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Research Paper

Developing a performance correlation for counter-flow regenerative indirect evaporative heat exchangers with experimental validation

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HIGHLIGHTS

- The performance correlation for counter-flow regenerative IEHX is developed.
- Three dimensionless groups are identified to evaluate the thermal performance.
- The empirical constants are determined via data-fitting from simulation results.
- Experimental study is conducted to validate the developed correlation.

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ABSTRACT

The present article aims to determine a minimum parametric representation for evaluating the thermal performance of a counter-flow regenerative IEHX (indirect evaporative heat exchanger). Three dimensionless groups have been identified in order to develop a performance correlation based on non-dimensional forms of the governing equations. Numerical simulations were carried out to determine the empirical constants of the correlation by fitting the simulated dimensionless outlet temperature as a function of each dimensionless group. Simulations have been conducted by changing the value of each dimensionless group while keeping a constant value for other parameters. The simulated dimensionless outlet temperature was varied from 0.20 to 0.73. A prototype of a counter-flow regenerative IEHX was designed and experimentally studied. The correlation was validated by comparing the calculated results with experimental findings as well as published experimental data acquired from literature. The developed correlation is able to predict the performance of the counter-flow regenerative IEHX within a discrepancy of 12%. We further demonstrated that the correlation could be a practical approach to predict the performance and optimize the configuration of the IEHX.

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1. Introduction

The evaporation of water into the air is a natural phenomenon resulting in a reduction of the air stream dry-bulb temperature. Due to the large latent heat of water evaporation, the evaporative cooling system is considered as an effective and promising technique for cooling applications. The IEHX (indirect evaporative heat exchanger) is able to produce cooled air without increasing its absolute humidity. A typical IEHX comprises a series of plates separating the primary air in the dry channel and the secondary air in the wet channel.

To comprehensively study the simultaneous heat and mass transfer process that occurs in the evaporative cooler, mathematical modelling has been the subject of many research works found in literature [1]. For a conventional indirect evaporative cooling unit, the theoretical minimum temperature of the primary air is its wet-bulb temperature [2,3]. Theoretical studies showed that the thermal performance of IEHX is affected by several key parameters such as the channel dimension, the intake air humidity ratio and temperature [4]. Guo and Zhao [5] conducted parametric study and discussed the optimal parameters for designing the indirect evaporative cooler.

To achieve a sub-wet bulb cooling, researchers have proposed different methods to further improve the thermal performance of the indirect evaporative cooler. Hsu et al. [6] investigated four prototypes of the IEHX and indicated that the air can be cooled to a temperature lower than its inlet wet-bulb temperature by using

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Nomenclature

A	area [m^2]
α	thermal diffusivity [m^2/s]
c	molar concentration [mol/m^3]
c_{pa}	specific heat of moist air [kJ/(kg·K)]
D	diffusivity [m^2/s]
h_c	convection heat transfer coefficient [kW/(m^2·K)]
h_m	mass transfer coefficient [kg/(m^2·s)]
h_{fg}	specific latent heat of water evaporation [kJ/kg]
H	height of the channel [m]
k	thermal conductivity [kW/(m·K)]
L	length of the channel [m]
Le_f	Lewis factor
m	mass flow rate of air [kg/s]
M	molar mass [kg/mol]
Nu	Nusselt number
p	pressure [kPa]
T	temperature [°C]
u	velocity in x direction[m/s]
v	velocity in y direction [m/s]
W	width of the channel [m]
ω	humidity ratio [kg/kg]
ρ_a	air density [kg/m^3]
θ	dimensionless group
ξ	dimensionless coefficient
Π	dimensionless group
x	spatial coordinate in Cartesian systems; flow length in a channel [m]
y	spatial coordinate in Cartesian systems

Subscript

a	air
p	primary air, primary channel
s	secondary air, secondary channel
in	inlet
out	outlet
w	water film, plate
dew	dew-point temperature

Superscript

$*$	dimensionless parameter

the counter-flow closed-loop configuration. Maisotsenko [7] introduced an air flow arrangement, known as "M-cycle", to approach the supply air temperature to the dew-point [8]. Caliskan et al. [9] compared three air coolers operating on M-cycle using energy and exergy analyses. The main feature of this type of IEHX is to redirect part of the primary air into the secondary channel before it is finally delivered [10,11]. Zhao et al. [12] carried out a numerical investigation on a counter-flow dew-point evaporative cooler which is capable of achieving a wet-bulb effectiveness up to 1.3. Another plate type dew-point evaporative system was experimentally and numerically studied by Riangvilaikul and Kumar [13,14]. The design parameters were also optimized for the IEHX and investigated for its cooling effectiveness under different operating conditions [15,16]. Xu et al. [17] proposed a guideless irregular air flow channel for dew point cooling. Simulation results indicated that the heat exchanger showed an improved energy efficiency compared to the existing flat-plate heat exchangers. Lin et al. [18] presented an improved mathematical model and conducted a parametric study under varying geometric and operating conditions. She et al. [19] studied two different air flow patterns of evaporative cooling and dehumidification process to obtain the optimum configurations of a hybrid refrigeration system. Woods and Kozubal [20] presented numerical results and experimental data on a liquid desiccant enhanced evaporative air conditioner with a second stage having a plate type counter-flow regenerative IEHX.

Several researchers also investigated cross-flow IEHXs and compared their thermal performance in terms of the air flow arrangement [21,22]. Moshari and Heidarinejad [23] indicated that the counter-flow regenerative IEHX can produce lower temperature comparing to cross-flow IEHX. Lee et al. [24] investigated and compared the performance of flat plate, corrugated plate and finned channel type IEHXs. Zhan et al. [25,26] studied the performance of a counter-flow and a cross-flow M-cycle IEHXs. Their results demonstrated that the counter-flow arrangement could produce about 20% higher cooling capacity and 15–23% greater dew-point effectiveness in comparison to the cross-flow configuration. Anisimov and Pandelidis [27,28] developed a numerical model to study the effect of different flow patterns on the performance of IEHX. Their simulation results also indicated that the parallel and regenerative counter-flow configurations of IEHX improve the cooling effectiveness [29].

Besides the numerical model, several analytical models have been developed based on the modified ε-NTU method [30,31] or modified LMTD method [32] to account for the latent heat transfer due to water evaporation.

The evaporative cooling unit can be easily integrated with existing air-conditioning system to realize wider air-conditioning application [33]. For example, Heidarinejad et al. [34,35] proposed a hybrid system of nocturnal radiative cooling, evaporative cooling, and cooling coil. Kim and Jeong [36] evaluated the energy performance of an indirect and direct evaporative cooler assisted 100% outdoor air system. Montazeri [37] theoretically investigated the cooling performance of a water spray system with a hollow-cone nozzle. Islam et al. [38] experimentally and numerically investigated the performance of an air-conditioning unit with evaporative-cooled condenser. Researchers reported that the IEHX can be used as a pre-cooling unit combined with the conventional vapor compression system [39,40]. The moisture of the primary air may condense under humid climate conditions. Theoretical analysis has also been conducted to investigate the achievable rate of moisture condensation.

It can be observed from previous works that the performance of IEHX is influenced by a number of system parameters, such as channel height, channel length, intake air temperature, intake air humidity ratio, and intake air velocity. The literature review indicates several research gaps. Firstly, previous theoretical studies were conducted to examine the effect of a specific operating parameter [5,11–13,15,27]. However, existing works have yet to adequately analyze the combined influence of various design and operating parameters. Secondly, many numerical formulations employ complex numerical methods and require long computational time due to numerous iterative calculations in order to achieve the desired solution accuracy [11–13,22–25]. Few attempts have been made to develop practical correlations that enable one to conveniently evaluate the performance of counter-flow regenerative IEHXs without any iterative processes.

To address these issues, the present study proposes the development of an empirical correlation based on dimensionless groups for the purpose of evaluating the thermal performance of a

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