel gap = air flow ratio. The analysis can illustrate the most influential parameter so that the optimization on specific parameters should be paid more attention.

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Biography

Yi Chen, PhD student from Building Service Engineering of Hong Kong Polytechnic University. The major research interests lie in the analysis of heat and mass transfer process in indirect evaporative cooling as well as the system dynamic simulation.