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Optimal design of a hybrid liquid desiccant-regenerative evaporative air conditioner

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ABSTRACT

This paper presents the optimal design of a hybrid liquid desiccant-regenerative evaporative air conditioner. A hybrid air conditioner was proposed which comprises a liquid-to-air membrane energy exchanger (LAMEE) as a desiccant dehumidifier and a regenerative heat and mass exchanger (RHMX) as an evaporative cooler. The air conditions across the LAMEE and the RHMX were achieved by two heat and mass transfer sub-models, and validation of the sub-models was conducted by comparison of the simulation results against the published experimental measurements. Intake air flow rate, LAMEE-to-total length ratio and working-to-intake air flow ratio are regarded as design variables. The simplified conjugate gradient method (SCGM) was employed as an optimization scheme to find the optimum set of design variables, which maximizes the room cooling capacity (RCC) of the proposed hybrid air conditioner. The influences of different design and operating conditions on the optimal RCC and the optimum set of design variables were studied.

1. Introduction

Regenerative evaporative coolers (RECs) are economically feasible and environmentally friendly cooling systems, which can provide comfort in arid or semiarid regions. In a REC, a regenerative heat and mass exchanger (RHMX) with a series of dry and wet passages is incorporated (see Fig. 1(a)). In the dry passages, a product air stream is passed and sensibly cooled due to the evaporation of water in the adjoining wet passages. At the end of the dry passages, an indirectly precooled working air stream is extracted from the product air stream, and routed through the wet passages in order to absorb the heat of the product air stream. Finally, the cool product air stream is conveyed to the conditioned room and the moist and hot working air stream is released into the atmosphere.

Several research were performed to study RHMXs. Hsu et al. [1] conducted numerical and experimental investigations on counter flow and cross flow RHMXs in order to achieve a sub wet bulb temperature. Zhao et al. [2] performed a numerical analysis on a counter flow RHMX to obtain the maximum cooling performance. Hasan [3] conducted a numerical study on a RHMX and reported a wet bulb effectiveness of 116%. Riangvilaikul and Kumar [4,5] numerically and experimentally studied a RHMX to assess the exchanger performance at different climatic zones. Anisimove et al. [6] investigated a combined REC to attain the optimum values of operating variables and preferred climatic zones. Fakhrabadi and Kowsary [7] presented the optimal room cooling capacity of a typical RHMX by employing an optimization method.

The ultimate temperature that can be achieved by a REC is the dew point temperature of the entering product air stream. Thus, use of a stand-alone REC is limited to arid or semiarid climatic zones. In regions with humid and hot climates, and therefore high dew point temperatures, the cooling performance of a REC drops drastically [4–7]. To overcome the drawback of the cooler and extend its use to humid and hot climates, a desiccant dehumidifier could be installed at its inlet in order to precondition the incoming air stream. The desiccant dehumidifier absorbs moisture from the product air stream and reduces its dew point temperature; hence the cooling performance of the REC is enhanced.

Hybrid air conditioners comprise a desiccant dehumidifier and an evaporative cooler have been studied in several research. Goldsworthy and White [8] investigated a hybrid air conditioner comprises a desiccant wheel and an evaporative cooler in order to find the optimum secondary to primary and supply to regeneration flow ratios for the cooler and the desiccant wheel respectively. Woods and Kozubal [9] proposed a desiccant based evaporative cooler and performed numerical and experimental analysis for different operating conditions and compared the results. Gao et al. [10] conducted an experimental study on a hybrid air conditioner,

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Nomenclature

A	Heat and mass transfer area (m^2)
C_{sol}	Solution concentration (%)
c_p	Specific heat capacity (J/kg K)
D_h	Hydraulic diameter (m)
d_m	Membrane thickness in LAMEE (m)
d_w	Wall thickness in RHMX (m)
f	Objective function
H	Channel height (m)
h	Specific enthalpy of moist air (J/kg)
h_{fg}	Latent heat of vaporization (J/kg)
k	Thermal conductivity (W/m K)
L	Length (m)
Le	Lewis number
M	Mass flow rate (kg/s)
Nu	Nusselt number
P	Pressure (Pa)
Pe	Peclet number
R_m	Mass transfer resistance (m^2 s kg)
RCC	Room cooling capacity (W)
S	Search direction
T	Temperature (°C)
U	Overall heat transfer coefficient (W/m^2 K)
U_m	Overall mass transfer coefficient (kg/m^2 s)
V	Mean air velocity (m/s)
W	Channel width (m)
$\dot{W}$	Fan power (W)

Greek letters

α	Convective heat transfer coefficient (W/m^2 K)
β	Convective mass transfer coefficient (kg/m^2 s)
γ	Conjugate gradient coefficient
λ^*	Optimal step size
μ	Dynamic viscosity (Pa s)
π	Relative pressure
ρ	Density (kg/m^3)
ϕ	Design variable
ω	Humidity ratio (kg_{water}/kg_{dryair})
∇	Gradient

Superscripts

$\rightarrow$	Vector
i	Inlet
n	Node
o	Outlet
T	Transpose symbol

Subscripts

abs	Absolute
air	Air
f	Water film
i	Intake
in	Inlet
j	Iteration number
L	LAMEE
m	Membrane
msi	Membrane-solution interface
p	Product air
R	RHMX
sat	Saturated condition
sol	Solution
sup	Supply
T	Total
w	Working air; Wall

which incorporates a liquid desiccant (LD) dehumidifier and an M-cycle evaporative cooler, and adopted some indicators to assess the system's performance under various conditions. Heidarinejad and Pasdarshahri [11] studied a hybrid solid desiccant (SD)-evaporative air conditioner for the sake of obtaining the optimal regeneration temperature and speed of rotation for the desiccant wheel, in which the hybrid has the lowest output temperature. Kim et al. [12] proposed the integration of a LD absorber into an indirect direct evaporative cooler, and performed an energy simulation to evaluate the effect of the absorber on the cooler's performance. Gao et al. [13] numerically studied an integrated air conditioner comprises a desiccant wheel and a REC in order to assess the influences of operating factors on the conditioner's performance. Cui et al. [14] proposed a compact LD-evaporative air conditioner, and showed that by utilizing the proposed conditioner a sub dew point temperature can be achieved. Ham et al. [15] examined a hybrid air conditioner, which integrates a LD absorber and a REC, in order to evaluate the energy savings of the conditioner in comparison to a typical VAV system.

Study of investigations regarding hybrid LD-regenerative evaporative air conditioners reveals that merely parametric studies have been performed thus far and no optimization procedure has been conducted to come up with the optimal performance parameters of these systems. Although hybrid LD-regenerative evaporative air conditioners are economically feasible, they suffer from some shortcomings. Size of these systems is large, and this limits their use. Therefore, it seems essential to address this shortcoming of these systems and to reduce their size by optimizing their performance.

In this study, a hybrid liquid desiccant-regenerative evaporative air conditioner (LD-REAC) is proposed, and its performance is optimized at various climate, design and operational conditions by employing the simplified conjugate gradient method (SCGM). The proposed air conditioner comprises a liquid-to-air membrane energy exchanger (LAMEE) as an absorber, and a regenerative heat and mass exchanger (RHMX) as an evaporative cooler (see Fig. 1).

The sensible and latent effectiveness of the LAMEEs as air dehumidifiers in LD based air conditioners have been investigated by several researchers. Vali et al. [16] modeled a LAMEE having a counter cross flow pattern and compared its performance to counter and cross flow configurations. Ge et al. [17] carried out analytical and experimental investigations to assess the influences of various operating parameters on a LAMEE performance when incorporated as an absorber or a regenerator. Abdel-Salam et al. [18] numerically analyzed the performance of a LD air conditioner which incorporated LAMEEs both as an absorber and a regenerator by means of TRNSYS simulation software.

In the following sections, first the hybrid LD-REAC is described. Two heat and mass transfer sub-models that have been used to compute the air conditions throughout the exchangers are given thereafter, and validation of the sub-models was conducted by comparison of the simulation results against the provided experimental measurements. The optimization problem formulation is then presented. Subsequently, The SCGM is explained as an optimization approach. Afterwards the room cooling capacity (RCC) of the hybrid LD-REAC is maximized by setting the design variables intelligently. Finally, the influences of different design and operating conditions on the optimal RCC and the optimum set of design variables were studied.

2. Description of the hybrid air conditioner

Schematic of the proposed hybrid LD-regenerative evaporative air conditioner is presented in Fig. 2. This hybrid air conditioner