Energy-Harvesting Benefit of a Thermoelectric Generator for a Liquid Desiccant System in an Organic Rankine Cycle

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Abstract

A liquid desiccant (LD) system can be used for dehumidifying hot and humid outdoor air for air conditioning during the summer. The LD system requires thermal energy to regenerate the desiccant solution for stable dehumidification performance. In this study, we propose the use of heat generated from the organic Rankine cycle (ORC) in a combined heat and power system. In addition, waste heat is observed in a closed-loop LD system with an integrated ORC. Therefore, use of a thermoelectric energy harvester is suggested to reclaim the wasted heat by converting it into electricity. Finally, a detailed energy simulation model was developed to investigate the benefit of using the thermoelectric energy harvester in the LD system with integrated ORC during the summer.

Introduction

Recent research of the organic Rankine cycle (ORC) is being undertaken as global warming and energy waste gain worldwide attention. The thermal energy which is not generally converted to electricity dissipates the condenser stage of the ORC. Research into utilizing the wasted heat has also been pursued, with one proposed method using waste heat to regenerate a liquid desiccant (LD) solution. Dong et al. (2018) presented such a system and compared the primary energy consumption of a heating, ventilation, and air conditioning (HVAC) system operating using a solar energy ORC with an HVAC system including an LD system that uses a conventional power grid. Adequate dehumidification performance of LD system requires the heat source to regenerate the weakened desiccant solution. When humid and hot air enters the absorber part of the liquid dehumidification system, the LD solution weakens. In the regenerator part, the weak LD solution absorbs the heat energy and releases the moisture extracted from the outside air as a strong LD solution. The required thermal energy required is provided by the heat dissipated from the condenser part of the ORC. The energy performance of the system was observed to improve by reusing thermal energy through the implementation of a thermoelectric module (TEM). However, some thermal energy was observed to remain after regenerating the LD solution. The TEM recovered a small amount of thermal energy that is otherwise generally lost.

The TEM utilizes two main mechanisms; the Seebeck effect and the Peltier effect. The Seebeck effect generates electricity when a temperature difference is applied to the contact point between the *p*-and *n*-type semiconductors, which are the main components of the TEM. This effect is observed even when the temperature difference is small, such that a low-temperature heat source below 100°C can be used in the TEM for electricity generation. In a previous study carried out by Frederic and Nicolas (2013), the electricity generation performance based on fluid flow rate and temperature difference was evaluated in a range of 30–80°C using TEM.

Also fuel cell have the same characteristic as organic Rankine cycle which producing waste heat (Chen at al., 2010). Intended hot air in the 26-200 °C is sullied to pipe which attached 12 thermoelectric modules for simulate wasted heat recover. The thermoelectric effect was verified by intended hot air and outside cold air.

As a result, the feasibility of using a thermoelectric energy harvester (TEH) in an LD system combined with the ORC is analyzed in this study using detailed energy simulations based on theoretical and empirical models of components.

System overview

Liquid desiccant system

The LD system consists of an absorber part for dehumidification and a regenerator part for regeneration, as shown in Fig. 1. LD solution flows on the surface of the packed bed in the absorber and the regenerator. Heat and mass are transferred between the LD solution and the air on the surface of each part. In the absorber part, the supply air is dehumidified depending on the amount of water and heat transferred from the air to the LD solution. However, in the regenerator part, LD solution is regenerated depending on the amount of water and heat transferred from the LD solution to the exhaust air.

The components of the LD system and structures were designed based on a previous study (Cho and Jeong, 2018), and the system is operated by the HVAC system schedule of the building.

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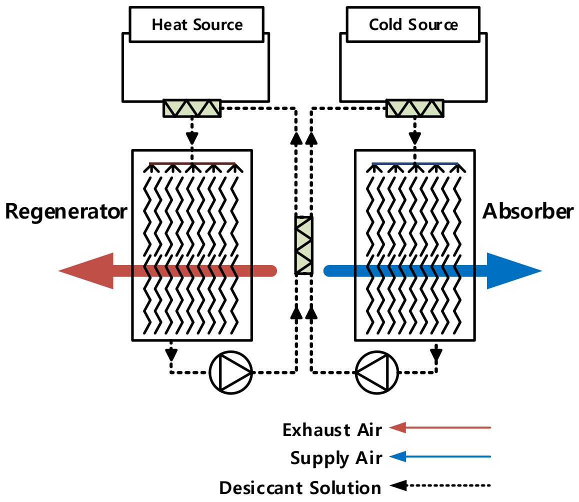


Figure 1: Schematic of the liquid desiccant system.

Organic Rankine cycle

Figure 2 is a schematic diagram of the ORC unit. The technical specifications of the ORC used in this study are described in Table 1.

The difference between a normal Rankine cycle and ORC is the use of an easily variable-phase fluid for the working system. Furthermore, the phase-change temperature of the working fluid is lower for the ORC.

In both the normal Rankine cycle and ORC, thermal energy is lost at the condenser, which is then not converted into electricity.

Table 1: Technical specifications of the organic Rankine cycle unit.

Descriptions	Specification
Working fluid	R245fa
Phase-change temperature	97°C
	50°C
Pressure	3.4 bar
	11.8 bar
Power generation	2.3 kWh

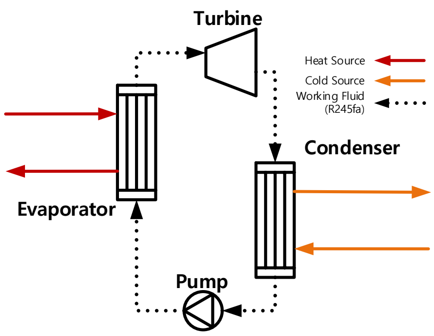


Figure 2: Schematic of the organic Rankine cycle unit.

Thermoelectric generation energy harvester

The TEH consists of TEMs, aluminum plates, water pipes, and the substrates. As shown in Fig. 3, the TEMs are arranged in a flat grid between two aluminum plates. At the surface of both plates, hot and cold fluid pipes are attached through substrates. Insulation is implemented by the finishing material to reduce unnecessary heat transfer to the surroundings. The hot water that carries the remaining heat energy after supplying the thermal energy to the regenerator flows through the hot fluid pipe. After cooling the LD solution, the cold water flows through the cold fluid pipe away from the absorber. The hot and cold fluids create the temperature difference between the hot and cold sides of the TEM. The technical specifications of the TEM are summarized in Table 2.

Table 2: Technical specifications of thermoelectric module.

Parameter	Value
Area (A)	0.04×0.04 m^2
Thickness (l)	3 mm
Number of thermocouples (N)	127
Maximum input voltage (V_{max})	24.6 V
Maximum input current (I_{max})	11.3 A
Maximum cooling capacity (Q_{max})	172 W
Maximum temperature difference (ΔT_{max})	69°C

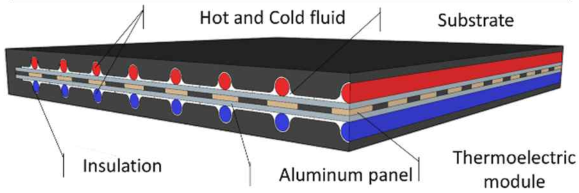


Figure 3: Cross-sectional diagram of the thermoelectric energy harvester.

A manifold is used to uniformly distribute the fluid to the TEH, as shown in Fig. 4. The hot and cold fluids pass through the inside of the TEH, generating electricity by the temperature difference.

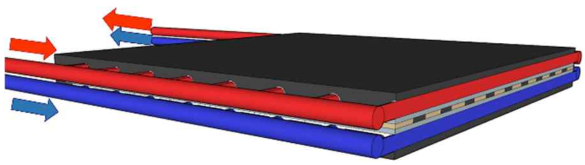


Figure 4: Three-dimensional diagram of the thermoelectric energy harvester with manifold.

Thermoelectric energy harvester in the liquid desiccant system with integrated organic Rankine cycle

A TEH is installed at the condenser inlet of the ORC system. The heat energy from the ORC unit is used in the regenerator, and the remain heating energy is reclaimed by exchanging heat with the cold water from the cooling tower after use in the LD system, as shown in Fig. 5.

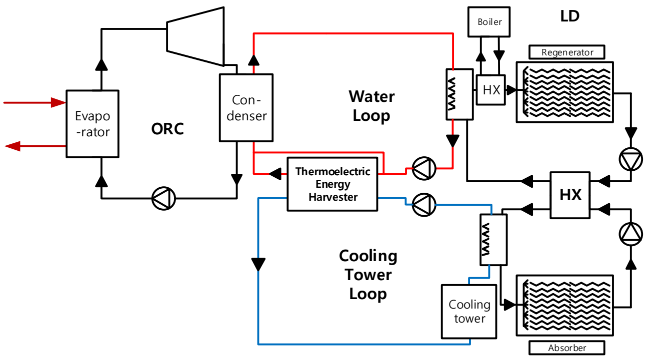


Figure 5: Schematic of the thermoelectric energy harvester in the liquid desiccant system combined with the organic Rankine cycle.

Simulation overview

Simulation assumptions

In this study, a simulation was conducted to examine electricity generation from the TEH using waste heat. There were two modeling assumptions made for the energy simulation. The first is that the amount of heat energy discharged from the hot fluid pipe, flowing into the cold fluid pipe, and passing through the TEM are all energetically balanced. The second is that heat conduction is not considered when heat transfers from the pipe through the aluminum plate and substrate to the surface of the TEM. In reality, some of the thermal energy is converted into electricity through the TEM so the amount of energy discharged from the hot fluid pipe and the amount of energy flowing into the cold side are different. However, the converted heat flux is very small due to the electricity generation efficiency of the TEM, and therefore this effect was neglected in order to simplify the simulation.

In addition, the thermal resistance to heat conduction between the water and the TEM surface is very small compared with the thermal resistance to the heat transfer via convection at the inner surface of the pipe. Therefore, this was also neglected for simplification purposes.

Liquid desiccant system

The temperature of the LD solution in the absorber part and the regenerator part was calculated with the constitutional elements of the building, the user, and the external air condition. The amount of heat required for regeneration and dehumidification of the LD solution is also calculated. The following Eqs. (1) and (2) are used to calculate the enthalpy change ratio for the movement of the humidity from the LD solution. h_{fg} is the heat of vaporization of water.

$$h_{LD,ab,out} = \frac{\dot{m}_{LD,ab,in} \times h_{sol,ab,in} + \dot{m}_{oa} \times (h_{oa} - h_{sa})}{\dot{m}_{LD,ab,out}} \quad (1)$$

$$h_{LD,reg,out} = \frac{\dot{m}_{LD,reg,in} \times h_{sol,reg,in} + \dot{m}_{ea} \times h_{fg}}{\dot{m}_{LD,reg,out}} \quad (2)$$

Organic Rankine cycle

The ORC used for the energy simulation generates 2-kW of electricity, and the evaporating and condensing temperatures are set to 104°C and 50°C, respectively. The high pressure for evaporation is set to 1177 kPa and the low pressure for condensation is set to 343 kPa. Distinct heat source was selected for the operational heating source of the ORC. For normal ORC operation, the condenser must bring the working fluid below the phase-change temperature. In this simulation, this means that the temperature must be kept below 40°C. The discharged and charged energy of each component is calculated by the following Eqs. (3) to (6) (Costiuc and Costiuc, 2017). $\dot{m}_{orc}$ is the working fluid amount of ORC.

$$\dot{W}_{pump} = \dot{m}_{orc} \times (h_{pump,out} - h_{pump,in}) \quad (3)$$

$$\dot{Q}_{ORC,in} = \dot{m}_{orc} \times (h_{evaporator,out} - h_{evaporator,in}) \quad (4)$$

$$\dot{W}_{turbine} = \dot{m}_{orc} \times (h_{turbine,in} - h_{turbine,out}) \quad (5)$$

$$\dot{Q}_{ORC,out} = \dot{m}_{orc} \times (h_{condenser,in} - h_{condenser,out}) \quad (6)$$

Thermoelectric generation energy harvester

For the purpose of designing the TEH, the temperature of the water entering the condenser of the ORC should be set. Steady waste heat discharge from the ORC occurs as water moves through the pipe. As previously mentioned, for normal operation of the ORC the temperature of the water entering the condenser must be below 40°C. The 40°C water receives the ORC waste heat from the condenser, raising its temperature to 66°C. The 66°C water provides thermal energy to the regenerator of the LD system and then flows to the hot side of the TEH. The temperature of the water entering the hot side ranges from 66.7°C to 49°C. The cooling water supplied from the cooling tower passes through the absorber part of the LD system and is supplied to the cold side. In the design of the TEH, the fluid temperature of the hot side and the cold side is set to the most difficult case where water at a temperature of 40°C is supplied to the condenser of the ORC.

Number of thermoelectric modules

Based on the temperature specified, we calculate the temperature change when the hot fluid and cold fluid pass through an individual TEM. At this time, the first assumption of energy balance (Eq. (7)) is applied. The thermal energy Q discharged from each fluid was calculated as follows:

$$Q_{Hotfluid,out} = Q_{TEM,pass} = Q_{Coldfluid,in} = Q_{ideal} \quad (7)$$

We then calculate the surface temperatures of the pipe, which is determined by the temperature of the hot and cold fluid (Eqs. (8) and (9)). A_{pipe} is the area of each fluid heat exchange part.

$$T_{Coldsurface} = T_{Coldfluid} + \frac{Q_{ideal}}{h_{Coldfluid} \times A_{Coldfluidpipe}} \quad (8)$$

$$T_{Hotsurface} = T_{Hotfluid} - \frac{Q_{ideal}}{h_{Hotfluid} \times A_{Hotfluidpipe}} \quad (9)$$

With the second assumption regarding thermal resistance, we can calculate the surface temperature of the TEM at the hot and cold sides.

Once the surface temperature is determined, the thermal energy that passes through the TEM can be calculated as in a previous study by Chen and Snyder (2013), which effective Seebeck coefficient of compact TEM (α), effective electrical resistivity of compact TEM

(ρ), effective thermal conductivity of compact TEM (κ), effective lumped Seebeck coefficient of the TEM (S) and electrical resistance of the TEM (R) are used for calculating the thermal conductivity (K) and generated power from the TEM (Eqs. (10) to (16)). f is packing ratio of total TEM area covered by thermo couples.

$$\alpha = \frac{\dot{Q}_{max}(T_{hotfluid} - \Delta T_{max})}{N \times T_{hotfluid}^2 \times I_{max}} \quad (10)$$

$$\rho = \frac{A \times f \left(T_{hotfluid} - \Delta T_{max}\right)^2 \times \dot{Q}_{max}}{2 \times T_{hotfluid} \times I_{max} \times N^2 \times I_{max}^2} \quad (11)$$

$$\kappa = \frac{I_{max}(T_{hotfluid} - \Delta T_{max})^2 \times \dot{Q}_{max}}{A \times f \times T_{hotfluid}^2 \times \Delta T_{max}} \quad (12)$$

$$S = \frac{2N \times Q_{max}(T_{hotfluid} - \Delta T_{max})}{N \times T_{hotfluid}^2 \times I_{max}} \quad (13)$$

$$R = \frac{4N^2 l}{Afp}\left(\frac{Af(T_h - \Delta T_{max})^2}{2T_h^2 l}\frac{Q_{max}}{N^2 I_{max}^2}\right)^{-1} \quad (14)$$

$$K = \frac{\kappa \times A \times f}{L} \quad (15)$$

Therefore, the thermal energy passing through the TEM, depending on the surface temperature, is calculated as follows:

$$Q_{TEM} = \frac{(T_{hotfluid} - T_{coldfluid}) \times K}{1 + \frac{K}{A \times h_{hotfluid}} + \frac{K}{A \times h_{coldfluid}}} \quad (16)$$

The temperature change of the fluid passing through the surface of TEM can be calculated based on the energy passing through the TEM (Eqs. (17) to (18)). Figure 6 shows the movement of thermal energy through the TEH. The amount of electricity generated in a TEM by the temperature difference can be calculated in Eq. (19).

$$T_{hotfluid,out} = T_{hotfluid,in} - \frac{Q_{tem}}{\dot{m} \times cp_{hotfluid}} \quad (17)$$

$$T_{coldfluid,out} = T_{coldfluid,in} + \frac{Q_{tem}}{\dot{m} \times cp_{coldfluid}} \quad (18)$$

$$P_{DC,TEG} = \left(N \times \alpha^2 \times \frac{\Delta T^2}{R} \times \frac{\frac{R_{load}}{R}}{\left(1 + \frac{R_{load}}{R}\right)^2}\right)/1000 \quad (19)$$

The temperature of the fluid passing through the surface of an individual TEM is not low enough to change the phase of the working fluid of the ORC. This means that the temperature of the hot fluid at the outlet should be at least lower than 40°C. This required the use of a larger number of TEMs, and the resulting behavior was simulated by repeating the calculation to meet the target outlet temperature required for the phase change of the working fluid. The number of TEMs was therefore determined for a peak load condition. After determining the number of TEMs in the TEH, the total amount of electricity generated from the TEM was calculated in hourly simulations.

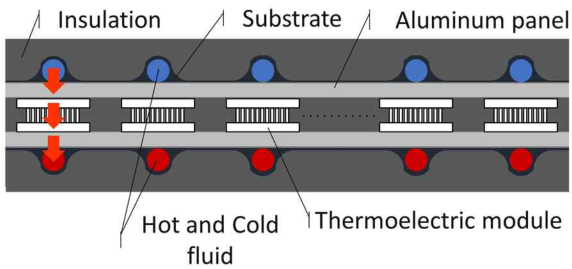
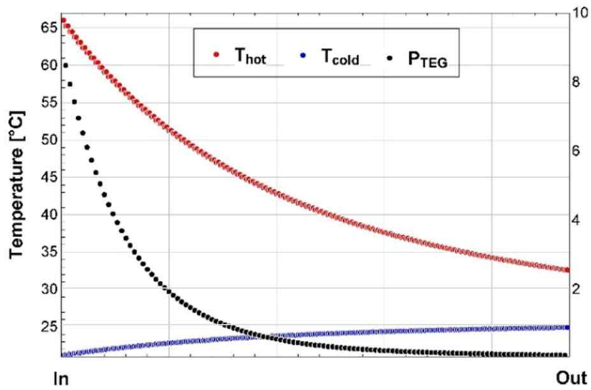


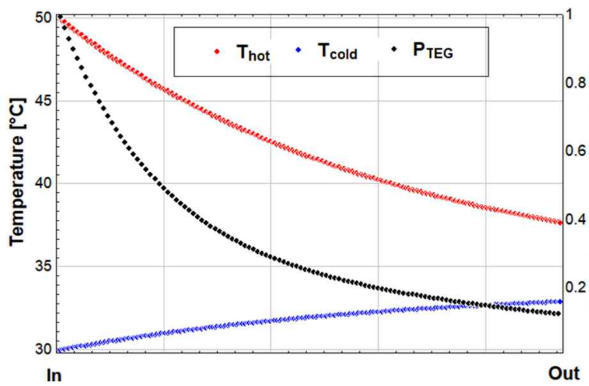
Figure 6: Heat flow diagram of the thermoelectric energy harvester.

Simulation results

In Fig. 7a, the hot and cold fluid temperatures were plotted together with the power generated over a period of maximum temperature difference without the operation of the LD system. In Fig. 7b, the thermal behavior was plotted with generated power when the LD system was operational. The x-axis shows the inlet and outlet of the TEH so that the transient fluid temperature change can be observed.



(a) Maximum temperature difference



(b) Minimum temperature difference

Figure 7: Thermal behavior and generated power in the thermoelectric energy harvester.

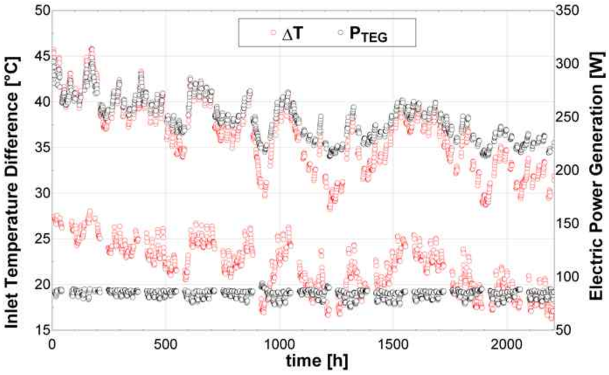


Figure 8: Temperature difference and generated power during summer.

The amount of energy required by the LD system varies depending on the condition of the outdoor air, the internal occupants, and the building HVAC schedule. As a result, the temperature of the fluids flowing into the TEH also varies. As shown in Fig. 8, the temperature difference took a value higher than about 27°C when the LD system was not operational. On the contrary, the temperature difference was lower than 27°C when the LD system was operational. The power generated was proportional to the temperature difference between the hot and cold sides of the TEM, and therefore the observed trend of the power generated showed very similar behavior to that of the temperature difference.

During summer conditions, an additional 317 kWh of electricity was generated by the TEH, producing 6.31% more electricity from the waste heat in the LD system with the integrated ORC unit.

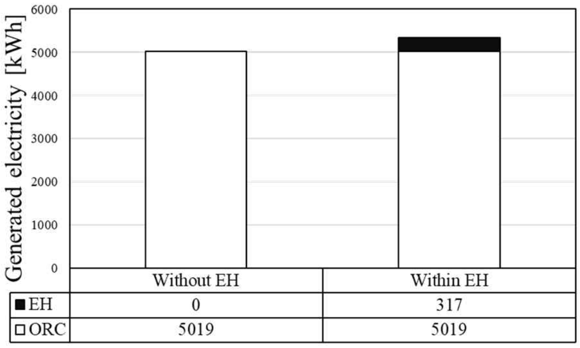


Figure 9: Generated power from the organic Rankine cycle and thermoelectric energy harvester during summer.

Conclusion

In this study, we analyzed the effect of a TEH when implemented in an LD system with an integrated ORC unit. Using the Seebeck effect of TEMs, the low-temperature waste heat was reclaimed by the proposed system. As a result, it was observed that the TEH application system can generate 6.31% more electricity compared to the previous LD system with integrated ORC unit.

However, additional energy losses and additional costs due to the application of TEH must be considered. In addition, the amount of energy recovered from waste heat becomes meaningful when the system is made larger than an appropriate size.

Acknowledgement

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