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Replication Studies

Performance analysis of counter-flow regenerative heat and mass exchanger for indirect evaporative cooling based on data-driven model

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ABSTRACT

This paper investigated the performance of a regenerative heat and mass exchanger (RHMX) for indirect evaporative cooling. A numerical model for RHMX was developed and validated with experimental data from the literature. Then, a data-driven model based on artificial neural network (ANN) algorithm was presented which was derived from the simulation results generated from the numerical model. The comparison between ANN prediction and experiment data showed good prediction accuracy. The average prediction error between the predicted and tested data was around 4% based on the air temperature change across the dry channel. With the data-driven model, parametric analyses were made to investigate the performance of the RHMX under different operating conditions. Finally, a design optimisation of the extraction air ratio was conducted under different ambient conditions. It was found that the optimal extraction air ratio decreased with the ambient temperature and/or relative humidity which ranged from 0.3 to 0.36.

1. Introduction

The outlook of future development reveals that we will encounter serious energy crisis. Among all the energy end-use, building sector accounts for more than 30%. Heating, ventilation and air-conditioning (HVAC) systems contribute a huge energy challenge in today's modern buildings. The traditional HVAC system is based on vapour-compression cycles which are not only consuming a lot of primary energy but also responsible for global warming [1] due to the utilisation of hydrochlorofluorocarbons and chlorofluorocarbons. The evaporative cooling is an alternative technique to solve the problems which traditional HVAC systems have to encounter. Generally speaking, the evaporative cooling can be divided as direct evaporative cooling (DEC) and indirect evaporative cooling (IEC). The DEC is used for the cooling purposes in the dry and hot regions. This type of system provides the sufficient cooling supply, but it increases the humidity of the supply air and reduces the comfort feeling of the occupants. The way to overcome the problem is the use of IEC, which separates the supply air from the working air to avoid the addition of any moisture content. Though conventional IEC handles the humidity properly, the effectiveness of this system is low which traps the IEC into HVAC applications.

A novel regenerative heat and mass exchanger (RHMX) for IEC, which utilises the advantageous aspects of both the DEC and IEC systems but minimises the drawbacks, had been put forward as early as 1976 by Maisotsenko and his colleagues in Soviet Union [2]. He developed a new thermodynamic cycle named as "Maisotsenko Cycle". It is also called the M-cycle which uses the conventional IEC, but with a much different airflow. The main advantage of the RHMX is that it uses part of cooling air in the primary channel into secondary channel, which helps improve its efficiency as shown in Fig. 1.

Several researchers had developed numerical models to estimate the performance of the RHMX. Zhao et al. [3] presented a numerical investigation of a counter-flow and cross-flow RHMX with the application for dew-point evaporative cooling techniques. Based on the simulation results, they indicated the RHMX cooling performance was mainly affected by the RHMX geometrical parameters, the extraction air ratio and the intake flow rate. Pandelidis and Anisimov [4–7] developed a two-dimensional heat and mass transfer model to study the effect of different flow patterns. The presented numerical model was validated against experimental data. Simulations results revealed that the counter-flow

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Nomenclature

c_p	Specific heat capacity at constant pressure (kJ/kg °C)
D_h	Hydraulic diameter (m)
dA	Incremental area between the dry and wet channel in the discretisation element (m^2)
H	Channel height (m)
h	Specific enthalpy (kJ/kg)
$\overline{h_w}$	Mean specific enthalpy in the wet channel of the discretisation element (kJ/kg)
k	Thermal conductivity (kW/m °C)
L	Channel length (m)
Le	Lewis number
m	Mass flow rate (kg/s)
Nu	Nusselt number
Q	Cooling capacity (kW)
RH	Relative humidity (%)
r_{ex}	Extraction air ratio
T	Temperature (°C)
$\overline{T_d}$	Mean temperature in the dry channel of the discretisation element (°C)
U	Overall heat transfer coefficient (kW/m^2 °C)
u	Air velocity (m/s)

Greek

α	Convective heat transfer coefficient (kW/m^2 °C)
β	Mass transfer coefficient (kg/m^2 s)
δ	Plate thickness (mm)
ε	Dew-point effectiveness
ω	Humidity ratio (kg/kg)
$\overline{\omega_w}$	Mean humidity ratio in the wet channel of the discretisation element (kg/kg)

Subscripts

1, 2, 3	State points in the RHMX
a	Air
d	Dry channel
dew	Dew-point
f	Water film
i	Inlet of the discretisation element
in	Dry channel inlet of the RHMX
o	Outlet of the discretisation element
p	Separating plate between the dry and wet channels
s	Supply air
sat	Saturated condition
w	Wet channel
wa	Moist air
wb	Wet-bulb

Abbreviations

ANN	Artificial neural network
DEC	Direct evaporative cooling
IEC	Indirect evaporative cooling
HVAC	Heating, ventilation and air-conditioning
M-cycle	Maisotsenko cycle
RH	Relative humidity
RHMX	Regenerative heat and mass exchanger

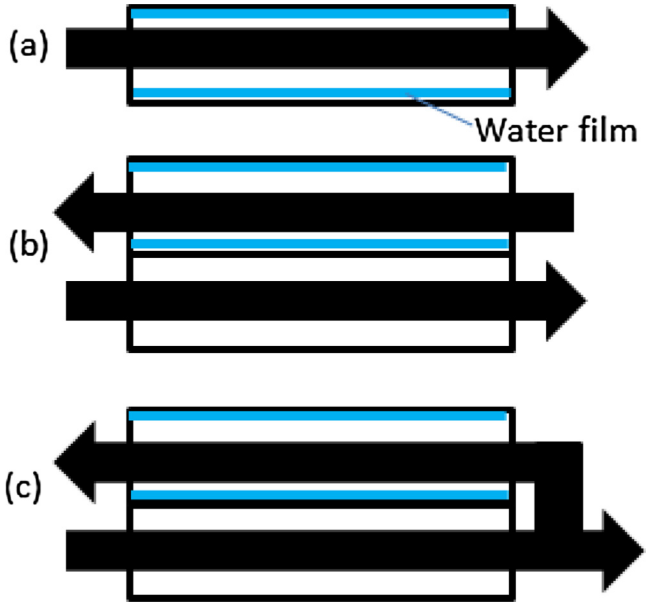

Fig. 1. Different heat and mass exchanger configuration for evaporative cooling (a. Direct; b. Indirect; c. Regenerative).

configurations RHMX showed better performance [8]. Zhan et al. [9,10] conducted a numerical model of cross-flow and counter-flow RHMX. The simulation purpose was to obtain thermal performance. The results also indicated that the counter-flow RHMX could produce a lower supply temperature as compared to the cross-flow one. Moshari and Heidarinejad [11] numerically simulated cross-flow and counter-flow RHMX with consideration of the longitudinal heat conduction through the heat transfer wall. Woods and Kozubal [12] presented modeling and experimental results on a liquid desiccant air conditioner, which consisted of two stages: a liquid desiccant dehumidifier and a counter-flow RHMX. Cui et al. [13] installed physical ribs in air channels and investigated its performance on a counter-flow RHMX. It was found that installing ribs enhanced the wet-bulb effectiveness by 10–20%. Another numerical study of a counter-flow RHMX consisting of separated working channels and product channels was also performed by Cui et al. [14]. Lin et al. [15] developed a transient model for a counter-flow RHMX. Their transient model approaching steady conditions agreed well with the steady state model and could predict the experimental data within 4.3% discrepancy. They [16] also presented an improved mathematical model for a single stage RHMX in a counter-flow configuration. Longitudinal heat conduction and mass diffusion of the air streams, channel plate and water film, as well as the temperature difference between the plate and water film, were accounted for in the model. Table 1 summaries the numerical studies of the RHMX and their respective simulation parameters.

Experimental researches on the RHMX were also conducted by several researchers. Hsu et al. [17] studied four types of the IEC and indicated that the RHMX could cool the air temperature to lower than its wet-bulb temperature. Zhan et al. [10] provided a comparative study of the performance of cross-flow and counter-flow RHMX for dew-point cooling. They showed that the counter-flow exchanger offered around 20% higher cooling capacity, as well as around 15%-23% higher dew-point and wet-bulb effectiveness. Lee et al. [18] experimentally studied a counter-flow RHMX with finned channels. In their RHMX, fins and heat transfer plates were made of aluminum and brazed for good thermal connection and a thin porous layer coating was applied to the internal surface of the wet channel in order to improve surface wettability. They showed that their RHMX could achieve leaving air temperatures below the wet-bulb temperatures of the inlet air. In order to determine the efficiency and water consumption of an RHMX, Rogdakis et al. [19] constructed an experimental installation which could provide multiple options of inlet conditions and supported by measurement systems. It was found that under different conditions and in the optimisation mode, the efficiency levels varied between 97% and