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Energy Performance of a Liquid Desiccant and Evaporative Cooling-Assisted 100% Outdoor Air System with Cascade Liquid Desiccant System Operation

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Abstract

The aim of this study is to propose a new type of liquid desiccant and evaporative assisted 100% outdoor air system (LD-IDECOAS) which utilizes a retrofitted additional liquid desiccant unit. The process air is dehumidified by the cascade liquid desiccant (CLD) for deep dehumidification. To evaluate its applicability, three different systems were analyzed: a conventional LD-IDECOAS, a CLD with direct evaporative cooler (CLD-DEC) and a retrofitted system (CLD-IDECOAS). Based on the LD-IDECOAS, the proposed system was utilized to air-condition an office building. An energy simulation was conducted under the outdoor air conditions of Seoul, Korea. The thermal load of the modeling space and the energy consumption of the proposed systems were evaluated via a commercial equation solver program (EES). The result shows that the CLD-IDECOAS yields the lowest SA temperature and humidity conditions. The cascade LD unit has the additional merit of generating deep dehumidification under the summer peak load design condition.

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Keywords: Liquid desiccant system; Evaporative cooling system; LD-IDECOAS; Cascade liquid desiccant (CLD); CLD-IDECOAS.

1. Introduction

A Liquid desiccant (LD) based air conditioning systems have recently raised attention as an alternative to conventional vapor-compression (CFC, HCFC) heating, ventilating, and air conditioning (HVAC) systems. According to the increment of interest in non-vapor compression HVAC technologies, many research have focused on non-vapor compression technology to propose a new type of HVAC system [1]. A liquid desiccant and indirect/direct evaporative cooling-assisted 100% outdoor air system (LD-IDECOAS) has been proposed for use as an HVAC system in building spaces [2, 3]. The LD-IDECOAS is a non-vapor compression system, a type of LD-based air-conditioning system used to adjust the conditions of the supply air (SA) (i.e., 15 °C) using 100% outdoor air (OA) without mixing exhaust air (EA). The LD-IDECOAS can supply 100% OA to process SA, and sufficient ventilation of OA improves the indoor air quality. While processing the OA, the LD-IDECOAS operates like a decoupled system, which means that the latent heat load of the OA is removed by the LD unit. The sensible cooling load of the OA is then adjusted via the indirect evaporative cooler (IEC) and direct evaporative cooler

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(DEC). Kozubal et al. [4] suggested a desiccant-enhanced evaporative air conditioner (DEVAP), which is similar to the LD-IDECOAS. The DEVAP system operates with an LD unit and high-performance IEC unit to meet the target SA condition (i.e., 15 °C) using mixed air (OA + room air [RA]). These systems use an LD unit to remove the moisture from OA and an evaporative cooler to treat the sensible cooling load of the process air. Due to these operation characteristics, the LD unit and evaporative cooler should be operated as major components in both systems.

In hot and humid climates, the OA is dehumidified via the LD unit; the IEC and DEC adjust the target SA conditions after the dehumidification process. The LD unit is used to enhance the cooling effect of the evaporative cooling equipment. In previous research on the LD-IDEOCAS, the pilot LD-IDECOAS has demonstrated the limitations of the LD unit [5]. When water-side free cooling was conducted to cool the desiccant solution, the dehumidification performance of the LD unit was not sufficient to remove the latent cooling load of the OA. Due to the low performance of the LD unit, the evaporative cooler showed limited ability to meet the SA conditions. Retrofit research has been conducted to overcome the limitations of the pilot system and improve energy savings [6]; however, when water-side free cooling is used as the cooling source for a desiccant solution, the issue of low dehumidification should be solved to reach target SA conditions.

Several studies have focused on improving the dehumidification performance of LD units using a multi-stage dehumidifier tower [7]. Under hot and humid OA conditions, a single LD unit does not suitably remove moisture from the OA; therefore, a multi-stage LD unit has been proposed to obtain sufficient dehumidification performance under the peak load conditions in summer. Liu et al. [8] suggest a liquid desiccant based outdoor air processor using a multi-stage dehumidifier to control the humidity of the SA. The annual electric and thermal performance was analyzed via the coefficient of performance (COP). Because the multi-stage LD unit can remove the entire latent heat load from the OA, the parallel indoor unit does not need to remove the latent load, allowing the use of relatively high temperature water (e.g., 15 – 18 °C) that can be used to control the required thermal load. Xie et al. [9] analyzed the outdoor air unit with liquid desiccant as a total heat recovery system. This study was conducted using a multi-stage desiccant unit to adjust the target SA humidity level under the OA humidity condition. To meet the target SA humidity level, this study proposes a SA humidity control strategy via LD units. Li et al. [10] proposed a new type of OA processor with a double-stage LD unit and comparatively analyze multi-stage LD according to the number of units. The multi-stage LD unit showed the high dehumidification performance compared to single unit. Xiong et al. [11, 12] suggested a two-stage LD unit using various types of desiccant solution. Lithium bromide (LiBr) solution was used in the first LD unit, and calcium chloride ($CaCl_2$) solution was used in the second unit to assist the dehumidification process [11]. Upon further research, a lithium chloride (LiCl) solution replaced the LiBr solution to enhance the energy consumption of the double-stage LD unit [12].

As in previous studies, the multi-stage LD unit used in this study is expected to improve the dehumidification performance. Based on previous studies of LD-IDECOAS [2, 3], this research proposes a new type of liquid desiccant and evaporation-assisted 100% outdoor air system (LD-IDECOAS) with the enhanced dehumidification performance of a liquid desiccant unit (CLD-IDECOAS). The proposed system is coupled with a cascade liquid desiccant (CLD), and direct and indirect evaporative coolers. The process air is dehumidified with CLD to improve the effectiveness of the evaporative coolers. To evaluate its applicability, three systems were analyzed: a conventional LD-IDECOAS (Base case), a CLD with direct evaporative cooler; CLD-DEC (Case 1), and retrofitted system; CLD-IDECOAS (Case 2). To analyze the energy performance of each system configuration during the cooling season, the simulation was conducted using design peak OA data from ASHRAE fundamentals in Seoul, Korea [13]. The thermal load of a model office space and the energy consumption of the proposed system are predicted via a commercial equation solver [14]

2. System overview

2.1. Base case: LD-IDECOAS

The base case of the LD-IDECOAS uses 100% OA as the SA for the conditioned space and can be divided into two main parts (Fig. 1). An LD unit is installed upstream of the process air for dehumidification of the OA, and an IEC and DEC are installed for sensible cooling of the process air to meet the SA condition (i.e., 15 °C). Induced OA is dehumidified through the liquid desiccant system, and then sensible cooling is carried out via continuous passage through the IEC and DEC. When the wet-bulb temperature (WBT) of the exhaust air (EA) is lower than that of the OA, EA should be supplied into the secondary channel of the IEC to improve the sensible cooling effect of the IEC. The sensible heat exchanger (SHE) and heating coil (HC) are located in the EA duct to maintain the EA condition for using the secondary air of the IEC. The SA flow rate is adjusted based on the required cooling load of the room as in a conventional variable air volume (VAV) system.

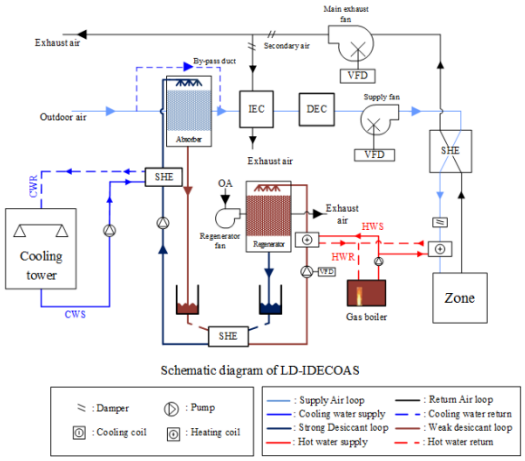


Fig. 1. Schematic diagram of LD-IDECOAS (i.e., Base case)

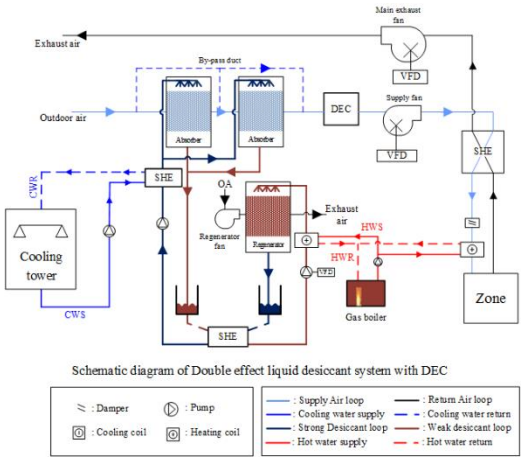


Fig. 2. Schematic diagram of CLD-DEC (i.e., Case 1.)

During the cooling season, the OA condition is hot and humid. To meet the SA target temperature, the LD-IDECOAS should be operated at full capacity. As shown in Figure 1, the LD system initially removes moisture from the OA until reaching a specified level of humidity in the process air. Following the dehumidification process, the process air is adjusted to the SA set point temperature (i.e., 15 °C) via passage through the IEC and DEC. The sensible cooling effect occurs when the process air enters the IEC; the adiabatic cooling effect is then carried out via the DEC. Before the SA supplies the room, the target SA temperature should achieve 15 °C and be saturated.

2.2. Case 1: CLD-DEC

The dehumidification performance of the LD unit is limited when water-side free cooling is conducted to supply a cooling source for the desiccant solution in hot and humid OA conditions. To increase dehumidification, a multi-case absorber tower cascade LD unit is considered (Fig. 2). In case 1, the single LD unit used in the base case has been replaced with the cascade LD, and the DEC performs the adiabatic cooling of the process air without the IEC unit. According to the OA temperature and humidity ratio conditions, if the induced OA is sufficiently dehumidified in the primary absorber tower, the outlet air of the primary absorber tower can bypass the secondary absorber tower.

2.3. Case 2: CLD-IDECOAS

In case 2, the cascade LD unit is applied in the base case of the LD-IDECOAS configuration. Based on the CLD-DEC configuration, the IEC unit is added to induce sensible cooling of the process air between the cascade LD and DEC units (Fig. 3). Case 2 focuses on the retrofitted process of the LD-IDECOAS. The cascade LD unit can achieve deep dehumidification to enhance the sensible cooling effect of the IEC. As in case 1, the cascade LD

unit should dehumidify to a specified level of induced OA humidity. Following the deep dehumidification process, the IEC and DEC operate to meet the target SA conditions. Under hot and humid OA conditions, the base case, LD-IDECOAS, cannot dehumidify the OA to meet the target SA conditions, because the water-side free cooling source is not sufficient to cool the desiccant solution to produce a suitable dehumidification effect in the single absorber tower [5]. In this case, the cascade absorber tower can generate sufficient moisture removal from the OA when the free-cooling system is conducted to cool the desiccant solution.

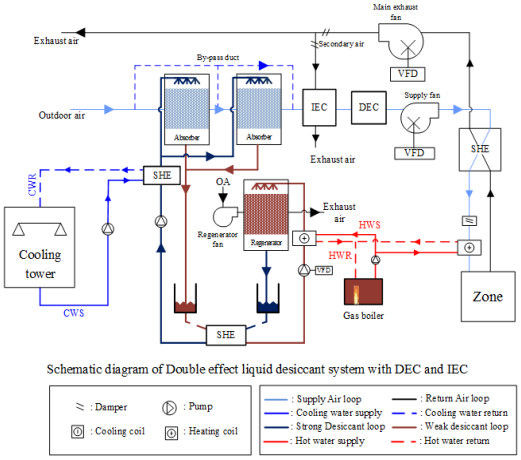


Fig. 3. Schematic diagram of CLD-IDECOAS (i.e., Case 2.)

3. Simulation overview

In order to analyze the cooling performance of various types of retrofitted LD-IDECOAS, the energy consumption of each system type is compared. The cooling operation energy consumption of multi-case retrofitted systems are estimated via design condition energy simulation based on the required cooling load of a model space in Seoul, Korea. The required cooling load is calculated on the basis of the design conditions from ASHRAE fundamentals [13].

3.1. Thermal load calculation

The required thermal load of the modeling space is estimated based on ASHRAE design conditions during summer in Seoul, Korea. The modeled space consists of two office buildings, each with a floor area of 42 m^2 and 5 occupants. The space conditions were designed to maintain a dry-bulb temperature (DBT) of 24 °C and 50% relative humidity during the cooling season. The internal gain from the occupants was calculated at 75 W of sensible heat and 75 W of latent heat emission from each person. The fluorescent lighting equipment is considered a luminaire with 25 W/m^2 of sensible heat emission.

Table 1. Thermal load parameters

Load parameters	Conducted values
Floor area	84 m^2 (e.g., each space: 40 m^2)
Room air conditions	24°C, 50%
U-value	Exterior wall: 0.52 W/m^2K, Ceiling: 0.84 W/m^2K
Window to wall ratio	30%
Occupants	People: 5 (Sensible heat: 75 W/person; Latent heat: 75 W/person)
Luminaire	Lighting: 25 W/m^2 (i.e., fluorescent lighting)

According to the ASHRAE fundamentals, the OA design conditions of Seoul were applied with a 0.4% annual cumulative frequency of occurrence of the wet-bulb condition (e.g., 29.8 °C, 73%) to estimate the design cooling load [13]. In addition, infiltration and leakage within the modeled space are not considered in the thermal load calculation. Table 1 summarizes the physical information of the thermal load parameters.

3.2. System models

An energy simulation was conducted in order to estimate the energy consumption of the retrofitted LD-IDECOAS during the cooling season. The condition of the process air was determined according to the outlet condition of the LD unit, IEC, and DEC. The DBT of the outlet condition at each system component (i.e., LD unit, IEC, and DEC) are estimated based on the system efficiency for setting the target SA DBT condition. The outlet DBT of the LD unit (T_{LD}) is determined by means of Eq. (1), while the OA temperature (T_{oa}), solution inlet temperature (T_{si}), and temperature efficiency are known ($\varepsilon_{LD.T}$). In addition, the DBT condition at the outlet of the IEC (T_{IEC}) can be calculated by means of Eq. (2) if the efficiency of the IEC (ε_{IEC}) is known. In this study, the IEC efficiency is assumed to be 70% and the inlet WBT condition of the secondary air ($WBT_{sec,IEC}$) is the same as with the EA WBT condition. Similarly, the DBT condition of the DEC outlet (T_{DEC}) is a target DBT condition of SA (T_{sa}), and is estimated by means of Eq. (3) when the efficiency of the DEC (ε_{DEC}) is given. In this study, a 95% DEC efficiency value was used. The humidity ratio of the outlet condition at the LD unit (ω_{LD}) is determined by means of Eq. (4) while assuming the dehumidification efficiency of LD unit (ε_{deh}). According to existing literature, the temperature efficiency of the LD unit ($\varepsilon_{LD.T}$) is similar to the dehumidification efficiency of the LD unit (ε_{deh}) [15, 16].

$$\varepsilon_\text{LD.T} = \frac{(\text{T_oa} - \text{T_LD})}{(\text{T_oa} - \text{T_si})} \tag{1}$$

$$\varepsilon_\text{IEC} = \frac{(\text{T_LD} - \text{T_IEC})}{(\text{T_LD} - \text{WBT_sec.IEC})} \tag{2}$$

$$\varepsilon_\text{DEC} = \frac{(\text{T_IEC} - \text{T_DEC})}{(\text{T_IEC} - \text{WBT_IEC})} \tag{3}$$

$$\varepsilon_\text{deh} = \frac{(\omega\text{_oa} - \omega\text{_LD})}{(\omega\text{_oa} - \omega\text{_equ})} \tag{4}$$

When the OA condition is hot and humid, the base case of the LD-IDECOAS should be operated at full capacity. In order to meet the SA condition (i.e., 15 °C), induced OA is dehumidified by the LD unit to reduce moisture content. The process air then continuously enters the IEC and DEC for sensible cooling and control of adiabatic cooling, respectively.

In the present work, the dehumidification and regeneration effectiveness of the LD unit are evaluated using existing models from the literature [17, 18]. These are empirical models of LD units using lithium chloride (LiCl) solution as the desiccant material. The empirical model of dehumidification effectiveness is proposed by Chung and Luo [17]. The regeneration effectiveness model of the LD unit is suggested by Martin and Goswami [18]. To consider the thermodynamic property of the LiCl solution, the F-chart software manual [14] and the previous chemical research by Conde et al. [19] were selected.

The initial operating conditions of the LD unit were controlled to evaluate the dehumidification performance of the LD system when the liquid-to-gas ratio remains constant at 1. The LD unit operates with a LiCl solution as a desiccant material, which conducts 30 °C of the solution inlet temperature and 40% of the solution inlet concentration. The required regeneration heat energy of the diluted desiccant solution is assumed depending on the rate of moisture removal from the OA. The diluted desiccant solution should be heated to 60 °C of the regeneration temperature before the entering the regenerator.

In the operation of the cascade LD, the operating condition was adjusted as mentioned in the initial conditions. The operating condition at the primary absorber tower is the same as that of the single absorber tower LD unit; however, when the process air enters into the secondary absorber tower, the process air conditions was changed by primary absorber tower operation. The regeneration energy is assumed via the total energy requirement of the solution regeneration occurring in the primary and secondary absorber towers.

3.3. Cascade liquid desiccant operating mode

In terms of the cascade LD unit performance, the induced OA should be dehumidified to a suitable humidity ratio while passing through the cascade LD unit. In this research, the suitable humidity ratio is defined as a target humidity condition of process air from the cascade LD unit. The target humidity condition is a target zone for the humidity ratio between an upper limit and lower limit. The upper limit is the humidity condition of room air (e.g.,

24 °C, 50%), and the lower limit is the typical SA humidity condition (e.g., 13 °C, 80%). Figure 4 shows a psychrometric chart of the target humidity condition of the cascade LD unit in summer OA conditions.

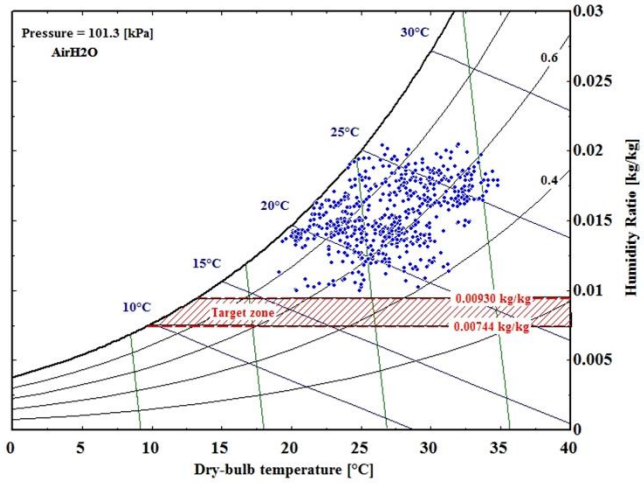


Fig. 4. OA conditions in summer of Seoul, Korea (July-August)

To meet the target humidity condition of the process air, the operating control strategy of the cascade LD unit is as follows. When the humidity condition of the OA is between the upper and lower limit, the induced OA can bypass the cascade LD unit; however, if the OA humidity condition is higher than the upper limit, it should be dehumidified at the primary absorber tower. Under this condition, the humidity of the outlet air from the primary absorber tower is applicable to the target humidity condition of the process air, which does not require a dehumidification process to meet the SA conditions. If the humidity of the process air from the primary tower is higher than the upper limit, it should enter the secondary absorber tower for additional dehumidification. Following the dehumidification process via the control strategy, the dehumidified process air is sensibly cooled using the IEC and DEC. Figure 5 shows a flow chart of the control strategy of the cascade LD unit.

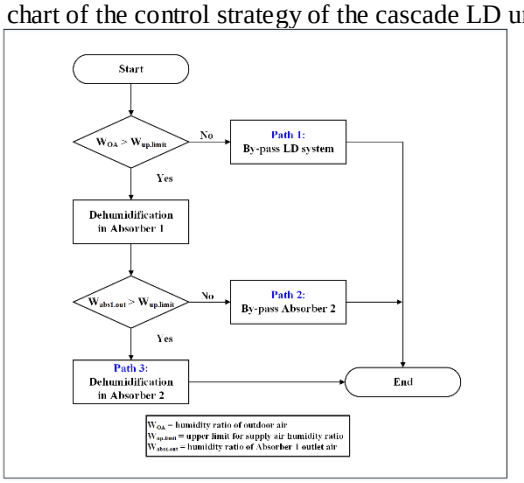


Fig. 5. Flow chart for the cascade LD unit operation modes.

3.4. Fan and pump models

To estimate the energy consumption of the fans and pumps, data was used from the fan and pumps used in a previous study on the pilot system of LD-IDECOAS [20]. The fan and pumps used in the retrofitted cases have a variable flow and the efficiencies of the fan and pumps are assumed to be 60%. The static pressure drop of each system component was applied under a design fan flow of 1000 m^3/h. Table 2 presents the static pressure drops of the system components.

Table 2. Static pressure drops of system components [20]

Component	Pressure drop at design fan flow (i.e., 1000m^3/h)
Liquid desiccant packing	120 Pa
IEC primary channel	234 Pa
IEC secondary channel	377 Pa
DEC Pad	10 Pa

Based on Table 2, the retrofitted LD-IDECOAS system pressure drop is calculated based on the retrofitted case configurations. In addition, the head loss for each system component is considered to estimate the pump energy consumption. In the LD unit, the solution pumps (absorber and regenerator) are applied as 13 m at the design solution flow. A recirculation pump of the IEC and DEC are considered to be 40 m at the design water flow. The energy consumption of the fan and pump are estimated based on the pressure drop and head loss, respectively. The affinity law is used to evaluate the energy consumption of the variable flow of the fan and pump.

4. Simulation results

In the present work, the energy consumptions of the LD-IDECOAS and its retrofitted cases are estimated and compared for system design during the cooling season. The OA conditions is conducted the ASHRAE design conditions [13] in summer of Seoul, Korea. The energy consumption of each retrofitted case is analyzed based on the OA conditions.

4.1. Psychrometric analysis

According to the ASHRAE fundamentals [13], the cooling design condition of Seoul is defined based on the dry-bulb and wet-bulb condition. The wet-bulb design condition is specified based on the latent heat load of the OA, which is proposed to occur with an annual cumulative frequency of 0.4, 1, or 2%. In this study, the 0.4% annual cumulative frequency occurrence of the wet-bulb condition (e.g., 29.8 °C, 73%) was applied to estimate the required thermal load of the modeled space. To evaluate the system performance of each proposed system, a psychrometric analysis was conducted to confirm the variations in the OA condition at each system component (Figs. 6-8).

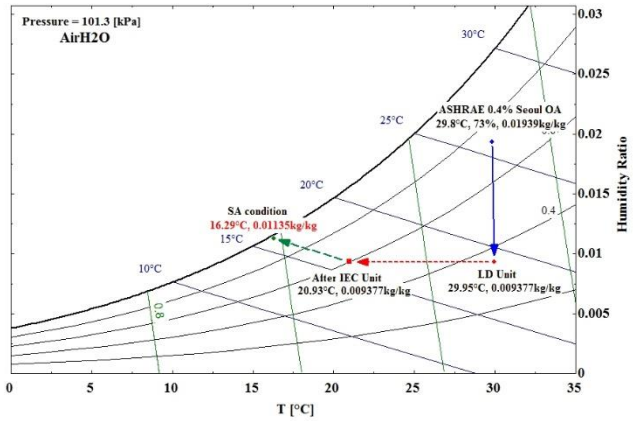


Fig. 6. Psychrometric chart for the base case.

As shown in Fig. 6, the induced OA is dehumidified by the LD unit. The dehumidification process is an exothermic chemical phenomenon, so the process air cannot be cooled while passing through the absorber tower. The dehumidified process air enters the IEC for sensible cooling, and then the process air is adiabatically cooled via the DEC. Based on the design condition of the OA, the base case of LD-IDECOAS cannot meet the target SA conditions due to the low dehumidification performance in hot and humid OA conditions while using water-side free cooling of the desiccant solution.

In terms of the case 1, the operation modes of cascade LD unit is considered to perform the moisture removal from induced OA for a deep dehumidification process (Fig. 7). In this case, the induced OA is dehumidified to the target humidity zone by passing through the primary and secondary absorber towers. The humidity level of the process air is suitable for supply as the SA, however the WBT of the process air is higher than the target SA condition. Therefore, Case 1 cannot meet the target SA condition without operation of the IEC (Fig. 7). In addition,

the high SA temperature causes an increase in the SA air flow rate, which increases the overall regeneration heating energy to adjust the concentration of the liquid desiccant solution. This CLD-DEC can dehumidify the OA to the target humidity zone; however it cannot adjust the SA temperature to maintain the indoor thermal condition based on the required thermal load in summer OA design conditions.

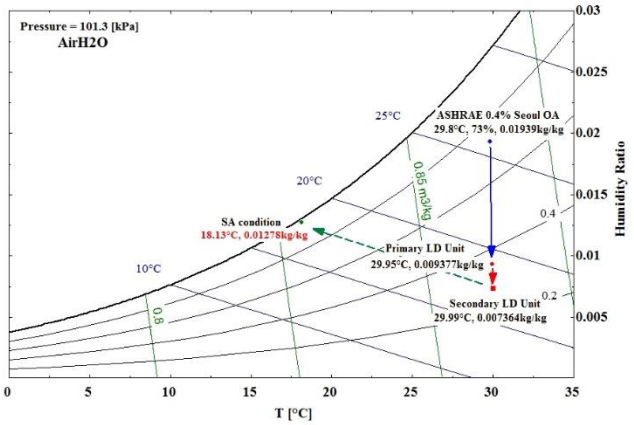


Fig. 7. Psychrometric chart for the case 1.

As in case 1, the IEC unit is applied to generate sensible cooling of the process air before entering the DEC unit. In this case, the cascade LD unit can achieve deep dehumidification to enhance the sensible cooling effect of the IEC. In order to meet the target SA conditions, the IEC and DEC units operate to perform sensible and adiabatic cooling. Under peak-load OA conditions, the OA is highly hot and humid so the LD unit in the base case cannot meet the target SA condition. However, the dehumidification within case 2 is sufficient to meet the target SA conditions (Fig. 8).

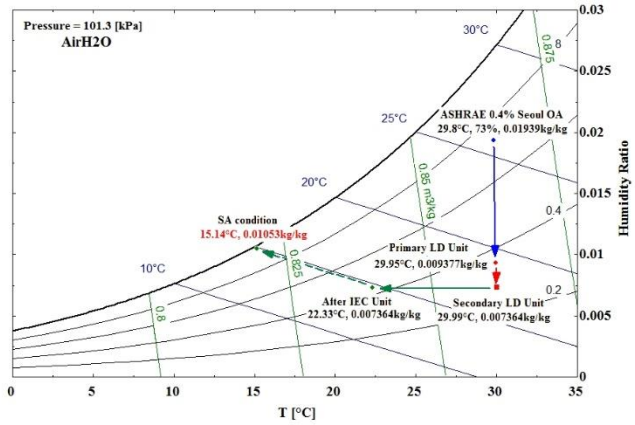


Fig. 8. Psychrometric chart for the case 2.

4.2. Energy consumption in system design

According to thermal behavior, the energy consumption in system design was calculated to analyze the energy performance of the proposed system cases (Fig. 9). The energy consumption of each system is dependent on the solution heating energy consumption, this is caused by differences in total moisture removal rate. The moisture removal rate is related to the SA flow rate and the amount of moisture removal from the OA, so a low SA design temperature means that the system can supply the low SA flow. Case 2 exhibits the lowest SA temperature, and the total moisture removal rate can be reduced while operating the cascade LD unit; therefore, Case 2 exhibits lower design energy consumption than the base case. The total energy consumption of Case 1 is higher than that of the base case. In this simulation, it was determined that the required regeneration energy in Case 1 is higher than that of the base case. This is caused by the increase in the SA flow rate and a large amount of dehumidification. Therefore, Case 1 consumes more regeneration energy than the base case and Case 1.

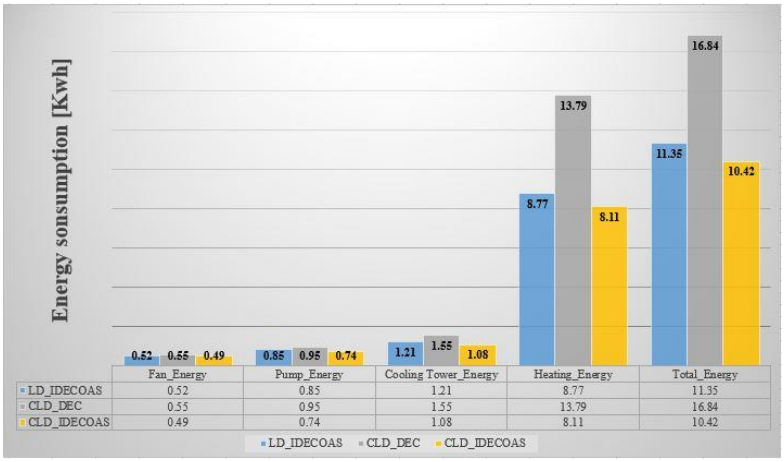


Fig. 9. Energy consumption of the proposed cases in system design.

5. Conclusions

To propose a new type of retrofitted LD-IDECOAS, a psychrometric analysis of the process air is performed and the energy consumption of the system is estimated according to the ASHRAE design conditions [13] during the summer in Seoul, Korea. The system was retrofitted with an additional liquid desiccant unit to generate deep dehumidification of the OA under hot and humid conditions. Based on the LD-IDECOAS, it was assumed as a base case of system configurations. In case 1, a cascade LD unit was used in place of the single LD unit, the DEC unit was then operated to adjust the SA conditions without operation of the IEC unit (CLD-IDECOAS). The IEC unit is added in Case 2 for the sensible cooling of the process air between the cascade LD and DEC units (CLD-IDECOAS). The cascade LD unit was controlled to adjust the humidity condition of the process air until reaching the target humidity zone.

From the results of the psychrometric analysis, Case 1 exhibits the lowest SA temperature and humidity condition. The cascade LD unit generates deep dehumidification under peak load design conditions in summer; therefore, Cases 1 and 2 can dehumidify the induced OA to the target humidity zone for processing the SA conditions. In terms of energy consumption, Case 2 generates energy savings of 8% over the base case. These savings are a result of the difference in the SA temperature design condition. In addition, Case 1 consumed 48% of the system design energy used in the base case.

In further research, energy simulations will be conducted to verify the actual operating energy consumption of the proposed system cases and to estimate system performance while considering the hourly weather conditions. The cascade LD unit is capable of generating deep dehumidification of the OA and can be adjusted based on indoor humidity conditions to comfortable levels in hot and humid climate zones. This will be verified by evaluating the indoor humidity condition under a variety of weather conditions.

Acknowledgements

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