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Practical thermal performance correlations for a wet-coil indirect evaporative cooler

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ABSTRACT

The objective of this research was to develop practical models for predicting the thermal performance of a wet-coil indirect evaporative cooler (IEC). Through statistical analysis of cooling and heat exchange effectiveness data generated by a simple $\varepsilon - NTU$ (number of transfer units) method, simplified models returning the thermal performance of a wet-coil IEC were developed. Linear regression equations were derived as a function of the major design parameters and interactions that strongly affected the wet-coil IEC's performance. A pilot wet-coil IEC unit was built to validate the proposed models. Effectiveness data were obtained under a controlled range of operating conditions in an environmental chamber. Then, the energy-saving potential achievable by integrating a wet-coil IEC into a conventional variable air volume (VAV) system for pre-conditioning the outdoor air intake was quantitatively evaluated. The experimental results showed that more than 75% cooling effectiveness and 59% heat reclaim effectiveness could be achieved under wet and dry operating conditions, respectively. The experimental data acquired using the pilot unit agreed well with the thermal effectiveness predicted by the proposed models. Consequently, the VAV system integrated with the wet-coil IEC showed more than 45% reduced annual operating energy consumption compared with the conventional VAV system.

1. Introduction

An evaporative cooling system, which uses the evaporative latent heat of water, is an attractive technology for saving energy in heating, ventilation, and air conditioning (HVAC) [1–3]. Indirect evaporative coolers (IECs) have been receiving increasing attention because they cool processed air without adding moisture. Scavenger air is cooled with sprayed water in wet channels. The processed air, at higher temperatures, passes through dry channels losing heat through walls that separate wet and dry channels. The retained water is sprayed onto the surfaces of the wet channels [4]. When water is not sprayed onto the surfaces of the wet channels, the IEC works as a sensible heat exchanger.

There are two types of IECs: dry-coil IECs and wet-coil IECs [5]. A dry-coil IEC is connected to a direct evaporative cooler (DEC) and a sensible heat exchanger (SHE) in series. The air leaving the DEC enters the secondary channels of the SHE, while the processed air passes through the primary channels of the SHE. In a wet-coil IEC, evaporative cooling and heat exchange occur in parallel.

Various empirical and theoretical models for predicting the thermal performance of the IEC have been proposed over the last few decades. Maclaine-Cross and Banks [6] proposed an approximate linear model for a wet-surface heat exchanger using an analogous solution for the wet-bulb temperature and wet-bulb depression. Erens and Dreyer [7] proposed a simplified model for predicting the effectiveness of an IEC by modifying Poppe's and Merkel's model, and then suggested the optimal cooler shape. Guo and Zhao [8] conducted a numerical parametric analysis of the thermal performance of an IEC. Stoitchkov and Dimitrov [9] presented a method for calculating the effectiveness of an IEC based on an improvement to Maclaine-Cross and Banks's model. Alonso et al. [10] derived a theoretical model for predicting the effectiveness of an IEC centered on the Maclain-Cross and Banks [6] and Erens and Dreyer [7] models, and validated the theoretical model using experimental data. El-Dessouky et al. [11] developed a model for predicting the efficiency of an IEC system and the Nusselt number correlation based on experimental results. Chengqin and Hongxing [12] developed a detailed analytical model for an IEC by applying non-unity values of the Lewis factor to incomplete surface wetting. Hettiarachchi et al. [13] produced a theoretical model for the effectiveness of a longitudinal IEC. Kiran and Rajput [14] suggested modeling approaches for predicting the performance of an

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Nomenclature

U	overall heat transfer coefficient [W/m^2 K]
α	thickness [m]
i	enthalpy of air [kJ/kg]
k	thermal conductivity [W/m K]
h_s	convective heat transfer coefficient [W/m^2 K]
h_m	convective mass transfer coefficient [W/m^2 K]
c_p	specific heat of air [kJ/kg K]
c_w	wet-bulb specific heat of air [kJ/kg K]
Nu	Nusselt number
Re	Reynolds number
Pr	Prandtl number
D_H	Hydraulic diameter
u	average fluid velocity [m/s]
$\dot{m}$	mass flow rate [m^3/s]
W	fin height [m]
D	fin spacing [m]
μ	dynamic viscosity [kg/m s]
ρ	density [kg/m^3]
Greek symbols	
ε	effectiveness [%]
Superscripts	
wb	wet-bulb temperature [C]
Subscripts	
a	air
pl	plate
wf	water film
p	primary channel
s	secondary channel
t	temperature [C]
i	inlet of channel
o	outlet of channel
Abbreviations	
HVAC	heating, ventilation, and air-conditioning
DBT	dry-bulb temperature
WBT	wet-bulb temperature
DEC	direct evaporative cooler
IEC	indirect evaporative cooler
SHE	sensible heat exchanger
RH	relative humidity

IEC using a fuzzy inference system, an artificial neural network, and adaptive neuro fuzzy inference systems. Zhan et al. [15] used the finite element method to develop a numerical model for the thermal performance of an IEC with an M-cycle cross-flow heat exchanger and validated the model through a comparison with an existing model derived from experimental data. Zhan et al. [16] conducted a comparative study of a counter-flow and cross-flow M-cycle IEC using a finite-element-based numerical computer model and validated their results using experimental data. Hasan [17] offered an analytical model for an IEC based on the $\varepsilon - NTU$ method and validated the model results using experimental data drawn from literature.

There are many other examples in open literature addressing the energy saving potential of employing the IEC for pre-conditioning the incoming outdoor air in the conventional HVAC system. Maheshwari et al. [18] presented incorporating the cooling energy saving potential to pre-cool the outdoor air using IEC in various locations in Kuwait. The cooling capacity, peak power-requirement, and seasonal energy savings of IEC unit were compared with those of a conventional packaged air-conditioner. Delfani et al. [19] investigated the performance of an IEC in pre-cooling in a conventional mechanical cooling system for four cities of Iran. The results showed that IEC reduces 75% of cooling load and 55% of electrical energy consumption during the cooling season. Chen et al. [20] conducted a case study for applying a regenerative IEC to an all-fresh-air hybrid air-conditioning system in Hong Kong. The results revealed that a regenerative IEC system can save more than 45% of the annual energy compared with rotating heat recovery wheel systems.

Established research on IEC performance prediction and its impact on building energy conservation is found in open literature. More research, however, is required for fitting IEC models into practical use in building HVAC system simulations, design, engineering, and controls, as well as estimating the annual energy saving potential of the wet-coil IEC in the HVAC system applications.

Consequently, the objective of this study was to develop two simplified models for the sensible effectiveness of a wet-coil IEC based on primary and secondary air conditions and physical information about the wet-coil IEC. The proposed IEC models were derived by analyzing the performance data using 2^k-factorial experiment design approach. For validating the proposed models, a wet-coil IEC unit was built and tested in an environmental chamber to collect real performance data and compare to the model predicted values. The cooling energy savings achievable with the IEC unit, compared with the cooling energy consumption of a conventional VAV system with wet-coil IEC pre-conditioning of incoming outdoor air ventilation, was also evaluated.

2. Indirect evaporative cooler

2.1. Theoretical model for a wet-coil IEC

The thermal performance of a wet-coil IEC can be expressed as a simple, steady-state, one-dimensional heat and mass transfer process. Fig. 1 shows the thermal resistance network of a wet-coil IEC under wet and dry operating conditions. Under wet operating conditions (Fig. 1(a)), heat is transferred from the secondary channel air to the water film by convection, and from the water film to the heat exchanger plate by conduction [21]. The primary air is cooled on the plate surface by convection (Eq. (1)). The heat exchanger plate temperature is assumed to be the same as the sprayed water temperature, and the water temperature is the same as the wet-bulb temperature of the intake air. The entire plate surface of the secondary channel is uniformly wetted by the sprayed water. The Lewis number is unity.

Under dry operating conditions (Fig. 1(b)), the mechanism for heat transfer between the primary and secondary channels is almost identical (Eq. (2)), but the medium is dry, and there is no water sprayed.

$$\dot{q}_{wet} = U_{pi-wf}A(t_{pi} - t_{wf,si}) \tag{1}$$

$$\dot{q}_{dry} = U_{pi-si}A(t_{pi} - t_{si}) \tag{2}$$

where

$$U_{pi-wf} = \left(\frac{1}{h_{a,p}} + \frac{a_p}{k_p} + \frac{a_{w,s}}{k_{w,s}}\right)^{-1}$$

$$U_{pi-si} = \left(\frac{1}{h_{a,p}} + \frac{a_{pl}}{k_{pl}} + \frac{a_s}{k_s} + \frac{1}{h_{a,s}}\right)^{-1}$$