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Simplified predicting models on Energy-saving Potential of Indirect Evaporative Coolers in Hong Kong

Min Yunran[a], Chen Yi[b], Yang Hongxing[a,*]

[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 Institute of Hong Kong, Hong Kong*

Abstract

An Indirect Evaporative Cooler (IEC), when used as a precooling unit in the fresh air system, can achieve heat recovery through the use of exhaust air and is attractive for energy saving. In hot and humid areas, the IECs can also realize considerable latent heat recovery due to the possible condensation. Based on statistical data derived by numerical models of different types of IECs, this research developed simplified models for predicting the annual energy saving potential of IECs applied in practices in hot and humid areas. Results showed that the predicted values of simplified models can agree well with the simulated values. By integrating the fitted regression equations to building energy consumption simulation, a case study of a wet market in Hong Kong was conducted. Consequently, the IEC can achieve 43.8 ~ 56.4% energy saving to the HVAC system.

Keywords: Indirect evaporative cooler; Cross flow; Counter flow; Simplified models; Energy saving

1. Introduction

Evaporative Cooling is an attractive technology for alternative air-cooling solutions due to it cost lower energy consumption and less greenhouse gas emissions since no CFCs usage. Indirect Evaporative Cooling technology is able to cool the air without adding extra moist to the produced air, which makes it's more suitable for humid areas. The plate type IECs are commonly used in HAVC systems of buildings for its cheap cost and compact volume. For

* Corresponding author.
E-mail address: hong-xing.yang@polyu.edu.hk (H. Yang)

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the plate type IEC, the spraying water wet the surface of wet channel, and absorbs heat from surrounding secondary air with aid of water evaporation on the wet surface of the plate, thus cools the plates between the wet and dry channels. The primary air in the dry channel is cooled by sensible heat transfer between air and low-temperature plate. This type of IEC equipment has advantages of simple configuration, convenient maintenance, low cost, high system stability and rare cross-pollution. In the plate type IEC, the heat exchange process between the primary air stream and secondary air stream mainly consists of parallel flow, cross flow and counter flow.

The complexity of coupled heat and mass transfer in the film evaporation increases the difficulty of IEC modeling, which has been extensively studied. At first, the analytical approaches were developed through several hypotheses. Maclaine-cross and Banks [1] proposed a linear approximate model by simplifying the specific enthalpy of the moist air is in a linear function of air temperature and air moisture content. Stoitchkov and Dimitrov [2] used mean water surface temperature to consider the real condition of flowing down water film and introduced an equation to calculate the ratio of total to sensible heat considering the barometric pressure. To further explore the distribution of air flow, temperature and humidity along both vertical and horizontal directions within an IEC heat exchanger, the numerical model is developed and used most frequently for its accuracy. By establishing a simulation model of hybrid liquid desiccant dehumidification and evaporative cooling system, Chen et al. [3] conducted a case study under typical Hong Kong weather condition which realized 23.5% energy saving ratio.

However, there is very limited research work regarding the IEC performance prediction in practical use combined with building simulation considering the possible condensation. The development of IECs in hot and humid area is restricted by the lack of performance assessment solutions which fit the IEC models in practice for the annual operation in building HVAC systems. In this regards, this paper investigated the simplified models for both sensible and latent heat transfer effectiveness of IEC applied in hot and humid areas, providing references for assessing the energy saving potential achievable with the IEC unit in engineering projects.

Nomenclatures			
A	heat and mass transfer area, m^2	h	heat transfer coefficient, W/m^2·℃
h_m	mass transfer coefficient, kg/m^2·s	m	mass flow rate, kg/s
i	enthalpy of air, J/kg	c_{pa}	specific heat of air, J/kg·℃
c_{pw}	specific heat of water, J/kg·℃		
Greek symbols			
ω	moisture content of air, kg/kg	ρ	air density, kg/m^3
η_{wb}	wet-bulb effectiveness	ε	enlarge coefficient

2. Numerical models

2.1. Counter flow IEC

The FDM is an adopted method in IEC modeling to discretize differential equations into algebraic form. The possible condensation in the primary air is also considered in this model. For each discretized component, the energy conservation equations are as follows. The item of primary air latent heat is also concluded in the equations to represent the dehumidification process. The Detailed description of the derivation process can be seen in previous work [4].

$$h_p(t_p - t_w)dA = c_{pa}m_p dt_p \tag{1}$$
$$h_{mp}(\omega_p - \omega_{tw})dA = m_p d\omega_p \tag{2}$$
$$h_s(t_w - t_s)\, dA = c_{pa}m_s dt_s \tag{3}$$
$$h_{ms}(\omega_{tw} - \omega_s)dA = m_s d\omega_s \tag{4}$$
$$m_s di_s - m_p di_p = c_{pw}t_{ew}m_s d\omega_s - c_{pw}t_{cw}m_p d\omega_p \tag{5}$$

The boundary conditions are: $x = \mathrm{H}, t_p = t_{p,in}, \omega_p = \omega_{p,in}$; $x = 0, t_s = t_{s,in}, \omega_s = \omega_{s,in}$. In this method, all the derivate terms in the governing equations and boundary conditions are replaced in terms of their discrete equivalents. The plate surface temperature t_w is iterated until all the energy balance equations can be satisfied. The saturated humidity at the water film temperature ω_{tw} is a non-linear function of plate surface temperature t_w, which increase the numerical procedure and calculation time for exact solution.

2.2. Cross flow IEC

The cross flow configuration is generally solved by the two dimensional models, in which the partial differential equations are involved and the iterative sequence is different from that of counter flow model. With condensation in the primary air into consideration, the energy conservation equations for each discretized component are as follows.

$$h_s(t_w - t_s) \cdot dxdy = c_{pa}\dot{m}_s \frac{\partial t_s}{\partial y} \cdot dy \quad (6)$$

$$h_{ms}(w_{tw} - w_s)\sigma \cdot dxdy = \dot{m}_s \frac{\partial w_s}{\partial y} \cdot dy \quad (7)$$

$$h_p(t_p - t_w) \cdot dxdy = c_{pa}\dot{m}_p \frac{\partial t_f}{\partial x} \cdot dx \quad (8)$$

$$h_{mp}(w_{tw} - w_p) \cdot dxdy = \dot{m}_p \frac{\partial w_f}{\partial x} \cdot dx \quad (9)$$

$$\dot{m}_s \frac{\partial i_s}{\partial y} - \dot{m}_p \frac{\partial i_p}{\partial x} = c_{pw} t_{ew} \dot{m}_s \frac{\partial \omega_s}{\partial y} - c_{pw} t_{cw} \dot{m}_p \frac{\partial \omega_p}{\partial x} \quad (10)$$

The boundary conditions are described as: $x = 0, t_p = t_{p,in}, w_p = w_{p,in}$; $y = 0, t_s = t_{s,in}, w_s = w_{s,in}$. The partial differential equations can be solved by the discretization of forward difference schemes. With the inlet air properties provided, the results on outlet air temperature and humidity can be derived to evaluate the effectiveness of IEC.

3. Simplified models

The detailed temperature and humidity distribution of IEC can be obtained by numerical models, while the iteration process of finite difference models needs huge computer memory and consume much time. For estimating the energy performance of IEC applied in hot and humid areas, it is essential to come up with dedicated predicting approaches on both sensible and latent heat transfer coefficient of IEC with practical convenience and reasonable accuracy.

Based on simulation models, seven influence variables were selected to vary between a high value and a low value as listed in Table 1. A 2-level factorial design method was employed on the simulation results of wet-bulb effectiveness η_{wb} and enlarged heat transfer rate ε to analyze the effect of each influencing parameter and interaction. There are 2^7=128 experiments included in the full factorial design method.

Table 1. Ranges of selected parameters on simulate conditions.

Parameter	Factor	Unit	Low	High
t_p	G	°C	30	40
RH_p	F	%	10	100
t_s	E	°C	16	28
RH_s	D	%	10	100
m_p	C	kg/s	0.008	0.01
m_p/m_s	B	-	0.5	2
NTU_p	A	-	0.3	5

The wet-bulb efficiency (η_{wb}) is an evaluation metric on sensibthe le cooling efficiency of IEC which used to estimate the dry-bulb temperature of the outlet primary air. The enlargement coefficient (ε) is a ratio of total heat transfer rate Q_{tot} and sensible heat transfer rate Q_{sen}, and it's suitable for IEC applied in hot and humid areas to evaluate the enlarged heat transfer rate with condensation occurred. With the η_{wb} and ε being provided, the Q_{tot} of an IEC operated under certain inlet air properties can be calculated using Eq. (3).

$$\eta_{wb} = \frac{t_{p,in} - t_{p,out}}{t_{p,in} - t_{wb,s}} \quad (11)$$

$$\varepsilon = \frac{Q_{tot}}{Q_{sen}} = \frac{c_{pa} \cdot m_p \cdot (t_{p,in} - t_{p,out}) + h_{fg} \cdot m_p \cdot (\omega_{p,in} - \omega_{p,out})}{c_{pa} \cdot m_p \cdot (t_{p,in} - t_{p,out})} \tag{12}$$

$$Q_{tot} = \eta_{wb} \cdot \varepsilon \cdot m_p \cdot (t_{p,in} - t_{wb,s}) \tag{13}$$

Based on the simulation results of η_{wb} and ε, the effect parameters and interactions were examined quantitatively through normal probability plot. Three-factor interactions were involved in the model while upper product terms were ignored due to relatively little contribution. The effect of points located on the fitted line could be regarded as insignificant, whereas the points distributed far away from the line have significant influences on the IEC performance. In this way, the significant influence variables and interactions can be identified based on the P value with >95% of confidence level. Results for cross flow IEC can be seen in Fig. 1 and 2.

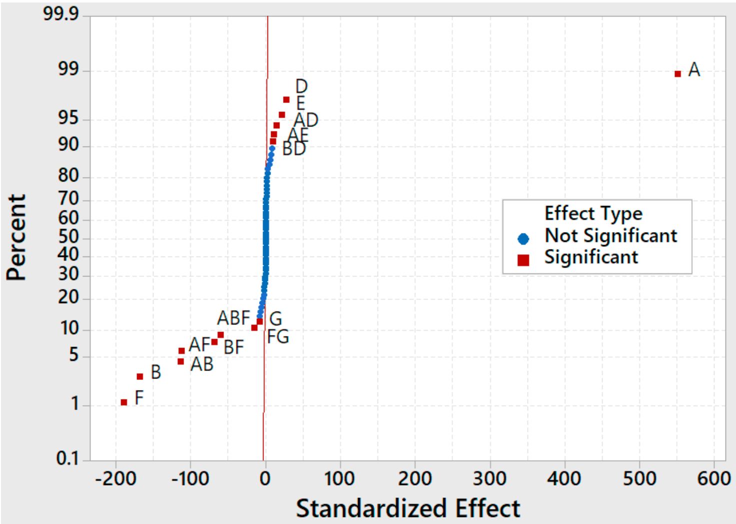

Fig. 1. Normal probability plot of effects on response of η_{wb}. (cross flow IEC)

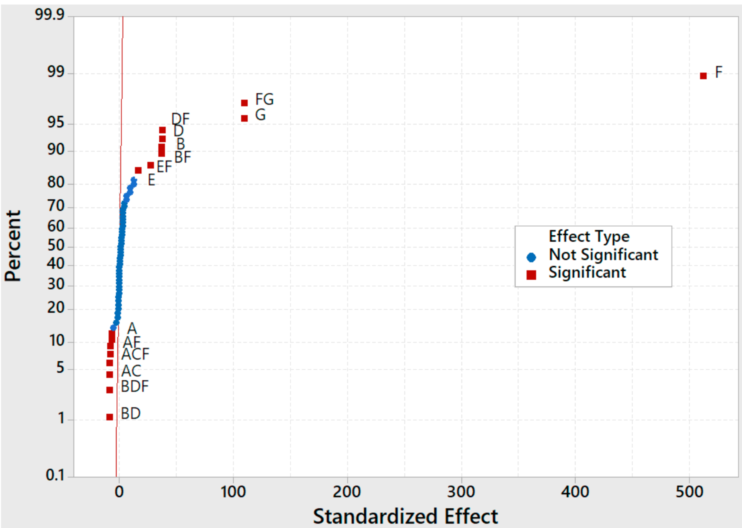

Fig. 2. Normal probability plot of effects on response of ε. (cross flow IEC)

The main factors (A, D, E) deviate from the straight line and have positive effects on the wet-bulb efficiency, while F, B, AB and AF on the left are inversely associated with η_{wb}. Similarly, normal probability plots for the energy efficiency of counter flow IEC can also be derived based on the simulation results of η_{wb} and ε.

3.1. Cross flow IEC

The codified equation (Eq. 14 and Eq. 15) for η_{wb} and ε of a cross flow IEC were derived as functions of seven factors with three-order interactions.

$$\begin{aligned}\eta_{wb} = {} & 0.122 + 0.1765(NTU_p) - 0.05\left(\frac{m_p}{m_s}\right) + 0.0098(RH_s) + 0.0007(t_s) - 0.1620(RH_p) + 0.001(t_p) \\ & -0.0296\left(NTU_p \cdot \frac{m_p}{m_s}\right) - 0.0001(NTU_p \cdot RH_s) + 0.0002(NTU_p \cdot t_s) + 0.0066(NTU_p \cdot RH_p) \\ & -0.012\left(\frac{m_p}{m_s} \cdot RH_s\right) + 0.0012\left(\frac{m_p}{m_s} \cdot t_s\right) + 0.0043(RH_p \cdot t_p) + 0.0269\left(NTU_p \cdot \frac{m_p}{m_s} \cdot RH_p\right)\end{aligned} \tag{14}$$

$$\begin{aligned}\varepsilon = {} & 3.4 - 0.572(NTU_p) + 0.011\left(\frac{m_p}{m_s}\right) - 0.493(RH_s) + 0.0295(t_s) + 0.109(RH_p) + 0.0731(t_p) \\ & +65.8(NTU_p \cdot m_p) + 0.0037(NTU_p \cdot t_s) + 0.253\left(\frac{m_p}{m_s} \cdot RH_s\right) - 0.563\left(\frac{m_p}{m_s} \cdot RH_p\right) \\ & -0.12(RH_s \cdot RH_p) + 0.0284(RH_p \cdot t_p) - 34.67(NTU_p \cdot m_p \cdot RH_p) - 0.2495\left(\frac{m_p}{m_s} \cdot RH_s \cdot RH_p\right)\end{aligned} \tag{15}$$

3.2. Counter flow IEC

For the counter flow IEC, the codified equation (Eq. 16 and Eq. 17) for η_{wb} and ε are as follows. Compared to cross flow IEC, they shared most of the main influence factors on η_{wb} and ε with, while differed in a few significant factors of interactions.

$$\begin{aligned}\eta_{wb} = {} & 0.195 + 0.1812(NTU_p) - 0.0748\left(\frac{m_p}{m_s}\right) + 2.1(m_p) + 0.0236(RH_s) + 0.0002(t_s) - 0.215(RH_p) \\ & -0.0145\left(NTU_p \cdot \frac{m_p}{m_s}\right) - 2.53(NTU_p \cdot m_p) - 0.0041(NTU_p \cdot RH_s) + 0.0278(NTU_p \cdot RH_p) \\ & -0.0114\left(\frac{m_p}{m_s} \cdot RH_s\right) + 0.0587\left(\frac{m_p}{m_s} \cdot RH_p\right) + 0.0063(RH_p \cdot t_p) + 0.0063\left(NTU_p \cdot \frac{m_p}{m_s} \cdot RH_s\right) \\ & -0.0512\left(NTU_p \cdot \frac{m_p}{m_s} \cdot RH_p\right) - 0.001(NTU_p \cdot RH_p \cdot t_p)\end{aligned} \tag{16}$$

$$\begin{aligned}\varepsilon = {} & 3.2 - 0.488(NTU_p) + 0.037\left(\frac{m_p}{m_s}\right) - 0.502(RH_s) + 0.0305(t_s) + 0.067(RH_p) + 0.0659(t_p) \\ & +62.2(NTU_p \cdot m_p) + 0.2431(NTU_p \cdot RH_p) + 0.327\left(\frac{m_p}{m_s} \cdot RH_s\right) - 0.73\left(\frac{m_p}{m_s} \cdot RH_p\right) \\ & -0.155(RH_s \cdot RH_p) + 0.0247(RH_p \cdot t_p) + 0.044\left(NTU_p \cdot \frac{m_p}{m_s} \cdot RH_p\right) - 0.2942\left(\frac{m_p}{m_s} \cdot RH_s \cdot RH_p\right)\end{aligned} \tag{17}$$

4. Energy simulation

It's more practical to estimate the energy-saving potential of an IEC with the obtained simplified models on its cooling performance. Under the typical weather conditions during cooling season in Hong Kong, a case study was conducted on a wet market with a total area of 260 m^2.

In this case study, the IEC is used as a component of combined HVAC system to pre-cool the fresh air with the exhaust air from air-conditioned space. Through heat recovery and dehumidification process caused by condensation, the IEC can achieve total energy saving for the HVAC system in the building. As the results shown in Fig.3, the total energy saving during the six months in the cooling season is 375 kWh/m^2 for counter flow IEC and 321 kWh/m^2 for cross flow IEC. According to the operating energy consumption of the HVAC system, 43.8 ~ 56.4% energy saving can be expected using IEC.

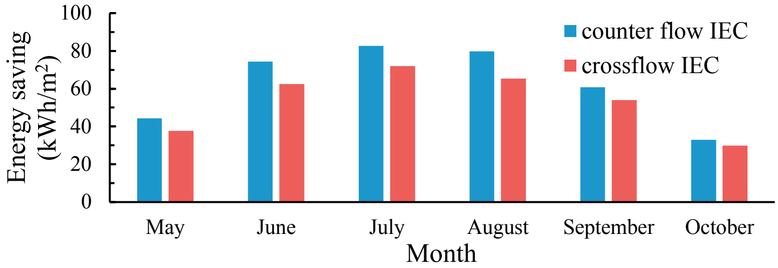

Fig. 3. Total energy saving of cross flow IEC and counter flow IEC per month.

5. Conclusions

In this paper, simplified models for estimation the cooling performance of cross flow and counter flow IEC were developed. Compared to sophisticated numerical models, the simplified models are more practical for estimating the annual energy performance of IEC applications. A case study was conducted based on the fitted regression equations integrated with building energy consumption simulation, and the energy saving achieved by IEC was analyzed. The main conclusion is as follow.

1. The cross flow and counter flow IEC share most of the main influence factors on the cooling effectiveness, while differ in a few significant factors of interactions. The simplified models can agree well with the simulation results to within ±10%.
2. The IEC applied in the wet market can achieve 43.8 ~ 56.4% energy saving to the HVAC system.

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