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

E.J. Choi, H.J. Kim and J.W. Jeong*

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

ABSTRACT
The applicability of a liquid desiccant and evaporative cooling-assisted 100% out door air system (LD-IDECOAS) in underground spaces was evaluated. Detailed energy simulation was performed to estimate the energy saving potential of the LD-IDECOAS. Two different types of heating, ventilating and air conditioning (HVAC) systems, the variable air volume (VAV) system and LD-IDECOAS, were applied in a modeled underground space to compare annual energy consumption. The thermal load of the underground spaces showed a different pattern compared with normal space. Maximum cooling and heating loads were relatively small in the underground spaces because of the stable condition of the surrounding environment compared with the above ground building. Based on the results, the size of the HVAC system in underground spaces could be smaller than in aboveground spaces. The LD-IDECOAS reduced 38% more primary energy consumption than the VAV system when applied with district heating system by managing regeneration energy.

KEYWORDS
Underground spaces, liquid desiccant and evaporative cooling-assisted 100% out door air system (LD-IDECOAS), district heating system

INTRODUCTION
Recent studies have been conducted regarding the application of heating, ventilating and air conditioning (HVAC) systems in underground spaces. The ventilation is very important because infiltration is negligible underground. Regarding conventional variable air volume (VAV) systems, the use of return air (RA) is a weak point in terms of indoor air quality (IAQ) and cross-contamination with lack of ventilation. To overcome this problem, a new type of HVAC system should be investigated to enhance the energy saving potentials and IAQ. According to a report from the Department of Energy (DOE), liquid desiccant (LD) and evaporative cooling technologies are alternatives to the conventional vapor compression system.
Previous studies have proposed the combination of LD and evaporative cooling systems, such as an LD and indirect/direct evaporative cooling-assisted 100% outdoor air system (LD-IDECOAS; Kim et al. 2012, 2013, 2014), a desiccant-enhanced evaporative air

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

conditioner (DEVap; Kozubal et al. 2012), and an LD and dew point evaporative cooling-assisted 100% outdoor air system (LDEOS; Ham et al. 2016). These are decoupled systems that treat latent and sensible loads separately. Moreover, they have a potential to save energy compared with conventional VAV systems. Specifically, the LD-IDECOAS showed an annual energy saving of 68% compared with the conventional VAV system in above-ground space application.
Accordingly, in this study, the application of the LD-IDECOAS in underground spaces was evaluated and the energy performance of the LD-IDECOAS was analyzed.

SYSTEM OVERVIEW

LD-IDECOAS

LD-IDECOAS consists of the LD system, indirect evaporative cooler (IEC) and direct evaporative cooler (DEC) (Figure 1). The LD system uses an LD solution to control the latent load of the OA. For consistent use of the LD solution, heat sources are required to regenerate weak solution. After the process air exits from 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 components.
While the conventional VAV system supplies mixing air (MA), which is the mixture of OA and RA, the LD-IDECOAS uses 100% OA. Fundamentally, the LD-IDECOAS prevents cross-contamination, which occurs during the process of mixing. Moreover, this system introduces more OA than the minimum ventilation rate to supply a supplemental amount of fresh air and improve indoor air quality.

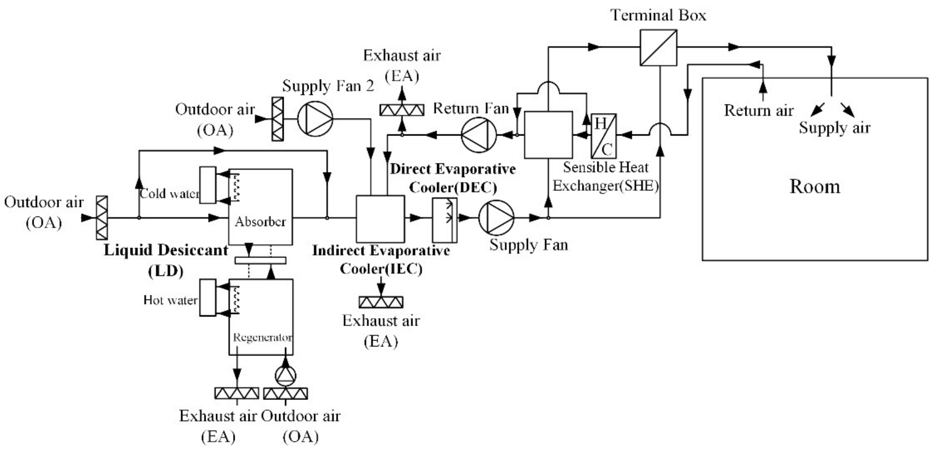


***Figure 1.** Schematic diagram of the LD-IDECOAS*

The LD-IDECOAS operation mode

According to previous research (Kim et al. 2012, 2013, 2014), the operation mode of the LD-IDECOAS is determined by OA conditions. The operation mode of the LD-IDECOAS can be classified into three modes; summer season, intermediate season and winter season.

During hot and humid summer season, 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 ℃). During the intermediate season, the LD system is deactivated because 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. During the winter season, the LD unit and the DEC are not required because the dry bulb temperature (DBT) of OA is lower than the SA target temperature (i.e., 15 ℃). The IEC operates 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 ℃), the additional SHE should be operated to meet the SA condition.

SIMULATION MODEL

Simulation model environment

Temperature distribution in the soil varies depending on the depth. To verify underground temperature, Florides (2004) proposed Equation 1. Underground temperature is calculated by Equation 1, as shown below:

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

where, T is the temperature of 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 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.

Figure 2 shows the temperature distribution of the soil 0 - 30m below the ground surface. Underground temperature varies from 8 ℃ to 17 ℃ throughout the year at the depth of 30 m. As shown in Figure 2, the temperature at depth 30 m varied less than at other depths. Therefore, in this study, the underground space was located in a 30 m-deep.

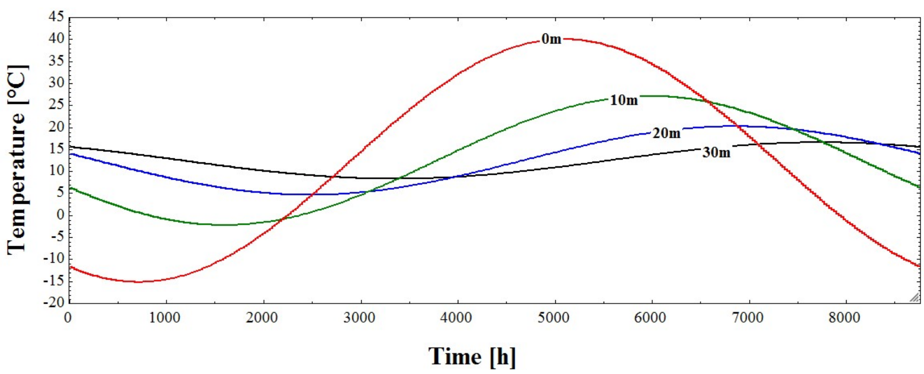


Figure 2. *Annual underground temperature*

Simulation building information

Table 2 shows the simulation building information. The building was located in Seoul, Korea. The typical meteorological year 2 (TMY 2) weather data was used. The size of the model building was 120 m^3(8 m × 5 m × 3 m) with 3 occupants. The model space was designed to maintain 24 ℃ of DBT and 60% of relative humidity during the summer, and 20 ℃ of DBT and 60% of relative humidity during other seasons. The occupant schedule of ASHRAE Standard 90.1 (2013) was applied. Internal heat gain by occupants was set at 75 W per person for sensible and latent loads. For simulation, OA was assumed to pass through the underground OA chamber.

Table 1. *Simulation building information*

Location	Seoul, Republic of Korea	
Building	8 × 5 × 3 m^3	
Schedule	AM 6:00 ~ PM 24:00	
Heat gain	Occupants	3 people
	Lights	25 W/m^2
U-value	Exterior wall	0.4724 W/m^2K
	Roof	1.712 W/m^2K

Space thermal loads of the underground building

In this study, thermal load of the model building located in the 30 m below the ground surface was estimated and then compared with that of the above ground building. Figure 3 shows the thermal loads of 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 tendency was resulted from the existence of solar radiation and the surrounding temperature of each building. Unlike the above ground building, the underground building was not affected by solar radiation. Moreover, the underground temperature which varied from 8 ℃ to 17 ℃ was responsible for the relatively constant sensible load of the underground space.

The greatest feature of the underground building was heating required during summer season. Indoor latent load was considered to occur underground and above ground equally and was not considered affected by infiltration.

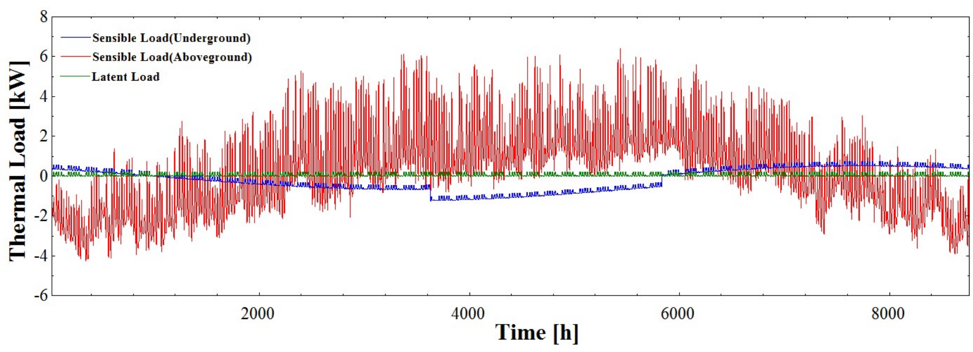


Figure 3. *Above ground and underground building thermal load behavior*

SIMULATION OVERVIEW

Simulation overview of the VAV system

The minimum ventilation rate was calculated using ASHRAE Standard 62.1 (2016). The SA condition was set at 15 ℃ of DBT and 80% of relative humidity for space cooling, and 20 ℃ of DBT and 60% of relative humidity for space heating. Particularly during winter season, a parallel heating system was activated to provide additional heating. The chiller model was based on the DOE-2 chiller model (Hydeman et al. 2002). The district heating system was heat source of the heating coil and parallel heating system.

Simulation overview of the LD-IDECOAS

The LD-IDECOAS was supplied with 100% outdoor air to condition the space latent and sensible loads. The SA condition of the LD-IDECOAS was equal to that of the VAV system. Operation of each component was determined according to the operation mode. The inlet and outlet air condition of each component was calculated using the equations shown below.

For the LD unit, the outlet temperature of LD ($DBT_{LD,out}$) is calculated by using Equation 2 with three parameters: DBT of the OA (DBT_{OA}), solution inlet temperature ($T_{sol,in}$), and effectiveness of LD unit ($\varepsilon_{LD,T}$). The temperature and dehumidification effectiveness of LD were assumed to be equivalent as shown by Katejanekarn et al. (2009) and Katejanekarn and Kumar (2008). The dehumidification effectiveness of LD ($\varepsilon_{LD,w}$) was calculated using the existing model of Chung and Luo (1999). Then, the outlet temperature and humidity ratio of the LD unit was calculated with Equation 2 and 3, respectively.

For IEC and DEC, the effectiveness were assumed to be 80% and 95%, respectively. The outlet temperature of the IEC unit ($DBT_{IEC,pri,out}$) is obtained by Equation 4. After that, the outlet temperature of DEC is determined using Equation 5.

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

$$\varepsilon_{LD,w} = \frac{(W_{OA} - W_{LD,out})}{W_{OA} - W_{e}} \quad (3)$$

$$\varepsilon_{IEC} = \frac{(DBT_{LD,out} - DBT_{IEC,pri,out})}{DBT_{LD,out} - WBT_{IEC,sec,in}} \quad (4)$$

$$\varepsilon_{DEC} = \frac{(DBT_{IEC,pri,out} - DBT_{DEC,out})}{DBT_{IEC,pri,out} - WBT_{IEC,pri,out}} \quad (5)$$

During the summer operation mode, the district heating system is used to heat the solution to the effective regeneration temperature.

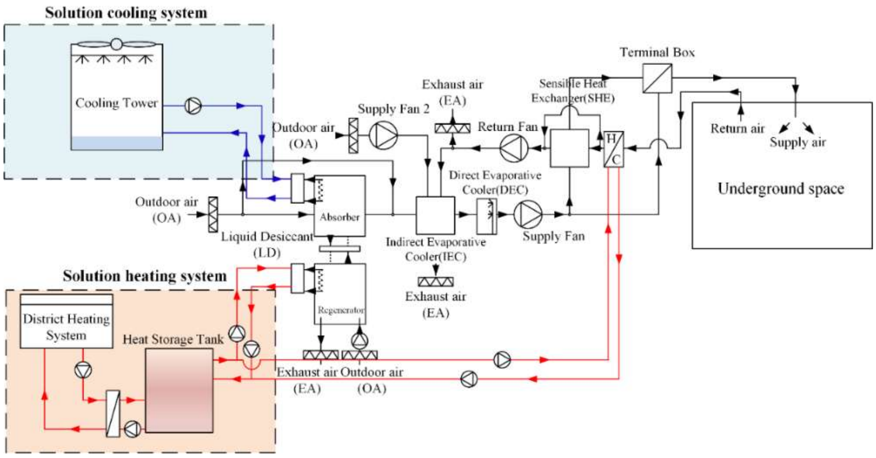


Figure 4. *The schematic of the LD-IDECOAS*

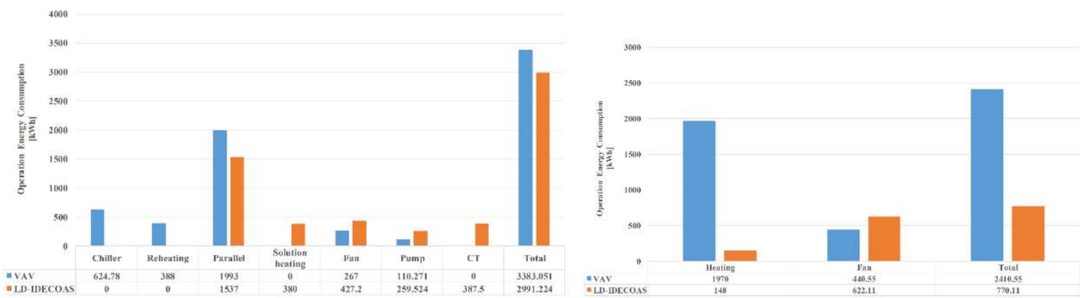
SIMULATION RESULTS

Primary energy consumption during summer and winter

Figure 6 shows the comparison of primary energy consumption during summer (June, July and August) and winter season (January, November and December) operations.

During the summer operation, LD-IDECOAS did not use a chiller or reheating energy to meet the SA condition. However, the conventional VAV system required a chiller, reheating coil and parallel heating system resulting in additional energy consumption. As the LD treats the latent load, the regenerator required district heat energy for solution heating. Additionally, the fan and pump energy required for the LD-IDECOAS was higher than for the conventional VAV system due to the increased pressure drop across the IEC and DEC. Consequently, as shown in Figure 6 (a), the LD-IDECOAS achieved an operating primary energy saving of 11.6% compared with the conventional VAV system.

During the winter operation, the LD-IDECOAS and the conventional VAV system consumed heating energy to meet the required thermal load of underground spaces while ensuring the required minimum ventilation. Likewise, during the summer season, the LD-IDECOAS consumed more fan energy because of the increased pressure drop across the IEC and sensible heat exchanger (SHE). As a result, the LD-IDECOAS showed a reduction of up to 68% in primary energy consumption compared with the conventional VAV system (Figure 6 (b)).

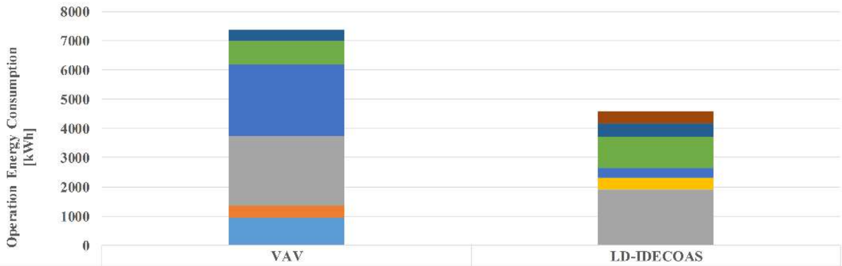


(a) Summer *(b) Winter*

Figure 5. *Operating primary energy consumption*

Annual primary energy consumption

The LD-IDECOAS did not require a chiller and reheating energy to meet the target SA conditions compared with the conventional VAV system. However, the conventional VAV system consumed more primary energy due to the chiller and reheating energy during the summer season and heating energy during the winter season compared with the LD-IDECOAS. The fan and pump energy represent more operation primary energy consumption due to a high pressure drop compared with the conventional VAV system. As a result, the LD-IDECOAS showed an annual total primary energy saving of 38% when compared with the conventional VAV system.



	VAV	LD-IDECOAS
Total	7374.74	4579.55
CT	0	421
Pump	384.48	440.55
Fan	801	1068
Heating	2456	340
Solution heating	0	410
Parallel	2375	1900
Reheating	429.1	0
Chiller	929.16	0

Figure 6. *Annual operating primary energy consumption*

CONCLUSTION

In this study, we analyzed the applicability of the LD-IDECOAS for underground spaces and compared the primary energy consumption to a conventional VAV system used in underground spaces. Underground spaces have a nearly stable condition and consequently, the thermal load and thermal load variation are not significant compared with the above ground space.

Based on the developed energy simulation, LD-IDECOAS operation showed 11.6% and 68% primary energy savings during summer and winter, respectively, and a 38% annual operating primary energy savings compared with the conventional VAV system. In this study, we determined that LD-IDECOAS is a suitable alternative HVAC system that can replace the conventional VAV system for underground spaces. The LD-IDECOAS can achieve primary energy savings. Further studies are necessary to analyze the potential energy savings as a heat source required to regenerate the ground source heat pump instead of a district heating system.

ACKNOWLEDGEMENTS

This work was supported by a National Research Foundation (NRF) grant (No. 2015R1A2A1A05001726) and by the Korea Institute of Energy Technology Evaluation and Planning (KETEP) and the Ministry of Trade, Industry & Energy (MOTIE) of the Republic of Korea (No. 20164010200860).

REFERENCES

American Society of Heating, Refrigerating and Air-Conditioning Engineers, Inc. 2016. ASHRAE STANDARD Ventilation for Acceptable Indoor Air Quality. ASHRAE Standard 62.1

American Society of Heating, Refrigerating and Air-Conditioning Engineers, Inc. 2013. ASHRAE STANDARDE Energy Standard for Buildings Except Low-Rise Residential Buildings. ASHRAE Standard 90.1

Chung T. and Luo C. 1999. Vapor pressures of the aqueous desiccants, Journal of Chemical Engineering Data. 44 : 1024–1027.

Hydeman M, Webb N, Sreedharan P, and Blanc S. 2002. Development and testing of a reformulated regression-based electric chiller model, ASHRAE Transactions. 108 PART 2 : 1118–1127.

Ham S.W, Lee S.J, and Jeong J.W. 2016. Operating energy savings in a liquid desiccant and dew point evaporative cooling-assisted 100% outdoor air system, Energy and Buildings. 116 : 535-552.

Katejanekarn T. and Kumar S. 2008. Performance of a solar-regenerated liquid desiccant ventilation pre-conditioning system, Energy and Buildings. 40 : 1252–1267.

Katejanekarn T, Chirarattananon S, and Kumar S. 2009. An experimental study of a solar-regenerated liquid desiccant ventilation pre-conditioning system, Solar Energy. 83 : 920–933.

Kozubal E, Woods J, and Judkoff R. 2012. Development and analysis of desiccant enhanced evaporative air conditioner prototype, National Renewable Energy Laboratory

Kim M.H, Choi A.S, and Jeong J.W. 2012. Energy performance of an evaporative cooler assisted 100 % outdoor air system in the heating season operation, Energy and Buildings. 49 : 402–409.

Kim M.H, Park J.S, and Jeong J.W. 2013. Energy saving potential of liquid desiccant in evaporative-cooling-assisted 100% outdoor air system, Energy and Buildings. 59 : 726–736.

Kim M.H, Park J.Y, Sung M.K, Choi A.S, and Jeong J.W. 2014. Annual operating energy savings of liquid desiccant and evaporative-cooling-assisted 100% outdoor air system, Energy and Buildings. 76 : 538–550.

Florides G. and Kalogirou S., 2004. Measurements of ground temperature at various depths, Poceedings of the SET 2004, 3rd International conference on sustainable energy technologies on CD-ROM