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Primary energy savings in desiccant and evaporative cooling-assisted 100% outdoor air system combined with a fuel cell

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HIGHLIGHTS

- A LD-IDECOAS integrated with a PEMFC was proposed.
- A pilot system was installed and tested during cooling operation.
- The proposed system powered by the PEMFC saved 21% of the primary energy consumption during cooling.

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ABSTRACT

The main purpose of this study involved investigating the primary energy saving potential of a liquid desiccant and evaporative cooling-assisted 100% outdoor air system (LD-IDECOAS) integrated with a proton exchange membrane fuel cell (PEMFC). During the cooling season, the heat produced by the PEMFC was used to regenerate a weak desiccant solution, and the electricity generated was used to operate the LD-IDECOAS. A pilot LD-IDECOAS powered by a PEMFC was installed and operated in an office space to experimentally verify the annual operating energy savings of the proposed system. The findings indicated that the heat reclaimed from the PEMFC saved 42% of the desiccant solution regenerating energy when compared to that in the case of a conventional gas-fired water heater. The results also suggested that the LD-IDECOAS combined with a PEMFC consumed 21% less primary energy when compared with that of a system powered by grid electricity and a conventional gas-fired water heater.

1. Introduction

Previous studies [1–9] suggested the use of a liquid desiccant and indirect/direct evaporative cooling assisted-100% outdoor air system (LD-IDECOAS) as a non-vapor compression heating, ventilation, and air conditioning (HVAC) system [10]. The direct evaporative cooler is used in dry and mild climates where the wet bulb (or enthalpy) of the process air is relatively low. However, the direct evaporative cooler shows limited cooling capacity in hot and humid climate zones owing to the high wet-bulb temperature (or enthalpy) of entering process air. In order to meet a target supply air condition using the direct evaporative cooler only, the process air should be dehumidified significantly before reaching the direct evaporative cooler such that its wet bulb temperature is lowered close to the target temperature. The indirect evaporative cooler was located between the liquid desiccant unit and direct evaporative cooler in the LD-IDECOAS to overcome this limitation. This decreases the wet-bulb temperature of the process air to a temperature close to the target temperature with less dehumidification. The LD-IDECOAS is a variable air volume system that supplies 100% outdoor air. The dehumidification performed by the LD unit enhances the cooling performance of evaporative coolers. However, heat is required to regenerate the desiccant solution.

Kim et al. [1] proposed and evaluated an LD-IDECOAS; energy saving performance was evaluated via detailed simulation and was compared with that of a conventional variable air volume system. The investigation of annual operating energy savings of the proposed system revealed that the proposed system provided 68% energy savings over the conventional variable air volume system [2]. Woods and Kozubal [3] developed a numerical model of a desiccant-enhanced evaporative air conditioner, and they verified the model by experimental testing of the prototypes. They also proposed a design method with sensitivity and parametric analysis for a desiccant-enhanced evaporative air conditioner [4]. Cui et al. [5] proposed a compact desiccant-evaporative heat and mass exchanger by combining the regenerative indirect evaporative cooling system and the LD system, and they investigated the

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Nomenclature

b_X	systematic standard uncertainty (%)
c_w	specific heat of water (kJ/kg °C)
CF	primary energy conversion factor
h	enthalpy (kJ/kg °C)
HV_{fuel}	heating value of fuel (MJ/m^3)
$\dot{m}$	mass flow rate (kg/s)
$\dot{Q}_C$	cooling capacity of the system (kW)
$\dot{Q}_{pri}$	total primary energy (kW)
$\dot{Q}_{in}$	total input energy (kW)
$\dot{Q}_{SC}$	desiccant solution cooling load (kW)
$\dot{Q}_{SH}$	desiccant solution heating load (kW)
s_X	random standard uncertainty (%)
T	temperature (°C)
U_X	overall uncertainty (%)
$\dot{V}_{fuel}$	volume flow rate of fuel (m^3/h)
W	electric energy consumption (kW h)
$\dot{W}_{net}$	net electric power consumption (kW)
$\dot{W}_{out}$	power output (kW)
E	total energy consumption (kW h)
G	gas consumption (kW h)

Greek symbols

ε	effectiveness (%)

Subscripts

abs	absorber
cw	cooling water
hw	hot water
ele	electric
FC	fuel cell
in	inlet
NG	natural gas
out	outlet
r	return
reg	regenerator
s	supply
th	thermal
to	total
w	water

Acronyms

CHP	combined heat and power
DBT	dry-bulb temperature (°C)
DEC	direct evaporative cooler
HC	heating coil
HEX	heat exchanger
HVAC	heating, ventilation, and air conditioning
IEC	indirect evaporative cooler
LD	liquid desiccant
LD-IDECOAS	liquid desiccant and evaporative cooling-assisted 100% outdoor air system
LiCl	lithium chloride
PEMFC	proton exchange membrane fuel cell
SHE	sensible heat exchanger
SOFC	solid oxide fuel cell
WBT	wet-bulb temperature

influence of several key parameters on the performance of the proposed system. Gao et al. [6] developed a liquid desiccant indirect evaporative cooling system by utilizing the Maisotesenko-cycle, and they conducted parametric analysis through experiments. Audah et al. [7] proposed a solar-powered liquid desiccant system to meet both building cooling and fresh water needs, and they observed that the system produced 15 l of fresh water a day and delivered 17–18 °C of dry air. Xiao et al. [8] examined a dedicated outdoor air system by adopting a liquid desiccant system and found that using the total heat exchanger improved the system COP by 19.9–34.8%. Abdel-Salam and Simonson [9] developed a membrane liquid desiccant air conditioning system and found that the proposed system reduced 19% annual primary energy consumption and 12% life cycle cost when compared with those of a conventional air conditioning system.

Conversely, the use of a combined heat and power (CHP) system could be an effective solution to minimize the energy used and to obtain high-energy efficiency [11–13] in thermally driven air conditioning systems such as LD systems and absorption chillers. The CHP system supplies electricity and heat required to operate thermally driven air conditioning systems and increases the energy and thermal performance efficiencies of the entire system [14–25].

Havelsky et al. [16] indicated that the use of a CHP system in air conditioning systems could result in enhanced annual energy savings. Kong et al. [17] experimentally investigated a gas engine and adsorption chiller and showed that the system saved 9.1–23.3% primary energy when compared with that of a conventional air conditioning system powered by purchased electricity. Khatri et al. [18] operated a diesel engine and absorption chiller combination on a laboratory scale and indicated that the system reduced CO_2 emission by 60.7%. Buker et al. [19] performed an experimental analysis of a LD cooling system coupled with a photovoltaic/thermal roof collector and observed that the system provided 3 kW of heating and generated 10.3 MW h/year of electric power. Tippawan et al. [20] simulated an absorption chiller integrated with a solid oxide fuel cell (SOFC) and showed that the system could provide a 32% enhancement in energy efficiency because the waste heat from the SOFC was used in the absorption chiller operation.

In contrast, Zink et al. [21] examined an absorption heating and cooling system for buildings integrated with a SOFC and indicated that the system provided 87% energy efficiency. Margalef and Samuelsen [22] investigated the feasibility of coupling a molten carbonate fuel cell with a direct exhaust double-effect absorption chiller and suggested that the system could provide a 71.7% overall energy efficiency. Al-Sulaiman et al. [23] conducted an energy analysis of a tri-generation plant that used an SOFC and an organic Rankine cycle. The maximum energy efficiency of the system was 74%. Yu et al. [24] proposed a tri-generation system composed of an SOFC, a heat recovery steam generator, and a double-effect water/lithium bromide absorption chiller. The energy performance of the system was evaluated by using a numerical model. Fong and Lee [25] also proposed a SOFC integrated tri-generation system for a high-rise building. The monthly-averaged energy efficiency of the system ranged from 74.1 to 76.7%. Ge et al. [26] derived a simulation model of a micro-turbine integrated with an ammonia-water absorption chiller and experimentally verified their model. Freschi et al. [27] studied economic and environmental benefits of a CHP system with an absorption chiller for the food-industry by using an optimization procedure, and they found that accurate sizing of the CHP system was necessary to reduce environmental effects. Popli et al. [28] investigated the technical and economic feasibility of a combined cooling, heating, and power system (CCHP) consisting of gas turbines and absorption chillers. The system indicated significant operating cost savings within a very short simple