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Primary energy saving potential of a liquid desiccant and evaporative cooling-assisted 100% outdoor air system in underground spaces

Eun-Ji Choi[a], Dong-Seob Yoon[a], Min-Suk Jo[a], Jae-Weon Jeong[a,]*

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

Abstract

The purpose of this paper is to evaluate the applicability of a liquid desiccant and evaporative cooling-assisted 100% outdoor air system (LD-IDECOAS) in underground spaces. A detailed energy simulation is performed for estimating the energy saving potential of the LD-IDECOAS. The simulation is conducted using TRNSYS 17 and a commercial engineering equation solver program (EES). The ground source heat pump (GSHP) is integrated with the liquid desiccant (LD) system in the LD-IDECOAS to supply heating for the desiccant solution. The thermal load of underground spaces shows a different pattern compared with that of above ground spaces. Maximum cooling and heating loads are relatively small in the underground spaces because of the almost stable condition of the surrounding environment, in comparison to an above ground building. As a result, the size of HVAC systems in underground spaces can be smaller than those in above ground spaces. In this study, the regeneration heat source was applied to GSHP system. The GSHP system yields 20% operating primary energy savings compared with the conventional gas-boiler in the summer because of the constant temperature in the underground space. The results also show that the integrated system was more suitable for underground spaces.

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Keywords: Underground spaces; liquid desiccant and evaporative cooling-assisted 100% outdoor air system (LD-IDECOAS); ground source heat pump (GSHP)

1. Introduction

Recent studies have been conducted regarding the application of heating, ventilating and air conditioning (HVAC) systems in underground spaces. There is a growing need for energy savings in HVAC systems in underground spaces because many large facilities, such as subway stations, underground shopping malls, and underground commercial complexes, have more underground space than above ground space. The ventilation of these spaces is also very important because infiltration of air is negligible underground. For conventional variable air volume (VAV) systems, the use of return air (RA) is a weak point in terms of indoor air quality because they introduce only required outdoor air (OA) for energy savings and can cause cross-contamination and lack of ventilation. To overcome these problems, new types of HVAC systems should be investigated to determine the potential energy savings.

According to a report from the U.S. Department of Energy, liquid desiccant (LD) and technologies employing evaporative cooling have been proposed as an alternative to the conventional vapor compression system as one of the new generations of air-conditioning technology. Previous studies have reported a variety of different types of desiccant evaporative cooling systems, including the combination of LD and evaporative cooling systems,

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* Corresponding author. Tel.: +82 2 2220 2370; fax: +82 2 2220 1945.
E-mail address: jjwarc@hanyang.ac.kr

such as a LD and indirect/direct evaporative cooling-assisted 100% OA system (LD-IDECOAS) [1–3], a desiccant-enhanced evaporative air conditioner (DEVap) [4], and an LD and dew point evaporative cooling-assisted 100% OA system (LDEOS) [5]. These are decoupled systems that treat latent and sensible loads separately. The LD-IDECOAS proposed by Kim (2012, 2013, 2014) were analyzed to gauge the energy performance of the system at a design level through a simulation study. These units have the potential to save energy compared with conventional VAV systems. Specifically, the LD-IDECOAS showed an annual energy savings of 30% compared with conventional VAV systems in above ground space applications. Also, the LD system consists of an absorber and regenerator. To maintain the humidity condition of SA, the dehumidification was performed by using desiccant materials in the absorber tower. For consistent use of the desiccant solution, the regeneration heat source should be supplied to meet the required heating load. Depending on the heat source, the system shows different patterns of energy consumption. Kim et al. [1] proposed a solar thermal system for regenerating the desiccant solution and investigated annual operating energy savings of the proposed system compared with the conventional VAV system. Kim and Jo [6, 7] simulated a fuel cell system, for regenerating the desiccant solution. Jo et al. [7] analyzed the applicability of a fuel cell system, which provides electric power and hot water simultaneously, and evaluated it with a detailed simulation. Also, the fuel cell systems yield primary energy consumption savings and reduce CO_2 emissions compared with the conventional gas-fired boiler system. Park et al. [8] proposed a waste heat recovery system as the regeneration heat source and applied it to the LD-IDECOAS and constant air volume (CAV) system.

Accordingly, in this study, the application of the LD-IDECOAS in underground spaces was evaluated as an HVAC system to introduce a supplemental amount of OA. If this system replaces the conventional CAV and VAV systems, it is determined that it will alleviate environmental problems with the potential to save energy. Also, to applicability of the LD-IDECOAS, we analyzed energy performance and primary energy consumption of the system in underground spaces when a ground source heat pump (GSHP) system is applied using a ground source, in a manner different to HVAC systems used for above ground spaces. Moreover, we evaluated the primary energy consumption during the summer with the applied GSHP system, compared to using a gas-boiler as the regeneration heat source.

2. System overview

2.1. LD-IDECOAS configuration

The LD-IDECOAS consists of the LD system, the indirect evaporative cooler (IEC), and direct evaporative cooler (DEC), which are the non-vapor compression systems for controlling latent and sensible loads separately (Fig. 1). The LD system uses an LD solution to control the latent OA load. For consistent use of the LD solution, heat sources are required to regenerate a weak solution. Depending on the heat source, the system shows different patterns of energy consumption. After the process air exits the LD, the IEC and DEC are operated for sensible cooling of the process air to satisfy the required temperature of the supply air (SA). The operation mode of the LD-IDECOAS is determined by the OA conditions and energy consumption of the system component's OA.

In order to prevent cross-contamination, the LD-IDECOAS used 100% outdoor air for the ventilation that introduces more OA than the minimum ventilation rate suggested in ASHRAE Standard 62.1 to supply a supplemental amount of fresh air and improve indoor air quality [9].

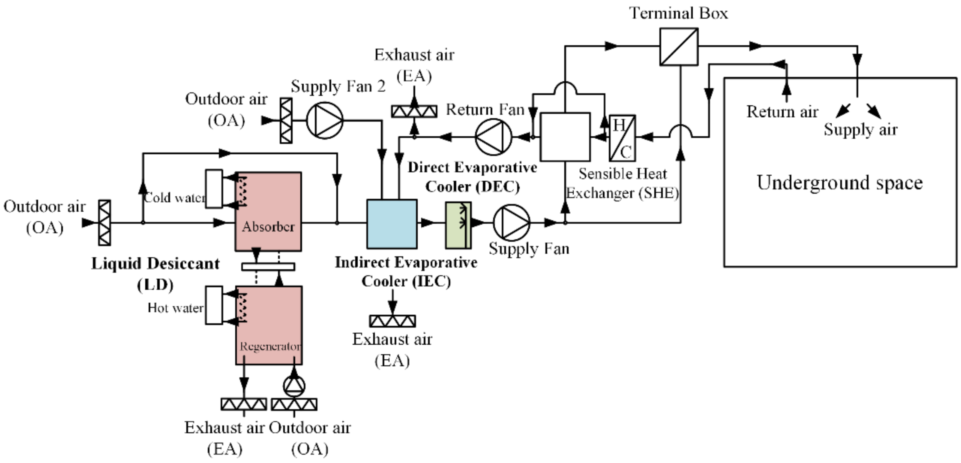


Fig. 1. Schematic diagram of the LD-IDECOAS

2.2. The LD-IDECOAS operation mode

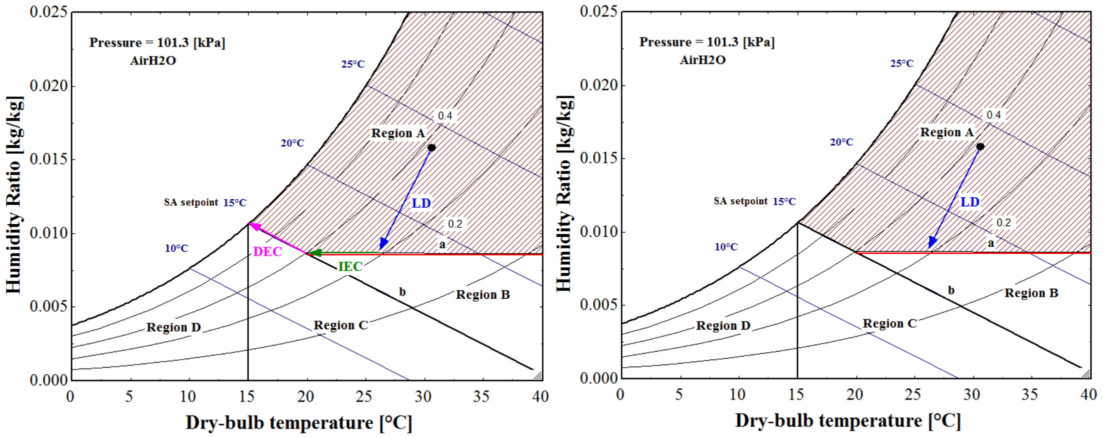
According to previous research, the operation mode of the LD-IDECOAS is generally determined by OA conditions [1–3]. The operation mode of the LD-IDECOAS can be classified into four modes; Regions A, B, C and D (Fig. 2).

Operating mode for Region A. In Region A, OA conditions are typically hot and humid. The LD system initially removes the moisture from the humid OA. After dehumidification, the process air enters the IEC for sensible cooling. Then the process air is adiabatically cooled by the DEC to reach the target SA temperature (i.e., 15 ℃).

Operating mode for Region B, C. In Regions B and C, the LD system is deactivated in the presence of dry OA. The induced OA bypasses the LD and is sensibly cooled by the IEC to reach the target SA temperature (i.e., 15 ℃). Additionally, the DEC is operated to meet the SA target temperature.

Operating mode for Region D. In Region D, the dry bulb temperature (DBT) of the OA is lower than the SA target temperature (i.e., 15 ℃), thus the LD unit and the DEC are not required. The IEC should be operated as a sensible heat exchanger (SHE) for heat recovery from the RA stream without injecting water into the secondary channel. If the SA condition is too low to meet the target condition (i.e., 15 ℃) with one stage heat exchange, the SHE should be operated to ensure the SA condition.

In this study, unlike previous research, during the summer, the operation mode (Region A) was modified depending on the thermal load characteristics of the underground spaces. Figure 2 (a) shows the LD-IDECOAS operation mode in an above ground building during the summer. The above ground building thermal load required cooling. So, in an aboveground building the LD system initially removes the moisture from the humid OA. After the process of dehumidification, the process air enters the IEC and DEC for sensible cooling. In the summer season, the underground building thermal load was the indoor sensible load needed for heating, compared to the above ground building thermal load (Fig. 2). As shown in Fig. 2 (b), it is assumed that the SA temperature and LD system outlet temperature (i.e., 25-26 ℃) are set equal to one another and operate only as dehumidifiers, without the need to cool the OA in the underground building. So in the underground building, LD-IDECOAS was operated only with the LD system. The other operation modes are the same as the conventional above ground building.



(a) Above ground building

(b) Underground building

Fig. 2. Region A of psychrometric chart

2.3. Ground source heat pump (GSHP)

The GSHP uses geothermal heat as a heat source. GSHPs are outstanding systems that have high thermal efficiency when compared to the conventional air-source heating and cooling systems. GSHP systems have a longer life expectancy, operate more quietly, and result in less carbon dioxide emission than conventional heat pumps. The GSHP consisted of an underground heat exchanger and a heat pump. Performance of the underground heat exchanger is determined by the efficiency of the system. The performance of the underground heat exchanger is dependent on the thermal characteristics of the components of the borehole, underground heat exchanger depth, and radius of the borehole. Also, the performance of the GSHP is determined according to the installation method of the underground heat exchanger. Installation methods for underground heat exchangers are classified as closed loop vertical underground heat exchangers, closed loop horizontal underground heat exchangers, and open loop ground water from a well underground heat exchanger.

The closed loop vertical GSHP system has the disadvantage of high initial installation cost. The performance advantage is that it can be used in a narrow land area compared to other methods, the system has high efficiency due to deep excavation depth, and high applicability through continuous research. Also, this system shows a small effect on the temperature of the outside air compared to the closed loop horizontal system. The closed loop horizontal system has the disadvantage of low efficiency because the excavation depth is not deep and it has a high initial cost due to the narrow land area. Open loop ground water from a well system has advantages of high efficiency and it requires a small installation area. However, it has the disadvantage of underground water pollution and underground water depletion because foreign matter is contained in the underground water. Also, it has the weakness of increased pump power consumption because of the deeper location of the water source. However closed loop horizontal systems are substantially influenced by seasonal temperature due to the shallow burial depth. In this study, an efficient closed loop vertical underground heat exchanger was simulated [10, 11].

3. Simulation model

3.1. Simulation model environment

Temperature distribution in the soil varies depending on the depth; conversely, the temperature of the soil below a certain depth is virtually constant regardless of the OA temperature. To verify the underground temperature, Florides (2004) [12] proposed Eq. (1) as shown below:

$$T = T_{mean} - T_{amp} \times \exp\left(-Z \times \sqrt{\frac{\pi}{365 \times \alpha}} \right) \times \cos\left(\frac{2\pi}{365} \times \left[t_{year} - t_{shift} - \frac{Z}{2} \right] \times \sqrt{\frac{365}{\pi \times \alpha}} \right) \tag{1}$$

where T is the temperature of the soil and T_{mean} and T_{amp} represent the mean surface temperature (average air temperature) and the amplitude of the surface temperature, respectively. Z is the depth below the surface and alpha is the thermal diffusivity of the ground (soil). t_{year} and t_{shift} represent the current time (day) and day of the year of the minimum surface temperature, respectively.

The surrounding temperature of the underground space can be analyzed in a 0 - 30 m deep basement. Figure 3 shows the temperature distribution. The underground temperature varies from 8 ℃ to 17 ℃ throughout the year at the depth of 30 m. As shown in Fig. 3, the temperature at 30 m varied less than at other depths. Therefore, in this study, the underground space was located in a 30 m-deep basement, so that the building load showed small variation. The underground temperature was applied to the building load calculation in the underground space.

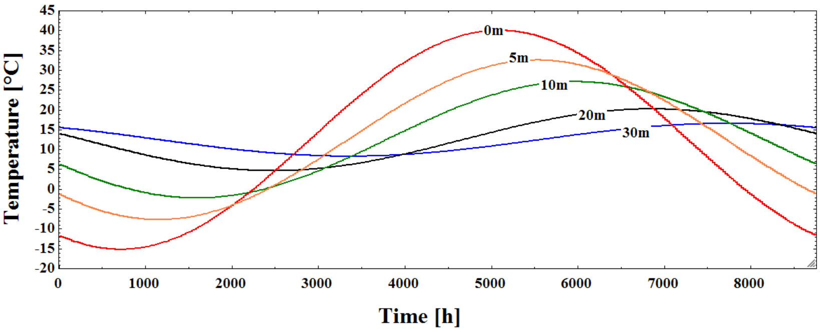


Fig. 3. Annual underground temperature

3.2. Simulation building information

Table 1 shows the simulation building information. The building was located in Seoul, Republic of Korea. Weather data was based on meteorological data provided by TRNSYS 17 [13]. The size of the model building was 1800 m^3(30 m × 20 m × 3 m) with 25 occupants. The model space was designed to maintain 24 °C of DBT and 50% of relative humidity during the summer seasons (i.e. June - August). The occupant schedule of ASHRAE Standard 90.1 (2013) was applied [14]. Internal heat gain by occupants was set at 75W per person for sensible and latent loads. Lighting was set to be a power consumption of 25W per $1m^2$. For simulation, the OA was assumed to pass through the underground OA chamber.

Table 1. Simulation building information

Parameters	Conducted values
Location	Seoul, Republic of Korea
Building size	30 × 20 × 3 m^3
Room condition	24 °C, 50% (During Summer season)
Schedule	AM 6:00 – PM 24:00 (ASHRAE Standard 90.1)
Occupants	People: 25 (Sensible heat: 75 W/person; Latent heat: 75 W/person)
U-value	Exterior wall: 0.4724 W/ m^2K, Roof: 1.712 W/m^2K
Lighting	25 W/m^2

3.3. Thermal load of simulation model building

The load of the underground building with the designed 30 m depth was calculated based on Table1. In this study, the thermal load of the model building in the portion 30 m below the ground surface was estimated and then compared with that of the above ground building. Figure 4 shows the thermal loads of the above ground and underground buildings. One may notice that the sensible load of the underground building was relatively constant compared to that of the above ground building. Such a tendency results from the existence of solar radiation and the surrounding air temperature of each building. Unlike the above ground building, the underground building is not affected by solar radiation. The above ground building is subject to large fluctuations in temperature while the underground building has a relatively constant temperature. Indoor sensible load has the greatest effect depending on the external conditions in the building. Above ground buildings was appeared largely width of the sensible load through the heat exchange between outside and inside of modelled space. However, in the case of underground building spaces, temperature variation appeared to be small compared to the large variation of the above ground building sensible load. Indoor latent load was considered to be equal in the underground and above ground building equally and was not to be considered affected by infiltration. The above ground and underground building indoor latent load showed the same pattern. Due to these various factors, the energy consumption of the HVAC system applied to the underground building is expected to be notably smaller than that of above ground building. The greatest feature of the underground building was that heating is required during the summer season. It is determined that the external temperature of underground building is maintained at a relatively low temperature relative to the above ground building. Also, it is maintained lower than the room temperature (i.e., 24 ℃) to the outside temperature (i.e., 15 ℃) of the underground building. Therefore, the underground building required heating.

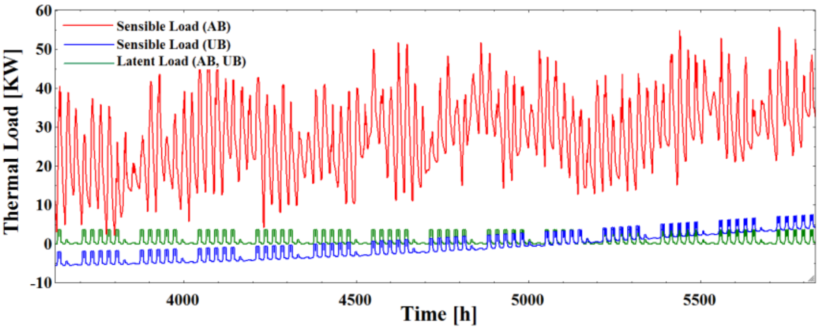


Fig. 4. Above ground and underground building thermal load behavior

4. Simulation overview

4.1. Simulation overview of LD-IDECOAS

The LD-IDECOAS used with 100% outdoor air to condition the space latent and sensible loads. The inlet and outlet air condition of each component was calculated using the equations shown below. For the LD unit, the outlet air temperature of the LD ($DBT_{LD,out}$) is calculated by means of Eq. (2) with three parameters: the DBT of the OA (DBT_{OA}), solution inlet temperature ($T_{sol,inlet}$), and the effectiveness of the LD unit ($\varepsilon_{LD,T}$). Also, the outlet air temperature of the IEC ($DBT_{IEC,pri,out}$) is calculated by means of Eq. (3) with the effectiveness of the IEC (ε_{IEC}). The outlet air temperature of the DEC ($DEC_{DEC,out}$) is calculated by means of Eq. (4) with effectiveness of DEC (ε_{DEC}). The outlet air humidity of the LD ($W_{LD,out}$) is calculated by means of Eq. (5) with the dehumidification effectiveness of the LD (LD_w). The temperature and dehumidification effectiveness of LD were assumed to be equivalent as shown by Katejanekarn et al. (2009) and Katejanekarn and Kumar (2008) [15, 16]. To determine the operation mode of LD-IDECOAS, the dehumidification effectiveness of the LD ($\varepsilon_{LD,w}$) was calculated using the existing model of Chung and Luo (1999) [17]. For the IEC and DEC, the effectiveness was assumed to be 80% and 95%, respectively.

$$\varepsilon_{LD,T} = \frac{(DBT_{OA} - DBT_{LD,out})}{DBT_{OA} - T_{sol,inlet}} \tag{2}$$

$$\varepsilon_{IEC} = \frac{(DBT_{LD,out} - DBT_{IEC,pir,out})}{DBT_{LD,out} - WBT_{IEC,\mathrm{sec},inlet}} \tag{3}$$

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

$$\varepsilon_{LD,w} = \frac{(W_{OA} - W_{LD,out})}{W_{OA} - W_e} \tag{5}$$

Additionally, to maintain a stable dehumidified condition of supply air (SA), an absorber was required to be applied to the free cooling system. In this study, underground water was used as a free cooling source for the LD-IDECOAS because the simulation model building was located in an underground space. For consistent use of the desiccant solution, the regeneration heat source should be supplied to meet the required heating load in the summer season. In this study, the regeneration heat source was assumed to be a gas-boiler and ground source heat pump (GSHP) system. The GSHP system was simulated using TRNSYS 17 [13]. The GSHP system was simulated with a vertical U-tube type underground heat exchanger in TRNSYS 17. Also, the type of heat pump that was used was a Type 919 water source heat pump, the underground heat exchanger is applied to the Type 557 vertical U-tube underground heat exchanger. The type of heat pump was used to calculate the inlet temperature and the flow rate of solution by means of Type 9c. Also, the depth of the underground heat exchanger is assumed to be 400m, with one borehole with a radius of 0.12m. The gas-boiler was applied to the primary energy conversion factors defined in the operating regulations of the building energy efficiency rating certification system (2015) [18]. Therefore, the LD-IDECOAS can be incorporated into the underground building's design as a suitable heating and cooling source (Fig. 5).

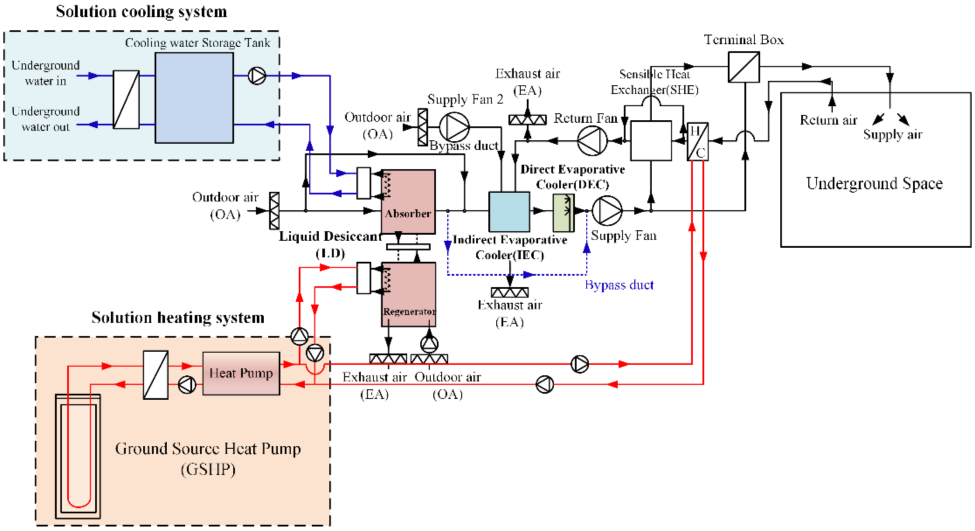


Fig. 5. The schematic of the LD-IDECOAS

5. Simulation results

5.1. Energy consumption of LD-IDECOAS

Figure 6 shows the energy consumption of the LD-IDECOAS during summer (i.e., June - August) seasons. During summer operations, to set supply air conditions the LD-IDECOAS consumed fan, pump, parallel heating, and solution heating energy. The underground building required heating, in contrast to the above ground building. This is because the external temperature of the underground building is maintained a lower temperature than the above ground building. So in the case of the underground building, an auxiliary heating system was needed because it had only a minimum supply of ventilation, unlike the above ground building. Thus the required heating in the underground building was processed by a parallel heating system. The regenerator of the LD was used to treat the indoor latent load. The weak solution, which was diluted from the dehumidification process in the absorber, needs to be regenerated, which requires a heating source for the regeneration. The fan and pump energy consumed 1.3 MWh and 0.56 MWh, respectively. The parallel heating energy and solution heating energy required were 7.8 MWh and 6.9 MWh, respectively. The parallel and solution heating energies consumed most of the energy used by the LD-IDECOAS. The amount of energy consumption depends on which type of heat source is used for heating the solution.

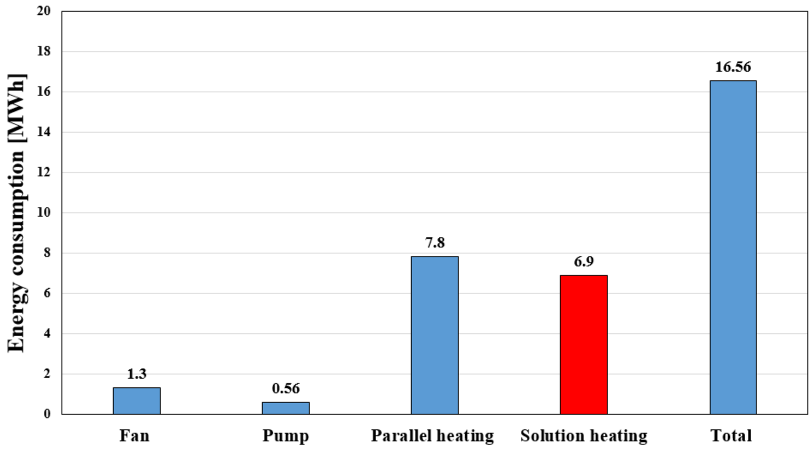


Fig. 6. Energy consumption of LD-IDECOAS in summer

5.2. Primary energy comparison

Figure 7 shows the simulation results on the regeneration heat source of the LD-IDECOAS, a gas-boiler and GSHP system. The primary energy consumption of the system was calculated by applying a primary energy conversion factor. In this study, the primary energy consumption of the gas-boiler and GSHP system was 7.6MWh and 6.1MWh, for solution heating, respectively. Consequently, the regeneration heat source of the GSHP system achieved operating primary energy savings of 20% compared with the conventional gas-boiler. Results showed a reduction in the primary energy consumption of the GSHP system because the applied heat used only a constant temperature geothermal source without being affected by the outside environment. By taking advantage of the benefits of the GSHP system, there is significant primary energy savings when compared to the gas-boiler. These are superior results in terms of energy efficiency, even when compared with other forms of alternative energy.

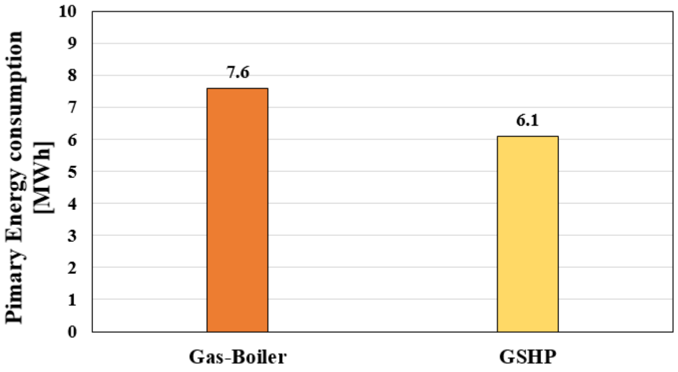


Fig. 7. Comparison of the primary energy consumption

6. Conclusion

In this study, we analyzed the applicability of the LD-IDECOAS for conditioning an underground building during the summer season. We studied using a regenerator heat source of the LD-IDECOAS using a GSHP system, and compared the primary energy consumption to that of a conventional gas-boiler. Underground spaces have a nearly stable condition and consequently, the thermal load and thermal load variation are not significant compared with above ground spaces.

Based on the developed energy simulation, the solution heating energy consumption is higher than the energy consumption of other components of the LD-IDECOAS, it was assumed to applied alternative heat source. In this study, the alternative heat source was applied using a GSHP system. As a result, 20% primary operating energy savings of GSHP system were achieved compared with the conventional gas-boiler in the summer because of the almost constant temperature in underground space.

In this study, we determined that a GSHP system is a suitable regenerator heat source of the LD-IDECOAS and can replace a conventional gas-boiler for an underground building. This can be determined through the demonstrated primary energy savings when a GSHP system is used as the regenerator heat source, rather than a conventional gas-boiler. Further studies are necessary to analyze the primary energy saving potential using geothermal energy as a regenerator heat source instead of the GSHP system.

Acknowledgements

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References

[1] Min-Hwi Kim, An-Seob Choi, and Jae-Weon Jeong., 2012. Energy performance of an evaporative cooler assisted 100% outdoor air system in the heating season operation, Energy and Buildings.Vol. 49, p. 402–409
[2] Min-Hwi Kim, Jen-Seok Park, and Jae-Weon Jeong., 2013. Energy saving potential of liquid desiccant in evaporative-cooling-assisted 100% outdoor air system.Energy, Vol. 59, p. 726–736
[3] Min-Hwi Kim, Joon-Young Park, Min-Ki Sung, An-Seop Choi, and Jae-Weon Jeong., 2014. Annual operating energy savings of liquid desiccant and evaporative-cooling-assisted 100% outdoor air system. Energy and Buildings, Vol. 76, p. 538–550
[4] Kozubal E, Woods J, and Judkoff R., 2012. Development and analysis of desiccant enhanced evaporative air conditioner prototype. National Renewable Energy Laboratory
[5] Sang-Woo Ham, Sung-Joon Lee, and Jae-Weon Jeong., 2016. Operating enegy saving in a liquid desiccant and dew point evaporative cooling-assisted 100% outdoor air system. Energy and Buildings, Vol. 116, p. 535–552
[6] Min-Hwi Kim, Hae-Won Dong, Joon-Young Park, and Jae-Weon Jeong., 2016. Primary energy saving in desiccant and evaporative cooling-assisted 100% outdoor air system combined with a fuel cell. Energy, Vol. 180, p. 446–456
[7] Su-Young Jo, Joon-Young Park, and Jae-Weon Jeong., 2014. "Applicablity of a fuel cell for primary energy saving in a liquid desiccant and evaporative cooling assisted 100% outdoor air system", *International building performance simulation association ASIM conference.* Japan: Nagoya, p. 870–877
[8] Joon-Young Park, Sung-Joon Lee, Dong-Seob Yoon, and Jae-Weon Jeong., 2016. Energy performance of a liquid desiccant and evaporative cooling-assisted 100% outdoor air system in commercial ships", *ASHRAE Annual Conference*. USA: St.Louis
[9] ASHRAE. 2016. ASHRAE Standard 62.1: Ventilation For Acceptable Indoor Air Quality. Atlanta: American Society of Heating, Refrigerating and Air-Conditioning Engineers, Inc.
[10] Sanner B, Karytsas C, Mendrinos D, and Rybach L., 2003. Current status of ground source heat pumps and underground thermal energy storage in Europe. Geothermics, Vol. 32, p. 579–588
[11] Chiasson A, Spitler J, Rees S, and Smith M., 2000. A model for simulating the performance of a pavement heating system as a supplemental heat rejector with closed-loop ground-source heat pump systems. Solar Energy Engineering, Vol. 122, p. 183–191
[12] Florides G, and Kalogirou S., 2004. "Measurement of ground temperature at various depths", *Proceedings of the SET 2004, 3rd International conference on sustainable energy technologies on CD-ROM*. UK: Nottingham
[13] Klein SA, Beckman WA, Mitchell JW, and Duffie JA. TRNSYS 17 transient system simulation program, user manual. Solar Energy Laboratory; 2010.
[14] ASHRAE. 2013. ASHRAE Standard 90.1: Energy Standard for Buildings Except Low-Rise Residential Buildings. Atlanta: American Society of Heating, Refrigerating and Air-Conditioning Engineers, Inc.
[15] Katejanekarn T. and Kumar S. 2008. Performance of a solar-regenerated liquid desiccant ventilation pre-conditioning system. Energy and Buildings, Vol. 40, p. 1252–1267
[16] Katejanekarn T, Chirarattananon S, and Kumar S. 2009. An experimental study of a solar-regenerated liquid desiccant ventilation pre-conditioning system. Solar Energy, Vol. 83, p.920–933
[17] Chung TW and Luo CM. 1999. Vapor pressure of the aqueous desiccant. Journal of Chemical and Engineering Data, Vol. 44, p. 1024–1027
[18] Duk-Joon Park, Ki-Hyung Yu, Yong-Sang Yoon, Kee-Han Kim and Sun-Sook Kim. 2015. Analysis of a building energy efficiency certification system in korea. Sustainability, p. 16086–16107