



Research Paper

Energy saving potential of thermoelectric modules integrated into liquid desiccant system for solution heating and cooling

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HIGHLIGHTS

- A thermoelectric module-assisted liquid desiccant system was proposed.
- Two cases of thermoelectric module-assisted liquid desiccant systems were analyzed via energy simulation.
- The thermoelectric modules operated at both heating priority and cooling priority.
- The heating priority operation exhibited less energy consumption than other cases.

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ABSTRACT

The main objective of this research was to investigate the impact thermoelectric modules (TEMs) integrated into a liquid desiccant (LD) system have on the heating and cooling of the desiccant solution, and to evaluate the energy saving potential of the proposed system. Two TEM-integrated LD systems were considered; in the first case (i.e., Case A), the TEMs accommodated the solution heating load at the regenerator and a portion of the solution cooling load at the absorber. The remaining solution cooling load was met by an auxiliary chiller. In the second case (i.e., Case B), the TEMs accommodated both the solution cooling and heating loads before the absorber and the regenerator, while extra heat released from the hot side of the TEMs was reclaimed and used to heat the scavenger air entering the regenerator. The conventional LD system, with a boiler and a chiller for heating and cooling the desiccant solution, was also considered as a reference case, to evaluate the energy saving potential of both TEM-integrated LD systems. Hourly energy consumption and temperature variation in the desiccant solution in each system case were predicted via detailed energy simulation with existing mathematical and empirical models for each system component, such as the absorber, regenerator of LD, and TEMs. An approach for determining the required number of TEMs and the optimum temperature difference between the hot side and the cold side of the TEMs is also suggested, based on the coefficient of performance (COP) of the TEMs. It was found that a primary energy saving of about 2% could be expected in Case A compared with the reference case, whereas 55% more primary energy was consumed in Case B. Consequently, based on detailed energy simulations for the TEM-integrated LD system, it was found that the TEMs should be sized to accommodate the regeneration heating load of the desiccant solution before the solution enters the regenerator. In this case, the cooling capacity of the TEMs would be insufficient for cooling the strong solution before the solution enters the absorber, and an auxiliary cooling device would be required.

1. Introduction

In recent years, the independent control of latent and sensible loads of air conditioning in buildings has attracted considerable interest because of its potential to realize energy savings and enhance the quality of indoor environments [1]. Liquid desiccant (LD) dehumidification has been considered as one of the promising alternatives for the independent handling of latent loads in building air conditioning

applications [2–4].

Dehumidification and regeneration are exothermic and endothermic reaction processes [5], respectively. Therefore, the strong desiccant solution entering the absorber should be cooled, and the weak solution that is conveyed to the regenerator should be heated in order to increase the efficiency of dehumidification and regeneration in LD units [2,6]. Consequently, the heating and cooling of the desiccant solution consumes the most operational energy in LD units, as indicated in

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Nomenclature

A	uniform cross-sectional area [m^2]
C	thermal capacity [kJ/K]
C_p	specific heat capacity [$\text{kJ/kg}\cdot\text{K}$]
f_p	packing fraction of total TEM area covered by a thermo-element [–]
H	total pump head [m]
I	input current [A]
K	thermal conductance of the lumped TEM [W/K]
l	thickness of the TEM [m]
$\dot{m}$	mass flow rate [kg/s]
n	number of thermoelectric modules [–]
N	number of thermocouples in one TEM [–]
P	electrical power consumption [kW]
P	pressure [kPa]
Q	thermal energy [kW]
$\dot{Q}$	thermal energy per second [kW/s]
R	electrical resistance of the lumped TEM [Ω]
S	seebeck coefficient of the lumped TEM [V/K]
T	temperature [$^\circ\text{C}$]
$\dot{V}$	volume flow rate [m^3/s]
Z	figure of merit [K^{-1}]
ZT	dimensionless figure of merit [–]

Greek symbols

α	seebeck coefficient for compact TEM [V/K]
χ	concentration [–]
Δ	difference [–]
ε	effectiveness [–]
η	efficiency [–]
κ	thermal conductivity of the compact TEM [$\text{W}/(\text{m}\cdot\text{K})$]
ω	humidity ratio [kg/kg_a]
ρ	electrical resistivity of the compact TEM [$\Omega\cdot\text{m}$]
Υ	relative area for the thermoelectric elements [–]

Subscripts

air	air
abs	absorber
atm	atmosphere
c	cold
cws	cooling water supply
deh	dehumidification
eq	equilibrium
h	hot
in	inlet
oa	outdoor air
out	outlet
ref	reference
reg	regenerator
rem	remain
sol	desiccant solution
strong	strong desiccant solution
tot	total
tw	tap water
v	vapor
w	water
wb	water block
weak	weak desiccant solution

Abbreviations

BEC	boiler efficiency curve
CAPFT	cooling capacity factor
COP	coefficient of performance
EIRFT	energy input to cooling output factor
LD	liquid desiccant
PLR	part load ratio
SHX	sensible heat exchanger
TEM	thermoelectric module

previous studies [4,7,8]. The installation of an independent cooler and heater may allow solution cooling and heating demands to be met. However, a heat pump can be used to simultaneously cool and heat the desiccant solution based on the cooling capacity of the evaporator, and heat from the condenser [9–11]. Lazzarin and Catellotti [9] investigated a heat pump LD dehumidifier for supermarkets, and it achieved energy savings that ranged from 26 to 63% compared with a traditional air handling unit. Zhang et al. [10] also revealed a good coefficient of performance (COP) of heat pump-driven LD dehumidification, which averaged 6.5 according to the method for removing additional condensing heat. Xie et al. [11] proposed a counter-flow heat pump-driven LD system that showed a COP of 3 to 12 for the number of transfer unit (NTU) values within the range of 1 to 4. Thus, simultaneous heating and cooling using a heat pump in an LD system exhibits a good COP. However, conventional heat pumps have their own drawbacks in terms of their large size and use of refrigerants, which may have negative effects on the environment [12–14].

As an alternative solution to conventional vapor compression heat pumps, a thermoelectric module (TEM) based on the Peltier effect has been studied to realize a non-vapor compression heat pump [15,16]. Even though the TEM heat pump has a lower COP for cooling at the current stage than traditional heat pumps, it has several advantages, such as its compact size, the absence of moving parts, its noise-free operation, its precision temperature control, and the absence of refrigerants [17].

On the other hand, various applications of TEMs, including in air conditioner systems and cooling radiant panels, have also been

proposed in literature. Tan and Zhao [18] used a TEM for space cooling together with a phase-change material to store cold thermal energy at night. The stored energy was used to reduce the hot-side temperature of a TEM with a water-cooled unit. Liu et al. [19] proposed a thermoelectric cooled ceiling integrated with a displacement ventilation system. They used a photovoltaic (PV) system to supply the input current for the TEM, and the hot side of the TEM was air-cooled. Tipseanporm et al. [20] designed a thermoelectric air conditioner combined with direct evaporative cooling to release the heat from the hot side of the TEM. In general, it is important to release the heat from the hot side of the TEM in order to maintain the required cold-side temperature.

Thus, although studies investigating the potential for using TEMs for cooling or heating have increased, very few approaches have been proposed that use TEMs for simultaneous cooling and heating. Yilmazoglu [21] investigated a prototype thermoelectric air heating and cooling unit using numerical analyses and experiments, and showed the possibility of realizing simultaneous heating and cooling with an average COP of 0.7 for cooling and 4.1 for heating. Ramousse and Perier-Muzet [22] proposed a design for a thermoelectric heat pump that used a multi-channel heat exchanger for cooling and heating the fluid, by minimizing entropy generation in their proposed system. However, these studies are at the basic research stage and no study, to the best of the authors' knowledge, has investigated the potential of TEMs for simultaneous cooling and heating in building applications.

Consequently, we propose a TEM-integrated LD system that simultaneously cools and heats the desiccant solution. We estimated its

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