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ENERGY PERFORMANCE OF DESICCANT AND EVAPORATIVE COOLING-ASSISTED 100% OUTDOOR AIR SYSTEM COMBINED WITH A THERMOELECTRIC MODULE INTEGRATED FUEL CELL

Hansol Lim, Jae-Weon Jeong*

Department of Architectural Engineering, College of Engineering, Hanyang University, Seoul 04763, Republic of Korea

**Corresponding email: jjwarc@hanyang.ac.kr*

SUMMARY

The energy performance of a liquid desiccant and evaporative cooling-assisted 100% outdoor air system (LD-IDECOAS) combined with a thermoelectric module integrated proton exchange membrane fuel cell (TEM-PEMFC) is investigated. During the cooling season, the heat produced by the PEMFC was used to regenerate a weak desiccant solution, and the generated electricity was used to operate the LD-IDECOAS. TEMs were operated as auxiliary heaters to supply the additional heat when the heat for regeneration was not enough in the cooling season. In the off-cooling season, a PEMFC was operated to generate electricity, and the generated heat was used to generate electricity again using TEMs. In this study, detailed energy simulations were conducted to compare the energy saving potentials of the proposed system comprising the LD-IDECOAS with the PEMFC. Using a TEM as a heater, it can operate with a mean coefficient of performance of 2.0 in the cooling season. Further, as an electricity generator, it showed a mean generation efficiency of 0.9%. Finally, the proposed system showed annual primary energy savings of 10.6% compared with an LD-IDECOAS without a TEM-PEMFC. Therefore, the advantages of using TEM integrated fuel cells as heating and energy-harvesting components were validated.

Keywords: Thermoelectric module, Fuel cell, Liquid desiccant, Evaporative cooling, Waste heat recovery

1 INTRODUCTION

The liquid desiccant and indirect/direct evaporative cooling-assisted 100% outdoor air system (LD-IDECOAS) was suggested as a non-vapor compression heating, ventilation, and air-conditioning (HVAC) system in previous studies (Kim et al., 2014). It showed good performance with energy savings; however, it still has potential uses that can save energy using waste heat recovery because the LD-IDECOAS uses a considerable amount of heat for cooling. The concept of using heat for cooling is defined as combined cooling, heating, and power (CCHP), such as a fuel cell (Ratlamwala et al., 2012). Further, the polymer electrolyte membrane fuel cell (PEMFC) has been applied in buildings for its high power density, cogeneration efficiency, and fast startup time owing to its low operating temperature (Adam et al., 2015). However, its low operating temperature also makes it difficult to use directly in a liquid desiccant system (Kim et al., 2015). Therefore, a thermoelectric module (TEM) is integrated with a PEMFC as a heater and generator in this study. Finally, operating strategies for the LD-IDECOAS with the PEMFC are suggested, and its energy performance is investigated based on a detailed energy simulation using theoretical and empirical models. To compare the energy performance of the suggested system with another, a conventional LD-IDECOAS was simulated as a reference case. It was operated based on the grid power and gas boiler for heating the weak solution in the regenerator of the LD system.

2 SYSTEM DESCRIPTION

2.1 LD-IDECOAS

Figure 1 shows a schematic of the LD-IDECOAS that consists of an LD system, an indirect evaporative cooler (IEC), and a direct evaporative cooler (DEC). For heating-mode operation, a heating coil and sensible heat exchanger (SHX) are installed. It is a variable air volume system without a mixing process; therefore, the supply air flow rate is modulated based on the load in the model space.

In the cooling season, an LD system operated to dehumidify the process air, and an IEC sensibly cooled the process air to meet the supply air (SA) condition of 15°C. If additional cooling was necessary, a DEC adiabatically cooled the process air. In the intermediate season, the IEC and DEC operate to meet the SA condition without operating the LD system using mild and dry outdoor air. In the heating season, the IEC operates as a sensible heat exchanger by reclaiming the heat from the exhausted air (EA). If the SA condition (i.e., a neutral temperature of 20°C) cannot meet with recovered heat from the EA, the heating coil operates to heat the EA to meet the supply air condition. The sensible load is accommodated using a parallel heating unit in the space in the heating season. Consequently, it has four operating strategies according to the outdoor air conditions (Kim et al., 2014).

The LD system is composed of an absorber and a regenerator. We used a lithium-chloride aqueous solution (LiCl) with a 38% concentration. The dehumidification process in the absorber is exothermic; therefore, the strong desiccant solution is cooled to maintain its dehumidification efficiency before entering the absorber using cooling water from the cold-water storage tank connected with a cooling tower. The target cooling temperature for a strong solution was 25°C. However, the weak solution should be regenerated in the regenerator by heating the solution entering the regenerator using a heating coil to maintain the regeneration efficiency. It is assumed that a gas boiler produces the hot water for heating the weak desiccant solution to 60°C. The liquid-to-gas ratio was assumed to be 1.2 in this study.

The IEC has primary and secondary channels. When it operates for cooling, the SA enters the primary channels for transferring its sensible heat to the secondary channel by evaporative cooling in the secondary channel. The air that enters the secondary channel can be outdoor air and exhausted air according to the wet-bulb temperature. During the heating season, both channels operate as dry channels without sprayed water, and the SA only sensibly exchanges its heat to the secondary air. In the DEC, the SA is insentropically cooled to meet the SA condition.

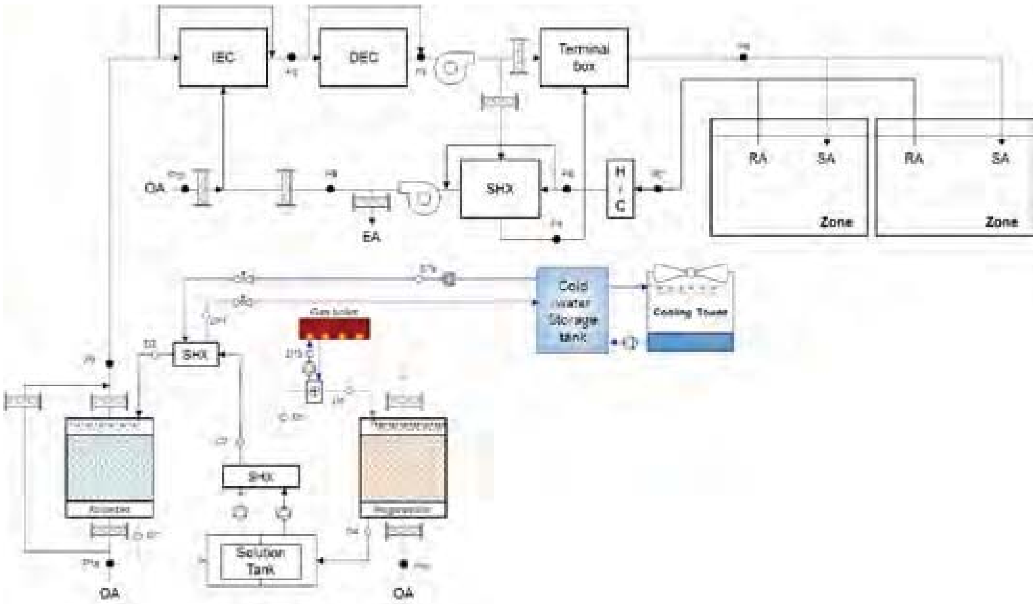

Figure 1. Schematic of LD-IDECOAS

2.2 LD-IDECOAS with a TEM-PEMFC

The proposed LD-IDECOAS with a TEM-PEMFC is shown in Figure 2. We suggested using the TEM-PEMFC for heating the weak solution at the regenerator in the cooling season. When using a PEMFC, the generated heat can be reclaimed; however, its temperature is not high enough to be used. Therefore, a TEM can be operated as a heater for a weak solution based on recovered heat from the PEMFC. At the hot side of the TEM, the weak solution was heated to meet the target temperature, and the heated 40℃ water entered the cold side of the TEM. Therefore, the recovered heat was absorbed and transferred to the hot side of the TEM by Peltier effects.

In the off-cooling season, the TEM is operated as an electricity generator. Owing to the Seebeck effect, a TEM can generate electricity based on the temperature difference between its hot and cold sides. When the heat is transferred through a TEM, part of the thermal energy is converted into electricity. At the hot side of a TEM, the heated water from the PEMFC maintains the temperature of the hot side. However, the cold water from the storage enters the cold side of the TEM to maintain surface temperature and remove the transferred heat from the hot side of the TEM.

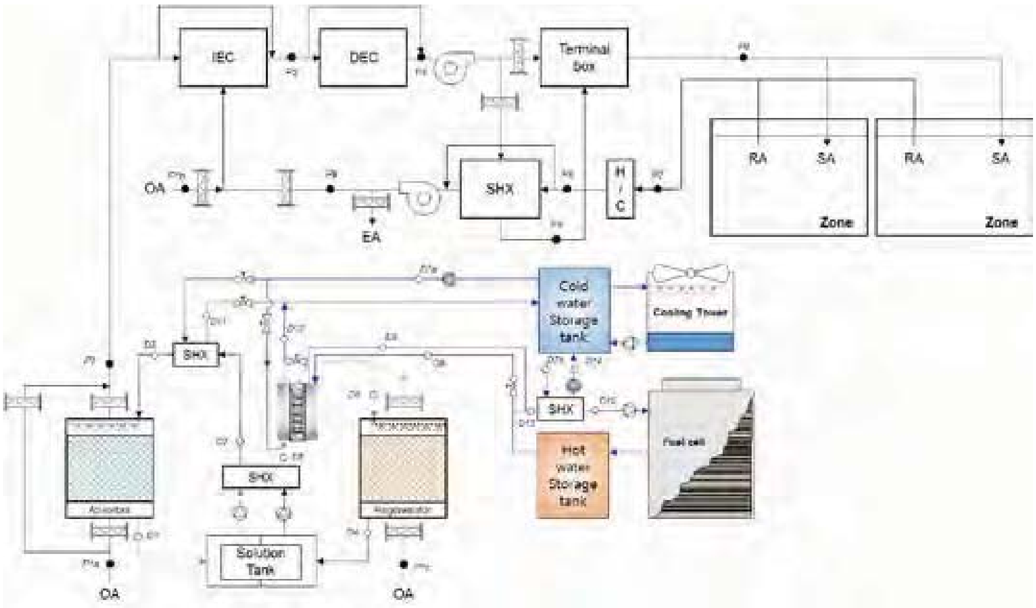

Figure 2. Schematic of LD-IDECOAS with a TEM-PEMFC

3 SIMULATION OVERVIEW

3.1 Model space

The sensible and latent loads of the simulated space were calculated by using TRNSYS 17. The two rooms whose floor area is 200 m^2 with a 3-m height have two windows at the south and west exterior walls with an area corresponding to 10 m^2. The selected window-to-wall ratio corresponded to 0.17. The sensible and latent heat generation rates of an occupant were selected as 75 W and 45 W, respectively, according to the ASHRAE Standard 90.1. Typical occupancy and system schedules for an office building were used to calculate the typical loads. The set points of the indoor temperature and relative humidity were 25°C and 50% for the cooling mode and 20°C for the heating mode. All U-values for the roof, ceiling, wall, and windows were used based on the local regulation of South Korea.

3.2 LD-IDECOAS

The LD performance was defined using an effectiveness value that was derived using an empirical model (Park et al., 2016) and a simulation method from a previous study (Lim et al., 2017). The IEC and DEC were simulated using Eq. (1) based on the effectiveness, and they were assumed to be 0.7 and 0.95 (Kim et al., 2014), respectively. The wet-bulb temperature ($T_{wet-bulb}$) in Eq. (1) is for the process air in the DEC and for the secondary channel air in the IEC.

$$T_{DEC\ or\ IEC,out} = T_{DEC\ or\ IEC,in} - \varepsilon_{DEC\ or\ IEC}(T_{DEC\ or\ IEC,in} - T_{wet-bulb}) \quad (1)$$

3.3 PEMFC

The empirical model used for the PEMFC was from a previous study (Ham et al., 2015). In this model, the input parameters were the part load ratio for operation and inlet water temperature for cooling the fuel cell stack. Then, the generated AC power, recovered heat, and amount of fuel consumed were derived according to the rated power capacity. In this study, we selected the capacity of the PEMFC to meet the peak heating loads of the LD-IDECOAS, and its rated power capacity was 10 kW. In addition, we used a part load ratio of 1.0 when the system was operated and 0.6 when the system was not operated according to the HVAC schedule. The inlet water temperature was set to be 33.8°C to obtain an outlet water temperature of 40°C. This is because the maximum outlet water temperature was 40℃ to prevent the breakdown of the stack in the fuel cell, and it was better to have the water temperature to be as high as possible in terms of heating the weak solution.

3.4 TEM

A TEM was simulated using a previously developed semi-black-box model (Chen and Snyder, 2013). The following thermophysical properties were derived using Eqs. (2) to (4): Seebeck coefficient (*S*), electrical resistivity (*R*), and thermal conductivity (*K*) These equations involve the maximum heat capacity (Q_{max}), temperature of the hot side (T_h), maximum temperature difference between the cold and hot sides of the TEM (ΔT_{max}), maximum input current of the TEM (I_{max}), uniform cross-sectional area of the entire TEM (*A*), and height of the thermoelement (*l*). With respect to the TEM that was used in the study, the packing fraction of the total TEM area was covered by a thermoelement (*f*) corresponding to 0.5, and the number of thermocouples in a TEM (*N*) corresponded to 127.

$$S = \frac{2Q_{max}(T_h - \Delta T_{max})}{T_h^2 I_{max}} \quad (2)$$

$$R = \frac{8N^4 l^2 I_{max}^2 T_h^2}{A^2 f^2 Q_{max}(T_h - \Delta T_{max})^2} \quad (3)$$

$$K = \frac{(T_h - \Delta T_{max})^2}{T_h^2}\frac{Q_{max}}{\Delta T_{max}} \quad (4)$$

When the TEM was used for heating the weak solution in the cooling season, the hot-side surface temperature of the TEM (T_h) that can heat the weak solution up to 60°C when the heat exchange effectiveness was assumed to be 0.7 according to Eq. (5) was determined. The heating load of the TEM ($\dot{Q}_{heating}$) and input current (*I*) to accommodate the heating load can be derived using Eqs. (6) and (7) (Lim et al., 2017). The mass flow rate of the weak solution ($\dot{m}_{weak\ solution,in}$) was determined based on a liquid-to-gas ratio of 1.2. The total number of TEMs (*n*) was assumed to be 216, and the cold-side temperature of the TEM (T_c) was 31.5°C lower than the hot side of the TEM (T_h).

$$T_h = T_{weak\ solution,in} + (60 - T_{weak\ solution,in})/0.7 \quad (5)$$

$$\dot{Q}_{heating} = \dot{m}_{weak\ solution,in} \times C_{p,sol} \times (60 - T_{weak\ solution,in}) \quad (6)$$

$$I = \frac{-S\Delta T + \left(\frac{Af\alpha^2 T_c^2}{l\rho I_{max}}\right) + \sqrt{(S\Delta T + \left(\frac{Af\alpha^2 T_c^2}{l\rho I_{max}}\right))^2 + 4(R - \frac{Af\alpha^2 T_c^2}{2l\rho I_{max}^2})(\frac{\dot{Q}_{heating}}{n} + \frac{Af\Delta T\kappa}{l})}}{2(R - \frac{Af\alpha^2 T_c^2}{2l\rho I_{max}^2})} \quad (7)$$

In the off-cooling season, the TEM operated as an electricity generator according to the temperature difference. The generated power was calculated using Eq. (8) when the load resistance (R_{load}) was 0.02 Ω. The DC-to-AC conversion efficiency ($\eta_{inverter}$) was assumed to be 0.95. The heat absorption and rejection from the hot and cold sides of the TEM were derived using Eqs. (9) and (10) (Lee, 2017).

$$P_{AC} = \eta_{inverter} \frac{S^2 \Delta T^2 R_{load} n}{2R(1+\frac{R_{load}}{R})^2} \tag{8}$$

$$Q_{h,TEM} = nN\left(\frac{ST_h I}{2N} - \frac{1}{2} I^2 R + K\Delta T\right) \tag{9}$$

$$Q_{c,TEM} = nN(\frac{ST_c I}{2N} + \frac{1}{2} I^2 R + K\Delta T) \tag{10}$$

4 RESULTS

The annual primary energy consumptions of two LD-IDECOAS systems are compared in Table 1. The primary energy conversion coefficient was 1.1 for gas and 2.75 for electricity according to the local regulation in Korea. In an LD-IDECOAS with a TEM-PEMFC, there is more pump energy from the cooling tower, SHX, and water circulation for the PEMFC. For electricity generation by the TEM, the cooling tower operated for a year, and more energy consumption occurred in the pump and fan.

The highest difference in terms of the consumed energy was shown in heating for regeneration. For heating the weak solution in summer, 27.0 MWh of primary energy was consumed using the TEM, while 33.4 MWh of primary energy was necessary when using the gas boiler. As a result, 10.6% of the primary energy could be saved using the TEM-PEMFC in the LD-IDECOAS instead of a gas boiler.

In addition, 72.9 MWh of electricity was generated from the PEMFC and 462.3 kWh of electricity was additionally generated from the TEM. This means that the amount of generated electricity was much more than needed, so the surplus electricity can be transmitted to the public grid for sale.

Table 1. Comparison of annual primary energy consumption

Unit: kWh

Component		LD-IDECOAS	LD-IDECOAS with a TEM-PEMFC
Pump	DEC	12	12
	IEC	9	9
	LD	4	4
	Cooling tower	8	36
	Storage – Cooling tower	110	571
	Storage – SHX	0	85
	Storage – TEM	0	196
	Storage – Absorber	203	410
	PEMFC pump	0	1,062
	Gas boiler pump	72	0
Fan	Supply air	1,645	1,645
	Return air	1,645	1,645
	Cooling tower	21	108
	Regenerator	103	103
Heating	Heating coil	1,415	1,415
	Reheating coil	797	797
	Gas boiler	33,389	0
	Parallel heating coil	1,838	1838
	TEM (Heater)	0	26,960

5 CONCLUSIONS

This study proposed an LD-IDECOAS with a TEM-PEMFC for heating the weak desiccant solution using a TEM in the cooling season and reclaiming the waste heat from the PEMFC in the off-cooling season. Through a detailed energy simulation, the annual energy consumption and generation were investigated and compared with the conventional LD-IDECOAS based on the gas boiler and grid power. From the results, the TEM as a heater combined with the PEMFC can operate with an average coefficient of performance of 2.0, and 10.6% energy savings can be achieved. Further, the heat from the PEMFC can be recovered as electricity using the TEM, and it was 462 kWh, which was 0.63% of the electricity generated from the PEMFC. Therefore, the possibility of using a TEM-PEMFC with an LD-IDECOAS was revealed. In future studies, the operation characteristics of the TEM-PEMFC will be evaluated for optimizing the proposed system.

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