Energy Saving Potential of Solar Organic Rankine Cycle in a Liquid Desiccant and Evaporative Cooling-assisted Air Conditioning System

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SUMMARY

A liquid desiccant indirect and direct evaporative cooling assisted 100% outdoor air system (LD-IDECOAS) was recently introduced as an alternative air conditioning system to conventional vapor compression-based systems. The LD-IDECOAS is a thermally driven cooling system due to the liquid desiccant. The liquid desiccant unit requires a relatively low-grade heat source to regenerate the weak desiccant solution. This study focused on evaluating the primary energy saving potential of a solar organic Rankine cycle (SORC) combined with the LD-IDECOAS based on a simulation study during the cooling season. The primary energy consumption of solar ORC with LD-IDECOAS is compared with LD-IDECOAS served by conventional grid power and a boiler. The results indicate that SORC integrated with LD-IDECOAS reduced primary energy consumption by 44% when compared to that of the base case. The LD-IDECOAS has more applicability of the SORC, which simultaneously generates heat and power, in terms of energy.

INTRODUCTION

Recent studies proposed a liquid desiccant evaporative cooling-assisted 100% outdoor air system termed as an LD-IDECOAS and evaluated the energy saving potential of the proposed system (Kim et al. 2013, 2014,2015, 2016b). The LD-IDECOAS is composed of a liquid desiccant (LD) system, an indirect evaporative cooler, and a direct evaporative cooler. The LD system was integrated to enhance the cooling effect of indirect and direct evaporative coolers. The LD-IDECOAS operates each component independently based on outdoor air conditions and provides air conditioning while satisfying the ventilation requirements of space. The LD-IDECOAS is a thermally driven cooling system due to the LD. When the LD system operates in summer, it requires a relatively low-grade heat source to regenerate a weak desiccant solution. The regeneration energy accounts for the majority of energy consumption in the liquid desiccant-assisted evaporative cooling system. Therefore, a renewable energy or combined heat and power system acts as an alternative heat source. Dong et al. (2017) evaluated the applicability of a district heat source that was applied to a desiccant-enhanced evaporative (DEVap) cooling system by comparing energy consumption with the same system served by the boiler. The findings indicated that the DEVap with the district heat source reduced primary energy consumption by 46.2%. Kim et al. (2016a) revealed that the LD-IDECOAS integrated with a proton exchange membrane fuel cell saved 21% primary energy when compared to that of the system powered by grid power and a boiler.

Consequently, the current study was conducted to evaluate the feasibility of a solar organic Rankine cycle (SORC) applied to an LD-IDECOAS. The primary energy consumption of an LD-IDECOAS served by SORC was compared to an LD-IDECOAS served by conventional grid power and a boiler. The simulation was performed under the cooling season operation in which the liquid desiccant mainly operates.

SYSTEM OVERVIEW

LD-IDECOAS

Figure 1 shows a schematic diagram of the LD-IDECOAS. The LD-IDECOAS is composed of a liquid desiccant (LD) system, an indirect evaporative cooler (IEC), and a direct evaporative cooler (DEC). A heating coil and a sensible heat exchanger are installed for the heating mode operation. The supply air flow rate is modulated based on the zone load as in a conventional variable air volume (VAV) system.

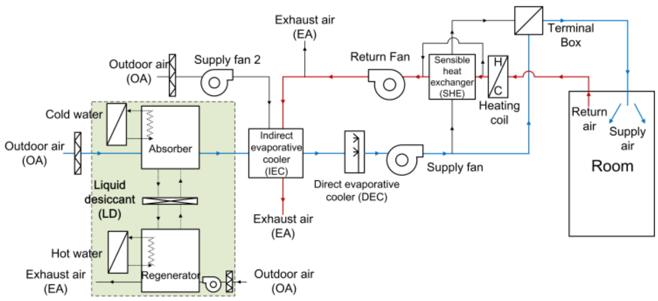

Figure 1. Schematic diagram of LD-IDECOAS

In the cooling season, the hot and humid outdoor air (OA) is dehumidified by the LD unit and sensibly cooled by the IEC. Subsequently, the supply air (SA) is additionally cooled by DEC to satisfy the SA set temperature (i.e., 15 °C). In the intermediate season, the IEC and DEC operates to meet the SA set condition without LD operation because the OA is relatively mild and dry. In the heating season, the IEC operates as a sensible heat exchanger by recovering heat from the exhausted air (EA). The LD and DEC are deactivated during the heating season.

The LD system consists of an absorber and a regenerator. A lithium chloride aqueous solution is used as a desiccant solution. The dehumidification and regeneration process occurs based on the vapor pressure difference between the air and desiccant solution. Dehumidification is an exothermic process, and thus desiccant cooling is required for an absorber performance. Water-side free cooling with a cooling tower is introduced to reduce the cooling energy consumption. Conversely, the regeneration is an endothermic process, and the heating device is required to maintain a regenerator performance.

The IEC is composed of primary and secondary channels. During the cooling season, the SA passing through the dry channels is cooled by transferring its sensible heat to the secondary air that undergoes evaporative cooling in the secondary channel. During the heating season, the SA only sensibly exchanges heat to the secondary air. The DEC isentropically cools the SA to meet the SA set temperature. The air leaving the DEC is humidified rather than initially dehumidified supply air in the LD system.

Figure 2 represents the operating mode of the LD-IDECOAS on a psychrometric chart. The LD-IDECOAS operates based on four different regions (i.e., Region A to D) based on the OA condition. Region A refers the OA condition located above lines ‘a’ and ‘b’. Line ‘a’ denotes the humidity ratio of the SA, and line ‘b’ denotes the 15 °C saturation condition which is the SA set temperature. In Region A, the LD, the IEC, and the DEC are activated to meet the SA set condition. The SA humidity ratio leaving the absorber ($\omega_{abs,out}$) is determined by dehumidification effectiveness ($\varepsilon_{abs,w}$) as shown in Equation 1. Similarly, the SA temperature leaving the absorber ($DBT_{abs,out}$) is determined by thermal effectiveness ($\varepsilon_{abs,T}$) as shown in Equation 2. The thermal effectiveness and dehumidification effectiveness exhibit similar values based on open literature. The SA temperature leaving the IEC ($DBT_{iec,out}$) and DEC ($DBT_{dec,out}$) are determined by Equations 3 and 4, respectively. Region B refers the OA condition between the line ‘a’ and ‘b’ on the psychrometric chart. In Region B, the IEC and DEC are activated without the LD operation to satisfy the SA set point. Region C indicates that the OA dry bulb temperature (DBT) exceeds the SA set DBT (i.e., 15 °C) and is lower than the SA saturation line (i.e., line ‘b’). In Region C, only DEC operates to satisfy the SA DBT set point. In Region D, the OA DBT is lower than the SA DBT set point. The LD and DEC are deactivated, and the IEC is used as the SHE. The auxiliary heating coil operates when additional heating is required to satisfy the SA set point.

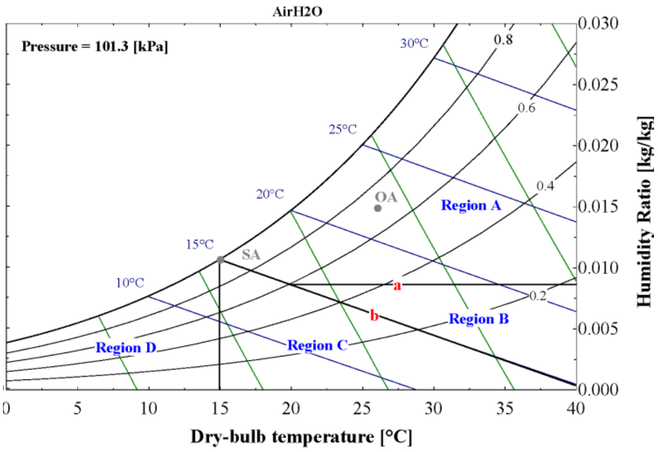

Figure 2. Operation mode of LD-IDECOAS

$$\varepsilon_{abs,w} = \frac{\omega_{oa} - \omega_{abs,out}}{\omega_{oa} - \omega_{abs,eq}} \quad (1)$$

$$\varepsilon_{abs,T} = \frac{DBT_{oa} - DBT_{abs,out}}{DBT_{oa} - T_{abs,L,in}} \quad (2)$$

$$\varepsilon_{IEC} = \frac{DBT_{abs,out} - DBT_{IEC,out}}{DBT_{abs,out} - WBT_{IEC,s,in}} \quad (3)$$

$$\varepsilon_{DEC} = \frac{DBT_{IEC,out} - DBT_{DEC,out}}{DBT_{IEC,out} - WBT_{IEC,out}} \quad (4)$$

SORC

The organic Rankine cycle (ORC) is composed of a turbine, a compressor, a condenser, and a pump. The ORC is based on a conventional Rankine cycle. The R245fa is used as a working fluid. The ORC requires a relatively low temperature heat source to generate power when compared to the Rankine cycle. The ORC is considered as a combined heat and power (CHP) system.

In the study, 2-kW ORC is introduced, and the evaporating and condensing temperatures are set to 135 °C and 70 °C, respectively. A solar thermal system is used as the heat source of the ORC. The evacuated tube collector (ETC) is applied to the solar collector to achieve a relatively high temperature. The auxiliary boiler is activated when the heating fluid temperature for evaporator that exists in the storage tank of the solar thermal system requires additional heating to satisfy the target heating fluid temperature (i.e., 150 °C).

Figure 3 shows a schematic diagram of a solar ORC (SORC) integrated with the LD unit in the LD-IDECOAS. The power generated from ORC can be supplied to the building for air-conditioning operation or lighting. The heat recovered from the ORC is used as solution heating or building space heating.

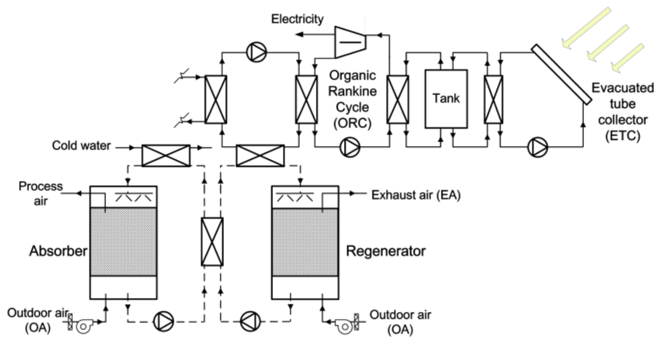

Figure 3. Schematic diagram of SORC

ENERGY SIMULATION

Model building

The model building used for the simulation is an office building located in Seoul, Republic of Korea. Energy simulation is conducted during the cooling season (i.e., June, July, and August). Table 1 shows the building information details. The hourly cooling load profile of the model building was obtained by using the building energy simulation software (i.e., TRNSYS 17). The operating energy consumption of the LD-IDECOAS was calculated by a commercial equation solver program (i.e., EES) by using each component model. In this study, the design SA flow rate for this building was 2000 m^3/h.

Table 1. Building information

Weather	Seoul weather data	
Occupancy density (ASHRAE 2016a)	5 people/100 m^2	
Schedules	Occupancy	ASHRAE Standard 90.1 (2016b)
	HVAC	ASHRAE Standard 90.1 (2016b)
Volume	900 m^3 (20 m W × 15 m D × 3 m H, single zone)	
Room set point (Kim et al. 2014)	Temperature	24 °C
	Relative humidity	55%
Supply air set point (Kim et al. 2014)	Temperature	15 °C
Internal heat gain	People	75 W/person (Sensible, latent)
	Electronics	PC: 230 W/person (Sensible)
U-values (Window to wall ratio: 17%)	Floor	0.952 W/ m^2·K
	Roof	0.630 W/ m^2·K
	Exterior wall	0.468 W/ m^2·K
	Window	5.68 W/ m^2·K

Liquid desiccant system

The LD performance is represented by the moisture-transfer-effectiveness value. The absorber effectiveness model proposed by Chung and Luo (1999) was used for the absorber. The liquid to gas ratio of the absorber is set as 4. In this study, the Martin and Goswami (2000) model was applied in the regenerator side. The liquid to gas ratio of the regenerator is set as 1.

The dimension or inlet parameter of LD system used in the simulation was based on LD-IDECOAS pilot system (Kim et al. 2015). The specific surface area of both absorber and regenerator was 223 m^2/ m^3. The inlet solution concentration of the absorber was set to 38%. The initial desiccant cooling and heating temperature were set to 30 °C and 55 °C, respectively. If the solution for regeneration requires additional heating to satisfy 55 °C, the auxiliary boiler operates. It was assumed that dehumidification rate and regeneration rate were equal. The dehumidification effectiveness (ε_{abs}) was calculated by using Equation 5, and the outlet humidity ratio of the absorber was then calculated by using Equation 1. Similarly, the regeneration effectiveness ($\varepsilon_{reg,w}$) was calculated by using Equation 6, and the outlet humidity ratio of the regenerator was then calculated by using Equation 7. The regenerator enthalpy effectiveness ($\varepsilon_{reg,h}$) was calculated by using Equation 8, and the outlet air enthalpy of the regenerator was then calculated by using Equation 9. The outlet temperature of the regenerator was calculated from the outlet air enthalpy ($h_{reg,out}$). The expressions are as follows:

$$\varepsilon_{abs} = \frac{1-\left(0.024\left(\frac{G_{in}}{L_{in}}\right)^{0.6} exp\left(1.057\left(\frac{DBT_{oa}}{T_{L,in}}\right)\right)/(\alpha Z)^{-0.185}\pi^{0.638}\right)}{1-\left(0.192 exp\left(0.615\left(\frac{DBT_{oa}}{T_{L,in}}\right)\right)/\pi^{-21.498}\right)} \quad (5)$$

$$\varepsilon_{reg,w} = 1 - 48.3\left(\frac{L_{in}}{G_{in}}\right)^{\left(0.396\left(\frac{\gamma_L}{\gamma_c}\right)-1.57\right)}\left(\frac{h_{oa}}{h_{L,in}}\right)^{-0.751}(\alpha Z)^{\left(0.0331\left(\frac{\gamma_L}{\gamma_c}\right)-0.906\right)} \quad (6)$$

$$\varepsilon_{reg,w} = \frac{\omega_{reg,out}-\omega_{oa}}{\omega_{reg,eq}-\omega_{oa}} \quad (7)$$

$$\varepsilon_{reg,h} = 1 - 3.77\left(\frac{L_{in}}{G_{in}}\right)^{\left(0.289\left(\frac{\gamma_L}{\gamma_c}\right)-1.12\right)}\left(\frac{h_{oa}}{h_{L,in}}\right)^{-0.528}(\alpha Z)^{\left(-0.0044\left(\frac{\gamma_L}{\gamma_c}\right)-0.365\right)} \quad (8)$$

$$\varepsilon_{reg,h} = \frac{h_{reg,out}-h_{oa}}{h_{L,in}-h_{oa}} \quad (9)$$

where G_{in} and L_{in} are the OA and inlet solution flow rate, respectively, α is specific surface area, Z is the packing height, π can be expressed as a function of the vapor pressure of pure water and solution ($(p_{water} - p_{L,in})/p_{water}$), and γ_L and γ_c are solution and critical surface tension, respectively.

Evaporative coolers

There are two evaporative coolers, namely the IEC and DEC. The leaving air conditions of each evaporative cooler were calculated by Equations 3 and 4. The effectiveness of indirect and direct evaporative cooler were assumed as 80% and 95% (Kim et al. 2014), respectively.

Organic Rankine cycle

In this study, the simplified model developed by Quoilin (2011) was used. The ORC operated at a full load (i.e., 2 kW power) based on the HVAC schedule. Water was used for the cooling fluid for the condenser as well as the heating fluid for the evaporator. The efficiency for turbine and pump were assumed as 80%. The evaporating and condensing temperatures were set to 135 °C and 70 °C, respectively. The ORC efficiency was calculated as 9.1%.

Solar thermal system

The heating fluid for evaporator circulates between the storage tank and evaporator. The evaporating temperature is 135 °C, and thus it is necessary to ensure a higher temperature of the heating fluid. The heating fluid temperature is assumed as 155 °C, and therefore the solar thermal system displays a relatively high temperature. The evacuated tube collector (ETC) operates at a high temperature. The efficiency for the collector was assumed as 70%. The ETC operates based on the ORC schedule. The useful energy (q_u) was estimated by using Equation 10 to evaluate the performance of the collector. The useful energy was modified by using an incidence angle modifier. The incidence angle modifier ($\kappa_{\alpha\tau}$) for ETC was defined as Equation 11 in this study. The incident angle (θ) is 42°, and this represents Seoul latitude (37°) plus 15°. The heat from ETC is collected in the storage tank. If the heating fluid temperature leaving the storage tank does not correspond to 155 °C, then the auxiliary boiler is activated to satisfy the set temperature. The expressions are as follows:

$$q_u = A_c F_R [G_t \tau\alpha - U_L (T_{f,i} - T_{oa})] \quad (10)$$

$$\kappa_{\alpha\tau} = 1 + 0.29(\frac{1}{cos\theta} - 1) \quad (11)$$

where A_c is collector area, F_R is heat removal factor, G_t is total solar energy, $\tau\alpha$ is transmittance-absorptance product, U_L is solar collector heat transfer loss coefficient, and $T_{f,i}$ is temperature of the fluid entering the collector.

Boiler and cooling tower

In order to compare the energy consumption using SORC with that of a conventional gas boiler, it was assumed that a hot water boiler located inside the building was used for the regenerator solution heating. The SORC integrated with LD-IDECOAS also used an auxiliary boiler to satisfy each set point. The boiler performed part load operation based on the required heating loads. The boiler energy was estimated by considering the impact of the boiler efficiency and efficiency performance curve, which corresponds to a cubic efficiency curve provided by EnergyPlus (2013). The theoretical efficiency of the boiler is set to 82% in the study (EnergyPlus 2013).

The cooling tower operates for solution cooling in both SORC and conventional LD-IDECOAS. The cooling approach and range are set to 2 °C and 10 °C, respectively.

Fans and pumps

The LD-IDECOAS includes three variable air volume fans, namely supply, return, cooling tower and regenerator fans. The fan efficiency (η_{fan}), air flow rate ($\dot{V}_{fan}$), and pressure loss (ΔP) are the required variables (Equation 12) for the fan power (P_{fan}) calculation. The pressure loss of the fan from (Kim, Yoon, et al. 2016) is based on 1000 m^3/h, and thus the actual pressure loss for the study (i.e., 2000 m^3/h) is calculated by the fan affinity law for pressure loss.
The LD-IDECOAS includes additional fans when compared to those in a conventional variable air volume system. Pumps are required for the absorber, regenerator, cooling tower, IEC, and DEC. When integrated with the SORC, it is necessary to additionally install the circulation pumps for ORC and solar collector. With respect to the pump power (P_{pump}) calculation, the pump efficiency (η_{pump}), fluid density (ρ) and flow rate ($\dot{V}_{pump}$), gravity acceleration (g), and head loss (H) correspond to the required variables (Equation. 13). The head loss of pump is based on (Kim, Yoon, et al. 2016). The expressions are as follows:

$$P_{fan} = (\dot{V}_{fan} \cdot \Delta P)/\eta_{fan} \quad (12)$$

$$P_{pump} = \rho \cdot g \cdot \dot{V}_{pump} \cdot H / 1000\, \eta_{pump} \quad (13)$$

SIMULATION RESULTS

The energy performance evaluation of the LD-IDECOAS driven by SORC was conducted during the cooling season (i.e., June, July, and August). Figure 4 shows a comparison of the energy consumption between the SORC LD-IDECOAS and base LD-IDECOAS. The power and heat consumption were converted into primary energy consumption. It is assumed that the electricity is supplied from the existing power grid in both cases, and the LNG is used for the gas boiler. The regional condition is considered, and the primary energy factors for each energy source recommended by the Korean Energy Agency are introduced. The local primary energy factors correspond to 2.75 for electricity and 1.1 for fuel.

The power consumption consists of fan and pump energy that differ from those of the conventional variable air volume system in which chiller energy corresponds to the highest portion of the power consumption. This is because the LD-IDECOAS corresponds to a type of non-vapor-compression system that provides both sensible and latent cooling without or with the least use of a chiller. The operating energy for LD-IDECOAS is same in both cases. However, the SORC with LD-IDECOAS used 1.8 times the power consumed by the base LD-IDECOAS due to SORC operation.

The heat energy is required for solution heating and additional heating in a solar thermal system. The SORC integrated with LD-IDECOAS saves 55% heat energy when compared to that of the base case. The SORC LD-IDECOAS recovers heat from the ORC and the ORC obtains heat from the solar thermal system, and therefore the operation of the boiler is lower than that in the base case.

Consequently, the LD-IDECOAS driven by SORC consumed 44% less primary energy when compared with that of the base LD-IDECOAS. The ORC satisfies 87% of the power consumption of the SORC LD-IEDCOAS if the power for SORC-LDIDECOAS is supplied from the ORC that generates 2 kW.

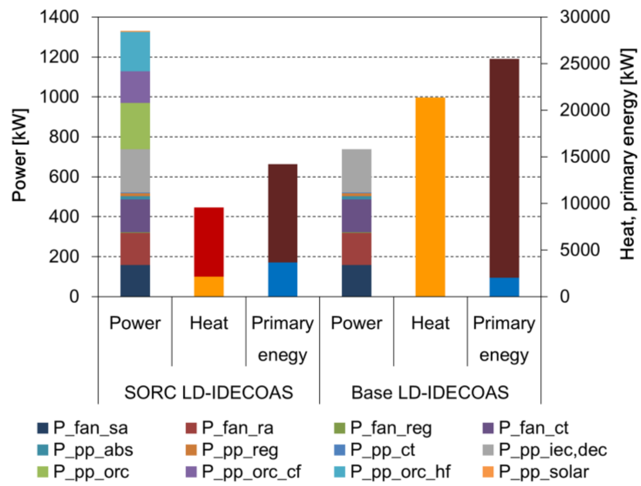

Figure 4. Comparison of the energy consumption between two types of LD-IDECOAS

CONCLUSIONS

This study was conducted to evaluate the primary energy consumption of the SORC applied to the LD-IDECOAS when compared to the LD-IDECOAS served by conventional grid power and a boiler during the cooling season. The results indicate that the SORC LD-IDECOAS consumed 1.8 times as much power and saves 55% of heat energy when compared to those of the base LD-IDECOAS. Furthermore, the SORC integrated with LD-IDECOAS reduced primary energy consumption by 45% when compared to that of the base case. Therefore, the LD-IDECOAS achieves energy saving when driven by the SORC. Additional studies are required to size the ORC and solar collector and analyze the annual energy consumption.

ACKNOWLEDGEMENT

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