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Multi-stage liquid-desiccant air-conditioner: Experimental performance and model development

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A R T I C L E I N F O

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A B S T R A C T

An experimental study evaluated the performance of a novel multi-stage liquid-desiccant air-conditioner featuring parallel inter-stage flows of cooling and heating water, and semi-series flows of desiccant. The system was tested at different inlet cooling water temperatures, ranging from 8 °C to 20 °C, using a solution of LiBr and water as the desiccant. Average total air cooling rates between 8.4 kW and 19.7 kW were observed, with higher cooling rates achieved with lower cooling water temperatures. The system was able to provide high sensible cooling rates of up to 8.8 kW. The cooling water temperature impacted the sensible cooling, but did not have a discernible impact on the latent cooling rate. The inlet air humidity was shown to have an impact on the latent cooling rate, with higher humidity leading to higher latent cooling rates. The energy consumption of the system was low, with an average thermal coefficient of performance (COP) of 0.58 and electrical COP of 4.7. A variable effectiveness model was developed in TRNSYS and proven to be accurate at predicting the air cooling, but further experimental work is required to improve the thermal energy consumption model. The modular design philosophy of the model allows for easy changes to the design (e.g., number of stages, fluid flow paths, operating conditions, etc.) enabling future work to improve the regenerator modeling once further experimentation is completed.

1. Introduction

To achieve thermal comfort during the warmer seasons of the year, HVAC systems need to reduce both the temperature (sensible cooling) and the moisture content of the air (latent cooling). Typical air-conditioning systems often use vapour-compression systems (VC) that excel in reducing the temperature of the air but are limited in their capacity to dehumidify. VC systems over-cool the air to reach the dew point and condense moisture from the air. The air must then be reheated to comfortable levels increasing the energy consumption of the system. The sensible cooling load in most climates is less than the latent load [1], making VC systems a less than ideal choice. VC systems also consume large amounts of electrical power.

A thermally driven liquid-desiccant air-conditioner (LDAC) solves both the problems of humidity control and high electrical power consumption. LDAC units use a liquid-desiccant to remove moisture from a process air-stream. During operation, the hygroscopic nature of the desiccant solution removes water-vapour from the air-stream, lowering the solution's concentration as the water is absorbed. To produce a continuous process, the diluted desiccant solution is pumped to a regenerator where low grade heat is used to reject the absorbed water into a scavenging air-stream.

When compared to a VC system, the LDAC system can reduce the electrical demand required for cooling as humidity control is achieved without the use of a compressor. Power is only needed for fans and pumps. Previously studied LDAC units showed the potential of these systems as an effective choice for air-conditioning when used as part of a dedicated outdoor air system (DOAS) [2]. They can treat the incoming ventilation air and decouple the sensible and latent cooling loads. A smaller secondary chiller can be used to provide sensible cooling if required. The performance of these systems is affected by the operating conditions (e.g., process-air temperature and humidity). For example, Yin et al. found that warmer air temperatures reduced the cooling rate while more humid air increased the cooling rate [3].

There are several technologies and designs available that use liquid-desiccants. Some designs used a semi-permeable membrane to separate air-streams from the desiccant solution [4]. This design

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Nomenclature

Variable definition

C_{min}	minimum heat capacity rate (kW · °C)
c_p	heat capacity (kJ/kg · °C)
h	enthalpy (kJ/kg)
$\dot{m}$	mass flow rate (kg/s)
p	partial pressure (Pa)
Q	energy (kJ)
$\dot{Q}$	power (kW)
RH	relative humidity (%)
T	temperature (°C)
X	mass fraction (−)
ε_{des}	effectiveness of water to desiccant heat transfer (−)
$\varepsilon_{moisture}$	effectiveness of air moisture removal (−)
ε_{regen}	effectiveness of desiccant regeneration (−)
$\varepsilon_{temperature}$	effectiveness of air to desiccant heat transfer (−)
ω	absolute humidity ratio (kg_w/kg_a)

Subscripts

a	air
abs	absorbed water
cw	cooling water
d	desiccant solution
elec	electrical energy
fg	evaporation
hw	heating water
in	inlet
lat	latent
load	thermal energy load of the regenerator
max	maximum
min	minimum
out	outlet
sen	sensible
tot	total

Abbreviations

abs. diff.	absolute difference
CIT	constant inlet temperature
COP_e	electrical coefficient of performance
COP_T	thermal coefficient of performance
DOAS	dedicated outdoor air system
exp.	experimental results
HVAC	heating, ventilation and air-conditioning
LDAC	liquid-desiccant air-conditioner
sim.	simulation results
VC	vapour-compression

eliminated the carryover of corrosive desiccant solution into the air-stream by using the membrane as a barrier between the air-stream and the desiccant solution, blocking desiccant transfer while allowing moisture transfer. Carry-over elimination is important because the desiccant solutions used are corrosive and can cause damage to downstream equipment. The semi-permeable membrane design's drawback is the additional thermal and mass-transfer resistance and its susceptibility to desiccant crystallization, both which of which can degrade performance.

Other studies have analysed internally cooled/heated low-flow laminar falling film configuration [5–8]. In this design a thin film of desiccant solution flows down the outside of a series of parallel plates, fins, or other surfaces. By maintaining a low flow rate and laminar flow, carry-over of the desiccant into the air-stream is effectively eliminated. This unit is not as susceptible to damage from desiccant crystallization as some crystallization can build up on the plates without affecting performance. The downside of this design is the complexity of the combined heat and mass exchangers.

There are many examples of using packed-beds as heat and mass transfer devices in LDAC systems [3,9–12]. In the conditioner, the desiccant solution is pre-cooled and sprayed over a bed of random or structured packing materials. As the desiccant flows through the bed, it comes into direct contact with the process air-stream being blown across the bed. This allows for the mass transfer of water into the desiccant solution. In the regenerator, the reverse process occurs and the desiccant is pre-heated and put into contact with a scavenging air-stream.

Internally cooled conditioners are typically performance-limited by the concentration reducing as the desiccant absorbs moisture inside the conditioner, whereas packed-bed systems are limited as the desiccant heats up as it absorbs moisture [6]. One method to reduce the impact of the temperature gain is to use multiple stages that allows for cooling of the desiccant between stages. This improved cooling can increase the dehumidification, due to the lower vapour pressures [13], as well as provide lower process-air outlet temperatures [12]. For the regenerator, the use of multiple stages can be used to maintain a higher temperature throughout the regenerator without having to use a higher inlet temperature. This is similar to how multiple stages can be used to lower the required hot water temperature in adsorption chillers [14]. Multiple stages were also found to increase energy efficiency in a novel electro-dialysis regenerator [15].

The present work experimentally studied and modeled a multi-stage, structured packed-bed, liquid-desiccant system. Other researchers [16,17] have used a variety of different multi-stage designs which have shown that additional stages can increase the performance of the system, chiefly the COP_T. An exergy destruction and performance analysis confirmed the benefits of multiple stages and found that three to four stages was an optimal number of stages so reducing exergy destruction [18].

The system's performance was monitored by determining the total, latent, and sensible air cooling rates ($\dot{Q}_{tot}$, $\dot{Q}_{lat}$ and $\dot{Q}_{sen}$) and by determining the system's thermal and electrical coefficient of performance (COP_T and COP_e). The COPs were calculated according to Eq. (1) and Eq. (2). The total air cooling load (Q_{tot}) was the combination of the sensible cooling energy and the latent cooling energy, while Q_{load} and Q_{elec} were the total amount of thermal energy needed to drive the regenerator and the total amount of electricity needed to run the system (including all pumps, fans, and control systems).

$$COP_T = \frac{Q_{tot}}{Q_{load}} \tag{1}$$

$$COP_e = \frac{Q_{tot}}{Q_{elec}} \tag{2}$$

The design studied in the present work features a packed-bed multi-stage design with a novel parallel cooling/heating water supply and a semi-series desiccant flow through the system. The objective of the present work was to determine if the packed-bed