# Basic study on the possible application of a thermoelectric module in a liquid desiccant system



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**Topic 1**: HVAC&R Components and Systems

# Basic study on the possible application of a thermoelectric module in a liquid desiccant system

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## ABSTRACT

This study suggests the design of a thermoelectric module (TEM) assisted liquid desiccant (LD) system along with an analysis of the energy potential. The point we focused is the applicability of using a TEM for cooling and heating simultaneously in an LD system. With the proposed design, the TEM takes charge of the cooling and heating loads with a water-cooled unit on the hot side to remove the extra heat rejection. An energy simulation was conducted for different cases to evaluate the primary energy consumption with a variation in the solution temperature. The results show that no energy saving occurs in the current stage; however, there is the possibility of applying TEMs in an LD system to reduce the system size, thereby simplifying the system operation without the use of a refrigerant.

## INTRODUCTION

An independent control of the latent and sensible load has become an attractive option owing to the reduction of the power requirements for air-conditioning systems. Liquid desiccant (LD) units are promising new alternatives for handling a latent load owing to their low electric demand, good dehumidification, and relatively low regeneration temperature (Ham et al. 2016).

Accordingly, many researchers have tried using LD units widely in air-conditioning systems, and the results of previous studies have shown that the energy consumption in LD units for heating and cooling make up the largest portion of the operation energy (Kim et al. 2016). This is because the simultaneous use of cooling and heating desiccant solutions is necessary to increase the efficiency of dehumidification and regeneration in LD units. The independent installation of a cooler and a heater is a simple way to satisfy demand, and energy conservation can be achieved if a heat pump is used in the heating and cooling generation (Zhang et al. 2016). A vapor compressor heat pump has been generally used to assist LD systems and has shown a good coefficient of performance (COP). However, vapor compression is also used for refrigerants, which brings about a concern regarding the possible destruction of the ozone layer and global warming.

As an alternative solution, the use of a thermoelectric module (TEM) as a non-vapor compression heat pump without a refrigerant has also been studied (Lee et al. 2015). Although a TEM shows a lower COP for the cooling than a traditional heat pump, it has certain advantages including a compact size, no moving parts, no noise, precision temperature control, and no refrigerants (Daly 2006). However, there have only been a few cases using TEMs for cooling and heating simultaneously during the initial stage. A prototype thermoelectric heating and cooling unit for air-conditioning was developed through experiments and a numerical analysis (Yimazoglu 2016). The results show the possibility of using cooling and heating simultaneously with an average COP of 0.7 and 4.1, respectively.

In this study, the designs for a TEM-assisted LD system are proposed based on the possibility of using a TEM for cooling and heating simultaneously without a refrigerant. Simulation models were developed for a TEM-assisted LD system. Through the simulations, the energy performance was evaluated during the cooling season. Finally, an LD system using an electrical chiller and a gas boiler was compared with the TEM-assisted LD systems in terms of energy consumption, COP, and variations in the solution temperature of the LD system.

## SYSTEM DESCRIPTION

An absorber, a so-called dehumidifier, and a regenerator are the main components of an LD system. A packed bed was selected for the estimation, and lithium chloride (LiCl) with a concentration of 38% was assumed for the desiccant solution in the system. The airflow rate of the process air at the absorber was assumed to be 2,000 $m^3/h$, whereas the airflow rate of the process air at the regenerator was assumed to vary to meet the equal mass flow rate of regeneration with that of dehumidification and thereby maintain the constant concentration of the desiccant solution. The target temperature of the inlet at the absorber and regenerator was 25℃ and 60℃, respectively (Kim 2016). The liquid-to-air ratio of the absorber was assumed to be 1.2, and thus the mass flow rate of the desiccant solution was a constant value of 0.67 kg/s. Solution tanks were placed at the outlet side of the absorber and regenerator, and a sensible heat exchanger was used between the strong and weak solutions before heating and cooling the solution. The cooling and heating components based on the particular case are described below.

### Boiler and chiller assisted LD system

As shown in figure 1, a general LD system was studied for a comparison without the use of a TEM. A gas boiler and an electric chiller were selected for heating and cooling the devices, respectively. The capacity of the gas boiler was selected based on the maximum heating load of the weak solution, and was 31.4 kW with an efficiency of 86.8%. On the other hand, a chiller with a capacity of 21.6 kW was selected based on the maximum cooling load of the strong solution. The input power of the chiller was 5.95 kW, and its chiller varied based on the part load ratio.

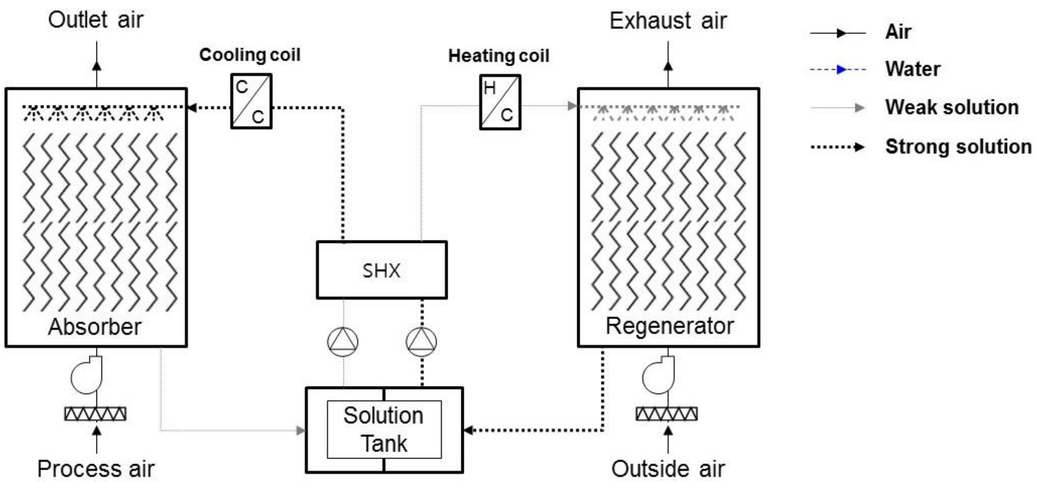

*Fig. 1. Boiler- and chiller-assisted LD system*

## TEM-assisted LD system

In a TEM-assisted LD system, the cooling load is fully handled using TEMs, as shown in figure 2. If the chiller is replaced with TEMs on the cold side, too much heat rejection occurs on the hot side, and thus the proper performance of the TEMs cannot be achieved without auxiliary cooling. Therefore, a water-cooled method was selected to remove the heat from the hot side of the TEMs. In addition, the excessive heat was delivered to the inlet of the process air at the regenerator through water. Heating the process air of the regenerator is expected to increase the effectiveness of the regeneration (Kim et al. 2015). In addition, it was assumed that tap water was used with a constant temperature of 15℃.

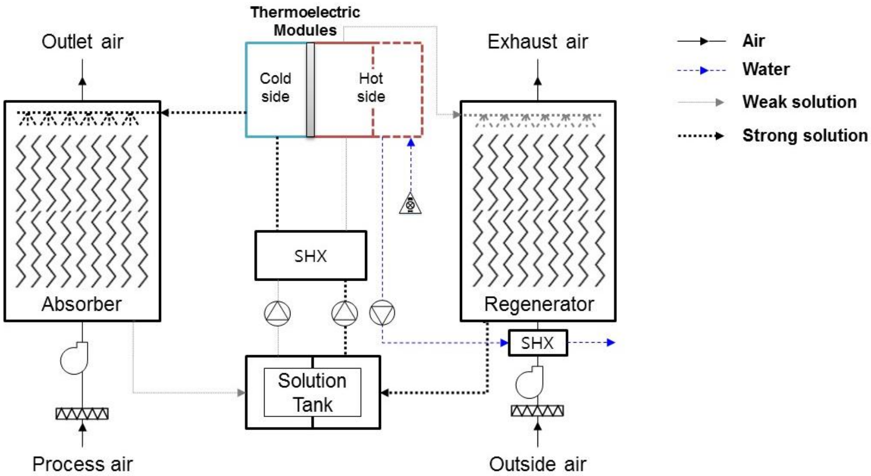


*Fig. 2. TEM-assisted LD system*

## SIMULATION MODEL

Energy simulations for three different cases were conducted using MATALAB, and the weather data from IWEC2 for Seoul, South Korea from August 1-31 were used to analyze the results. The weather data included the temperature, relative humidity, and humidity ratio during a total of 744 hours at hourly intervals.

## Liquid desiccant unit

To calculate the effectiveness of the dehumidification, an empirical model for a packed-bed absorber from a previous study (Park et al., 2016) was used to predict the effectiveness of the dehumidification based on the outdoor and LD operation conditions. This model consists of six parameters: the mass flow rates of air ($\dot{m}_{oa,abs,in}$) and the desiccant solution ($\dot{m}_{sol,abs,in}$), the temperature ($T_{oa,abs,in}$) and humidity ratio ($\omega_{oa,abs,in}$) of the process air, and the temperature ($T_{sol,abs,in}$) and concentration ($\chi_{sol,abs,in}$) of the solution. In addition, the valid range of the prediction was observed during the simulation applied in this study.

Using the theoretical effectiveness of the dehumidification ($\epsilon_{deh}$) in Eq. (1), the humidity ratio of the process air at the outlet ($\omega_{oa,abs,out}$) can be determined when the equilibrium humidity ratio in the absorber ($\omega_{eq,abs}$) is known. The equilibrium humidity ratio ($\omega_{eq}$) in the absorber or regenerator can be derived using Eq. (2). In addition, the vapor pressure ($P_v$) under the saturation conditions of the desiccant solution in the absorber or regenerator can be determined using a second-order polynomial equation from a previous study (Fumo and Goswami 2002). The temperature of the absorber at the outlet can be derived based on the assumption (Kim et al. 2013) that the effectiveness of the dehumidification or regeneration is similar with that of the temperature ratio.

$$\epsilon_{deh} = \frac{\omega_{oa,abs,in} - \omega_{oa,abs,out}}{\omega_{oa,abs,in} - \omega_{eq,abs}}, \quad (1)$$

$$\omega_{eq} = 0.621945 \times \frac{P_v}{P_{atm} - P_v} \quad (2)$$

Subsequently, the state of the solution at the outlet of the absorber can be predicted using the heat and energy balance. Along this same line, the temperature and concentration of the solution at the outlet of the regenerator can be derived. For the regenerator, the mass flow of the regeneration was assumed to be equal to that of the dehumidification by adjusting the mass flow of the process air at the regenerator.

**Sensible heat exchanger (SHX)**

The initial temperature of the desiccant solution in the absorber is 25℃, and the concentration of 38%. After passing through the absorber, the concentration of the solution decreases, that is, a weak solution occurs. On the other hand, a weak solution of 55℃, which enters the regenerator, and a strong solution will be produced for recycling. During this process, the weak and strong solutions exchange the heat in the SHX, thereby reducing the heating and cooling loads. The effectiveness of the SHX was assumed to be 0.7, and the outlet temperatures of the weak and strong solution were predicted using Eq. (3).

$$\varepsilon_{SHX} = \frac{T_{strong,SHX,in} - T_{strong,SHX,out}}{T_{strong,SHX,in} - T_{weak,SHX,in}} = \frac{T_{weak,SHX,out} - T_{weak,SHX,in}}{T_{strong,SHX,in} - T_{weak,SHX,in}} \quad (3)$$

**Thermoelectric modules**

The TEM was modeled using a previous developed "black box" concept model (Chen and Snyder, 2013), which can make a model based solely on the technical specifications of the TEM without a figure of merit (Z). The lumped thermophysical properties of the TEM were derived using three parameters: the Seebeck coefficient (S), electrical resistance (R), and thermal conductance (K).

Based on the traditional formulation for TEM in Eq. (4), the cooling capacity of TEM on the cold side (with a constant cold surface temperature, $T_c$) can be defined through Eq. (5). Meanwhile, the heating capacity on the hot side of the TEM can be calculated using Eqs. (5) through (7). The capacity of the cooling and heating, that is, the heating rejection and absorption on the hot and cold sides of the TEM, is independent of the input current and temperature of a cold surface. In addition, under this assumption, the temperature of the cold side is determined based on the temperature difference owing to the constant hot side temperature.

$$\dot{Q}_c = (SIT_c - K\Delta T - \frac{1}{2}I^2R)/1000 \quad (4)$$

$$\dot{Q}_c = (\frac{Af_p}{l}\left(\frac{\alpha^2 T_c^2}{\rho}\left(i - \frac{i^2}{2}\right) - \kappa\Delta T\right))/1000 \ \text{ where, } i = \frac{I}{I_{max}} \quad (5)$$

$$P = (V \times I)/1000 = \dot{Q}_h - \dot{Q}_c \quad (6)$$

$$V = IR + S\Delta T \tag{7}$$

**Thermoelectric cooling and heating unit**

The thermoelectric cooling and heating unit is composed of TEMs and three water blocks. The TEMs are connected electrically in series, and thermally in parallel. Therefore, the total cooling capacity and electrical power consumption can be defined through Eqs. (8) and (9). The number of TEMs can be determined based on their optimal COP according to the input current and cooling capacity.

$$\dot{Q}_{c,tot} = n \times \dot{Q}_c = n \times \frac{Af_p}{l}\left(\frac{\alpha^2 T_c^2}{\rho}\left(i - \frac{i^2}{2}\right) - \kappa\Delta T\right), \text{where} \quad i = \frac{I}{I_{max}} \tag{8}$$

$$P_{tot} = n \times P = n \times V \times I = n\,(\dot{Q}_h - \dot{Q}_c) \tag{9}$$

In a TEM-assisted LD, the cooling load is treated based on the cooling capacity of the TEMs. The extra heat rejection occurs on the hot side of the TEMs. Therefore, a water-cooled system was selected to maintain the temperature of the hot side surface. In addition, heated water was used for heating the process air of the regenerator. The temperature of the hot and cold sides can be determined using Eqs. (10) and (11).

$$T_c = T_{strong,SHX,out} - \frac{T_{strong,SHX,out} - T_{abs,in}}{\varepsilon_{wb}} \tag{10}$$

$$T_h = T_{weak,SHX,out} - \frac{T_{reg,in} - T_{weak,SHX,out}}{\varepsilon_{wb}} \tag{11}$$

The number of TEMs and the necessary cooling capacity are given, and thus the input current can be calculated using Eq. (12). This is also a quadratic formula for simultaneously solving equations consisting of Eqs. (7) - (9).

$$I = \frac{(nAf_p\alpha^2T_c^2) - \sqrt{(nAf_p\alpha^2T_c^2)^2 - 2\rho(nAf_p\alpha^2T_c^2)(\kappa\Delta T n a f_p + L\dot{Q}_{c,tot})}}{nAf_p\alpha^2T_c^2} \times I_{max} \tag{12}$$

Subsequently, the total cooling, heating capacity, and electrical power consumption of the TEMs can be determined using Eqs. (8) and (9). The needed heating capacity (i.e., the heating load) is already known, and thus the remaining heating capacity can be easily derived using Eq. (13).

$$\dot{Q}_{h,rem} = \dot{Q}_{h,tot} - \dot{Q}_{heating} \tag{13}$$

**Other components**

The simulation models for an electrical chiller and a gas boiler were selected from the DOE-2.1 building energy simulation program and EnergyPlus engineering reference, respectively. To estimate the pump energy consumption, the efficiency of the pump is assumed to be 60%, and the total head of each component used is based on the technical specifications and a previous study (Kim et al. 2016). The pump energy consumption can be determined using Eqs. (14) and (15). Based on the pump powers at the design volume flow rate, energy consumptions for a variable flow operation are estimated using the affinity law. Although fans should be used in all cases for controlling the process air of the absorber and regenerator, the operation energy was not simulated because no differences in the results were shown for any of the cases.

$$P_{pump,design} = \frac{\dot{V}_{fluid}\times \mathrm{H}\times 9.8}{\eta_{pump}} \quad (14)$$

$$P_{pump,operation} = P_{pump,design}(\frac{\dot{V}_{operation}}{\dot{V}_{design}})^3 \quad (15)$$

## COOLING AND HEATING LOADS

As shown in figure 3, the temperature variations on the hot and cold sides were estimated according to the cases based on the weather data. In figure 3a, the target inlet temperature of the absorber for a strong solution ($T_{abs,\ in}$) was 25°C. The outlet temperature of the absorber ($T_{abs,\ out}$) was 28.7℃ on average, and the standard deviation (STDEV) was 1.2 within a range of 26.6 to 31.8℃. After passing through the regenerator, the strong solution entered into the SHX. The average outlet temperature of the SHX for the strong solution ($T_{strong,\ hx,\ out}$) was 36.4℃ (STDEV: 0.5). In the TEM-assisted LD system, TEM treated the entire temperature difference between the strong solution after the SHX and the inlet of the absorber. Therefore, the temperature of the TEMs on the cold side ($T_c$) was 20.1℃ (STDEV: 0.2) within the range of 19.6 to 20.5℃.

The temperature variations of the weak solution are shown in figure 3b. The target inlet temperature of the regenerator for the weak solution ($T_{reg,\ in}$) was 60°C. The outlet temperature of the regenerator was an average of 54.4℃ (STDEV: 1.7) with a relatively wide range of 49.2 to 57.9℃. After passing through the absorber, the weak solution entered into the SHX. The average temperature of the SHX at the outlet ($T_{weak,\ hx,\ out}$) was 46.2℃ (STDEV: 0.8) within the range of 43.7 to 48.1℃. The mean temperature difference between the inlet temperature of the regenerator and the outlet temperature of the SHX was 13.8℃. Hence, the temperature of the TEMs on the hot side ($T_h$) was 65.9 ℃ (STDEV: 0.4) within the range of 65.1 to 67 ℃.

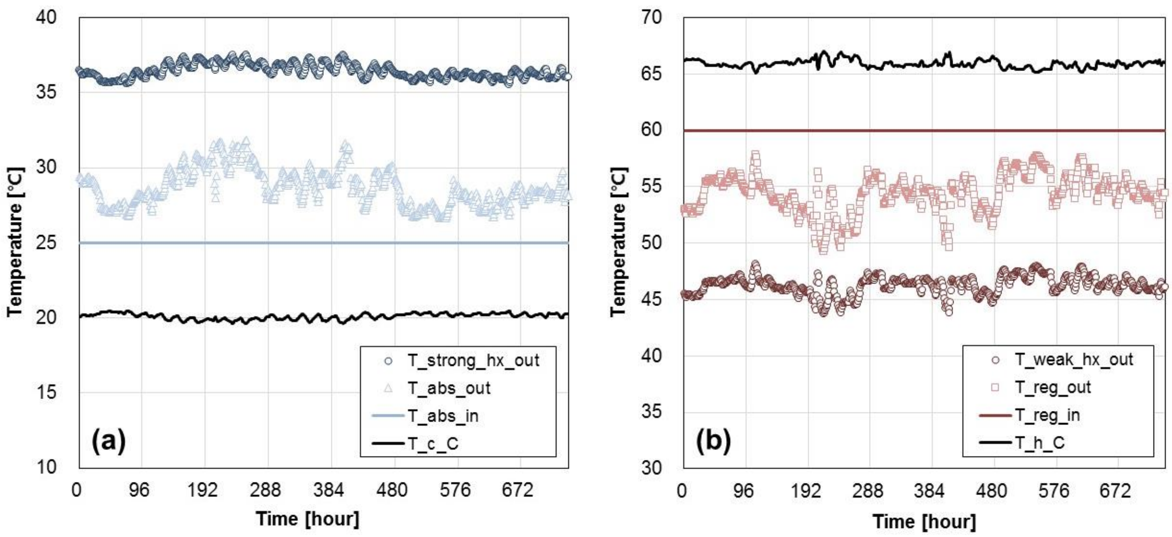


*Fig. 3. Temperature variation of (a) strong and (b) weak solutions during cooling season*

Finally, the cooling and heating loads were evaluated based on the temperature difference and mass flow of the solution. The loads were analyzed according to the operation time in hours, as shown in figure 4. An over heat rejection occurred owing to the heating capacity of the TEMs. The average heating capacity of the TEMs was 74 kW within the range of 66 to 86 kW. Therefore, the amount of overheat rejection was 43.3 kW on average (STDEV: 3.9) within the range of 36.5 to 53.3 kW. This overheat was released using a water-cooled system (Fig. 2) and the heat released was used for heating the process air of the regenerator.

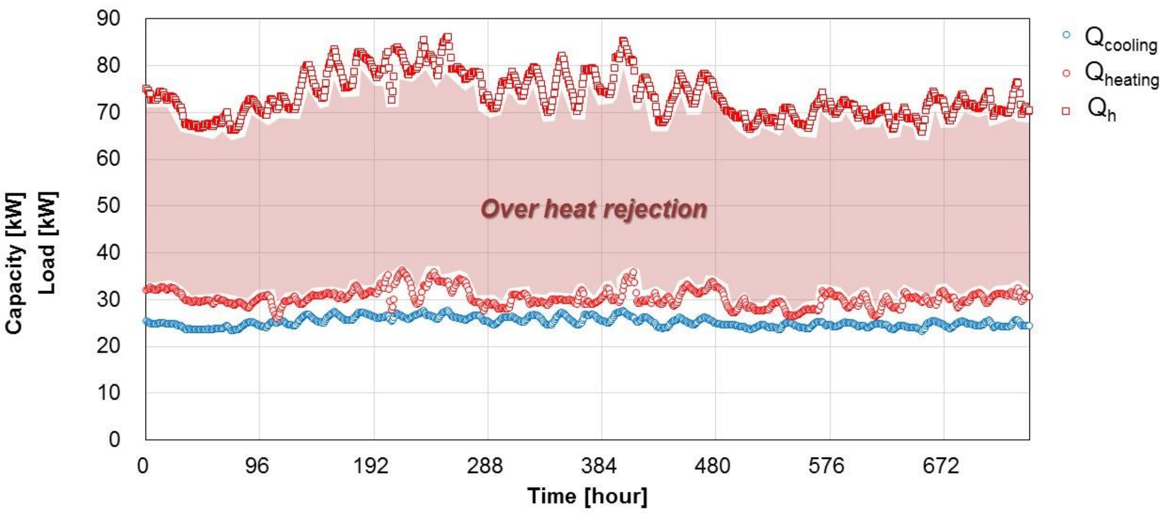


*Fig. 4. Total cooling, heating loads, and heating capacity of TEM-assisted LD system*

## OPERATING ENERGY CONSUMPTION

The hourly average values of electrical power consumption, gas energy consumption, and primary energy consumption were compared according to the case shown in figure 5. The pump was also considered for the simulation; however, the electric power consumption of the pumps was too small. Therefore, the results were only described in terms of the chiller, TEMs, and gas boiler, excluding the pumps.

In the general LD system, the electrical power and gas energy consumption were 4.0 and 37.4 kW, respectively. Even though these values were converted using a primary energy conversion factor of 2.75 for electricity and 1.1 for gas based on the local standard, the gas boiler used much more energy owing to the low COP and more heating loads. In the TEM-assisted LD system, only the electric power consumption of the TEMs occurred with an average of 48.5 kW, which was increased owing to the low COP of the TEMs for cooling.

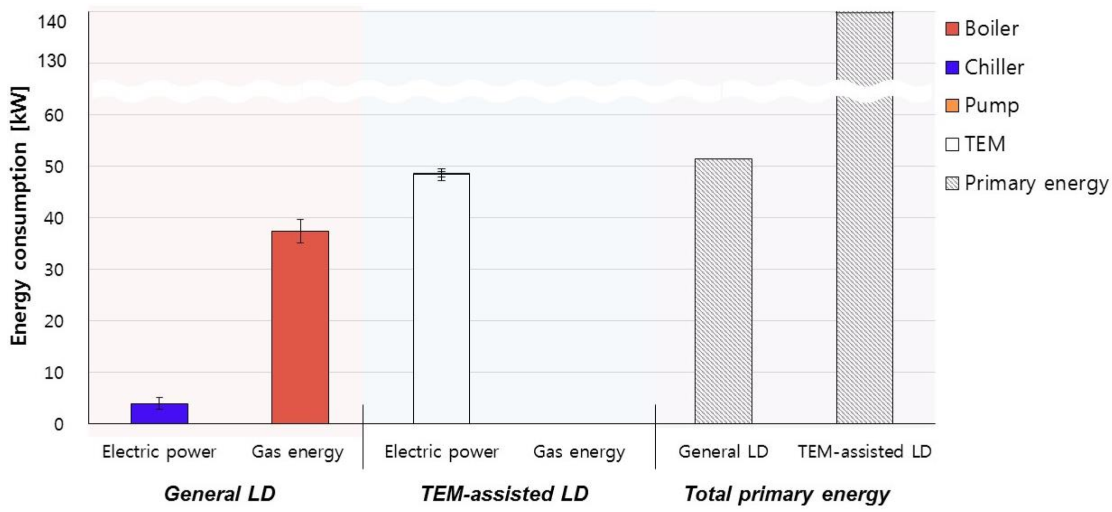


*Fig. 5. Comparison of average energy consumption during cooling season*

## CONCLUSION

This study proposed a TEM-assisted LD system considering the characteristics of the larger heating capacity than cooling capacity in a TEM. The proposed system was designed using only TEMs for treating the cooling and heating capacity concurrently. The overheat rejection is cooled by water and the heat is recovered to heat the process air of the regenerator. As a result, the primary energy consumption was increased 155% owing to the low COP of the TEMs for cooling. However, the size of the system can be reduced and simplified using a single energy source of electricity. In addition, it is expected that, if the performance of the thermoelectric materials increases, energy saving can also be achieved for cooling and heating simultaneously.

## ACKNOWLEDGEMENT

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