Energy Performance of a Desiccant and Evaporative Cooling-assisted Air-conditioning System under Various Climatic Conditions in China

S. Y. Li [1], H. S. Lim [1], J. H. Shin [1], M. S. Jo [1], and J. W. Jeong [1]

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

SUMMARY
The main purpose of this study is to evaluate the energy performance of a liquid desiccant and evaporative cooling-assisted 100% outdoor air system (LD-IDECOAS). To evaluate the cooling operation of the LD-IDECOAS, the energy consumption was compared to the conventional, variable air volume (VAV) system. Both LD-IDECOAS and VAV systems were used for air-conditioning an office building in three typical cities in China located in different climatic zones. To simplify the calculation process, the required thermal load of the model building was simulated using TRNSYS 17, and the energy consumption was calculated by a commercial equation solver program (EES). LD-IDECOAS uses significant amount of heat in terms of regeneration, which is applied to district heating. As a result, it has been confirmed that the energy consumption of LD-IDECOAS is lower than the energy consumption of the VAV system. The LD-IDECOAS can save approximately 68% of the annual energy consumption in conventional VAV systems during operation (Kim et al. 2014).

INTRODUCTION
With the continuous development of construction activity in China, the annual energy consumption in buildings has also been increasing. Most importantly, air-conditioning energy consumption accounts for approximately 2/3 of the total building energy consumption in China. This further shows that reducing the energy consumption of buildings in China is an urgent matter at present. Compared to the traditional vapor compression air-conditioning system, the LD-IDECOAS has attracted considerable attention as a non-vapor compression air-conditioning system because of its energy saving capability, relevance to environmental protection, and efficiency (Kim et al. 2013). In the dehumidification unit of the LD-IDECOAS, the liquid desiccant is cooled by using water-side free cooling to achieve the dehumidifying effect, and the solar water heating system is applied in the regeneration section to heat-regenerate the solution after dehumidification. The liquid desiccant system (LD) is the most important part of the proposed system. An LD system can reduce the energy consumption by using $CaCl_2$ solution as the dehumidifying solution. The proposed system performance test conducted under different outdoor air conditions shows that the system can save more energy than the standard air-conditioning system (Kinsara et al. 1996). The hybrid HVAC system consists of a liquid-desiccant system that applies independent humidity control, and is more efficient than the conventional air-conditioning system through analysis of simulation results (Liu et al. 2004). In the LD-IDECOAS, the LD unit overcomes the latent heat load in the processed air, and the sensible heat load is resolved by the indirect evaporative cooler (IEC) and the direct evaporative cooler (DEC) for the air that passes through the LD unit.

China has vast territories and diverse climates. Therefore, the choice of the HVAC technology for the specific local climate may have increased energy saving potential. Experimental methods were employed to analyze the cooling and energy saving capabilities of counter-flow regenerative evaporative coolers (REC) applied to the selected regions of China where variation in climate is observed (Duan et al. 2017). The LD-IDECOAS has several operating modes for each season, and each operation mode is executed based on the outdoor conditions. In this paper, adequate modifications of the LD-IDECOAS components were proposed with simulations in terms of energy consumption, depending on the climate characteristic of the three selected cities, thereby achieving energy saving compared to the VAV system.

Herein, the system operation strategies are proposed for each of the cities considered, in view of the fulfillment of the supplied air conditions and the energy consumption during the cooling season. Simulation energy analyses were carried out for the cooling season for comparison of the VAV and LD-IDECOAS systems.

SYSTEM OVERVIEW

LD-IDECOAS
As shown in Figure 1, the proposed system, LD-IDECOAS, consists of an LD, an IEC, and a DEC system on the processed air side, with an efficient heat exchanger (SHE) and a heating coil (HC) on the exhaust side of the system. The most important component of this system is the LD part that consists of a regenerator, a dehumidifier, an SHE, a solution heating coil, and a cooling coil. As the processed air passes through the dehumidifying part of the LD, the strong solution, which is sprayed on the dehumidifying part, removes the moisture. After the dehumidification process, the weak solution from the dehumidifier enters the regeneration section and turns into a strong solution through the water evaporation process. During the steam evaporation process, an increased vapor pressure is required, and the weak solution is first heated once it is in the SHE, followed by a secondary heating by the HC. The processed air that has been dehumidified by passing through the LD unit passes through the IEC and DEC to achieve appropriate heat cooling, thereby lowering the temperature. When the system is in operation, 100% ambient air is introduced and used. The processed air flow is controlled by the change in the thermal load of the target space, which is similar to the standard VAV system. The path highlighted in blue in Figure 1 is the path that supplies air to the air-conditioned space during the cooling season. Additionally, the part that is marked in red indicates the path of the indoor return air and the exhaust air.

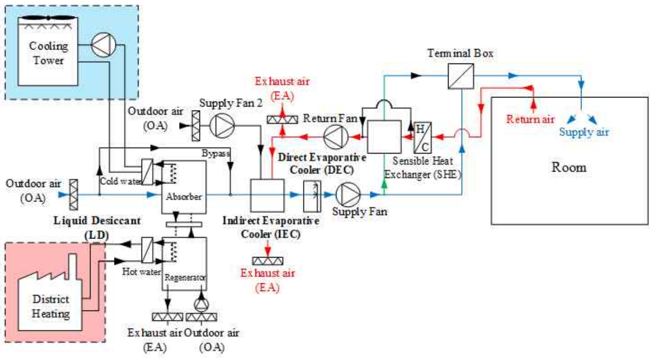


Figure 1. Schematic of LD-IDECOAS

OPERATIONAL MODES

The proposed system is divided into four operational modes (Figure 2). These four operational modes can be analyzed in accordance to the seasons, based on the ambient conditions.

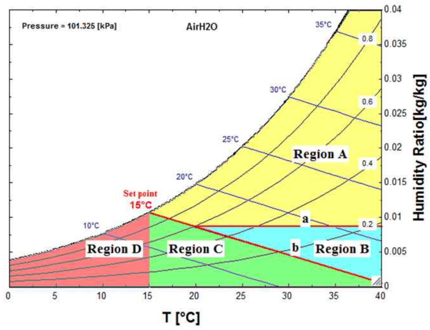


Figure 2. Each operating mode is represented using psychrometrics

First, the hot and humid atmospheric conditions during summer are represented by region A. In this case, the LD unit is used to dehumidify the air, and the IEC and DEC units operate to meet the target temperature of the air supply. Initially, the LD unit is used to carry out the dehumidification process up to the set air-supply humidity ratio line indicated by line “a” for the outdoor air within region A. The process is shown in Figure 3. The air then reaches the IEC and DEC that perform adiabatic cooling along the isentropic path until the air supply target is reached.

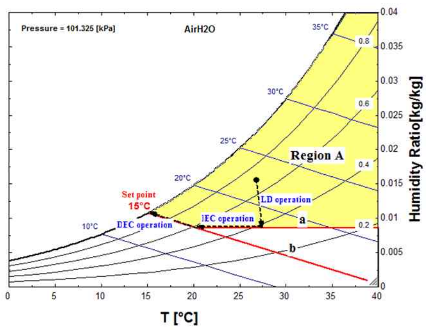


Figure 3. Process of outdoor air handling in region A

Regions B and region C are distinguished by line “b” and mean the middle season. Line “b” represents the enthalpy of the target set point (i.e., 15℃ saturation), and region B lies between lines “a” and “b” (Figure 4). When the system is operating in region B, the IEC is operated by an efficient heat cooling, and is used to supply the air wet bulb temperature (WBT), or the set point enthalpy. The DEC performs the adiabatic cooling process until it reaches the supply set point. The ambient temperature of zone C is higher than the set supply temperature, and is lower than the set point enthalpy. In this case, the DEC only operates adiabatically to the set point temperature of the supply air.

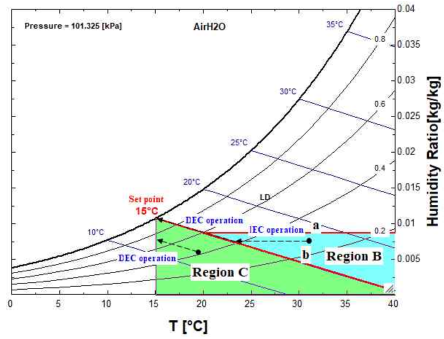


Figure 4. Process of outdoor air handling in regions B and C

In the last region D, the outside temperature is lower than the set temperature (Figure 5). In this area, LD and DEC are not operational because this region represents the heating season similar to winter. In this instance, the IEC is used like the SHE. That is, the sensible heat is recovered from the exhaust stream, and the OA is heated to the set point. If the target temperature is not reached, the auxiliary HC is operated.

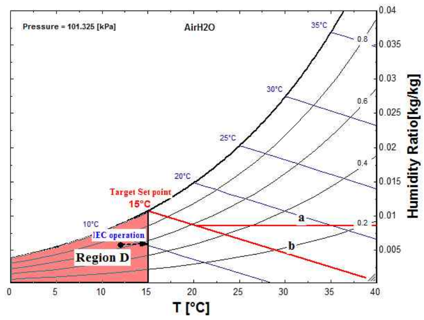


Figure 5. Process of outdoor air handling in regions D

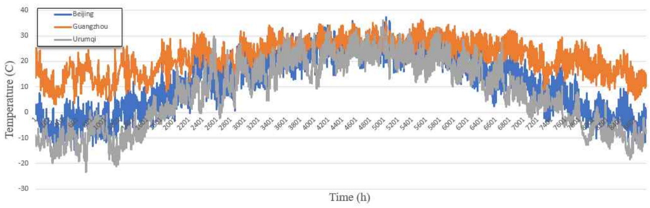
The description above applies to all operating modes of the LD-IDECOAS, which are modulated by the state of the outside air.

DIFFERENT CLIMATIC FEATURES IN SELECTED ZONES OF CHINA

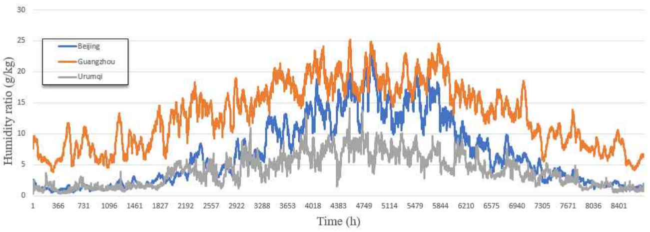
China has an area of approximately 9.6 million square kilometers, and is warmer in the summer, colder in the winter, and exhibits a higher range of temperatures than other regions at the same latitude, which have the same climate as continental climates observed in other regions around the world. Owing to the complexity of the terrain, China has developed a very diverse and distinct climate. According to GB 50176-93 (1993), it has been classified into five main areas with respect to the thermal designs for buildings, according to the characteristics of Chinese climate, namely, severe cold, cold, hot summer and cold winter, mild, and hot summer and warm winter (Figure 6). To analyze the energy performance of the proposed system, three cities were selected, which are located in geographically comparable areas with different climate characteristics.

Figure 6. Location of the three cities in China selected for this study

These three areas are Urumqi, which is a severely cold region, Beijing, which is a cold region, and Guangzhou, which is a hot summer and warm winter region. Figure 8 shows the differences in outdoor temperatures and relative humidity of the three selected cities throughout the year.



(a) Temperature



(b) Humidity ratio

Figure 7. Weather data of the three Chinese cities selected for this study

The differences in the outdoor air condition of these three regions are confirmed by Figure 8. In this study, it was confirmed that the temperatures in the three regions were high when the simulations were conducted in summer. Additionally, the humidity ratio plot shows that the most humid city is Guangzhou, followed by Beijing, while Urumqi is the driest region. The weather data of Urumqi, Beijing, and Guangzhou, based on TMY2 weather data, were exported using TRNSYS 17 (Klein et al. 2009).

ENERGY SIMULATIONS

SIMULATION OVERVIEW

The proposed system and the VAV system were applied to the selected air-conditioned space to compare energy performance. Therefore, the air-conditioned space selected for the simulation is an office building located in Guangzhou, China. The total area is 300 m^2, and it has one floor. To analyze the building load for the two selected areas, it was necessary to use TRNSYS 17 to perform building energy simulations to achieve the indoor conditions and sensible and latent heat loads. When conducting the simulation with TRNSYS 17, the standardized thermal transmittance, standard indoor temperature, and relative humidity, were determined by the Chinese National standards GB 50189–2015 (2015) and the "Design Code of Office Building" (JGJ67–2006 2006). The heat transfer coefficients of the exterior walls of the building in Beijing, Guangzhou, and Urumqi, are 0.50 W / $(m^2 \cdot K)$, 0.80 W / $(m^2 \cdot K)$, and W / $(m^2 \cdot K)$, respectively. According to JG67–2006, the standard indoor temperature is 26°C in summer and 18°C in winter. The relative humidity should be 60% or less in the summer, and in the winter season, it should be greater than or equal to 30%. According to the information provided in the international standard ISO 7730, the building's computer types, lighting, and the lighting/work schedule, will be set in accordance to the values listed in Table 1. The various parameters for this model building are listed in Table 1.

Table 1. Basic parameters of model building

Parameters \ City		Beijing	Guangzhou	Urumqi
Location		Guangzhou, China		
Area		300 m^2		
Window-to-wall ratio (GB50189–2015)		0.3 (≤ 0.7)	0.3 (≤ 0.7)	0.3 (≤ 0.6)
Indoor condition (JGJ67–2006)		Cooling season: 26℃ , $\leq$ 60% Heating season: 18℃ , $\geq$ 30%		
U-value ($W/m^2 \cdot K$)	Roof	0.45	0.5	0.35
	Exterior wall	0.5	0.8	0.43
	Window	2.7	4.0	2.6
Occupant (person)		15		
Computer (W)		230		
Lights (W/m^2)		13		

To compare the energy consumed when each system was operated in the cooling season in this study, and when the VAV system was operating, CC was used to cool and dehumidify the processed air to achieve the set temperature of 15 ℃. In the simulation, the system operating conditions, that is, the setting of the indoor temperature and the air flow rate, are assumed to be the same as the set conditions of the proposed system. For the conditions to be compared upon operation of the proposed system, most of the outdoor conditions belong to region A and are described by psychrometrics. That is, among all the operational modes, this constitutes the mode in which only the LD operation must be performed.

The dehumidification efficiency of the LD system (ε_{ab}) is proportional to the humidity ratio of the inlet air, and the humidity ratio of the inlet air to the LD minus the equilibrium humidity ratio. The regeneration efficiency (ε_{reg}) is also determined by the rate of the actual humidity evaporation and the ratio of equilibrium humidity. Consequently, Equations (1) and (2) are derived. Through these two equations, the humidity ratio of the air on the outlet side of the dehumidifier ($w_{ab.out}$), and the air humidity ratio on the outlet side of the regenerator ($w_{reg,out}$) are obtained. In this process, the dehumidifier efficiency, the humidity ratio of the inlet air ($w_{ab,in}$), the equilibrium humidity ratio of the dehumidifier ($w_{ab,e}$), the efficiency of the regenerator (ε_{reg}), the humidity ratio of the air entering the regenerator ($w_{reg,in}$), and the equilibrium humidity ratio of the regenerator ($w_{reg,e}$), must all be known. The equilibrium humidity ratios in Equations (1) and

(2) can be expressed by Equation (3). In the calculation of the equilibrium humidity ratio (w_e), the vapor pressure (p_s) of the dehumidifying solution in the saturated state is applied to Equation (4) proposed by Fumo and Goswami (Fumo and Gpswami 2002). The values of the various parameters shown in Equation (4) are given by Fumo and Goswami (Fumo and Gpswami 2002). The temperature of the air leaving the LD unit can be derived from Equation (5). The temperature difference ratio of the LD (ε_{T_LD}), the temperature of the air before entering the LD ($T_{LD.in}$), and the temperature of the strong solution that enters the dehumidifier ($T_{sol.in}$), should be known variables. Based on literature (Katejanekarn and Kumar 2008 and Katejanekarn et al. 2009), it is confirmed that ε_{T_LD} is very similar to the dehumidification or regeneration efficiency.

$$\varepsilon_{ab} = \frac{w_{ab,in} - w_{ab.out}}{w_{ab,in} - w_{ab,e}} \quad (1)$$

$$\varepsilon_{reg} = \frac{w_{reg,out} - w_{reg.in}}{w_{reg,e} - w_{reg,in}} \quad (2)$$

$$w_e = 0.622 \frac{p_s}{101.325 - p_s} \quad (3)$$

$$p_s = (a_0 + a_1 \cdot T_L + a_2 \cdot T_L^2) + (b_0 + b_1 \cdot T_L + b_2 \cdot T_L^2) \cdot C + (c_0 + c_1 \cdot T_L + c_2 \cdot T_L^2) \cdot C_L^2 \quad (4)$$

$$\varepsilon_{T\_LD} = \frac{(T_{LD.in} - T_{LD.out})}{T_{LD.in} - T_{sol.in}} \quad (5)$$

The dehumidification efficiency was derived using the experimental model constructed by Chung and Luo (Chung and Luo 1999) (Equation 6), and the theoretical model of Martin and Goswami (Martin and Goswami 2000) (Equation 7) was selected to calculate the regeneration efficiency.

$$\varepsilon_{ab} = \frac{\dfrac{1-0.024\left(\frac{G_{in}}{L_{in}}\right)^{0.6}\exp\left(1.057\frac{T_{G_{in}}}{T_{L_{in}}}\right)}{(aZ)^{-0.185}\pi^{0.638}}}{1-\dfrac{0.192\exp\left(0.615\frac{T_{G_{in}}}{T_{L_{in}}}\right)}{\pi^{-21.498}}} \quad (6)$$

$$\varepsilon_{reg} = 1 - 48.3\left(\frac{L_{in}}{G_{in}}\right)^{\left(0.396\frac{\gamma_L}{\gamma_C}-1.57\right)}\left(\frac{h_{A,in}}{h_{G,in}}\right)^{-0.751} \times (aZ)^{0.331\frac{\gamma_L}{\gamma_C}-0.906} \quad (7)$$

In this simulation, the liquid-to-gas ratio (L/G ratio) was assumed to be 0.5 to 1, and the solution concentration at the inlet of the dehumidifier was set to 40%. When the efficiency of the SHE in the LD system is set to 70%, the temperature of the inlet solution is assumed to be 30 ℃. In the regeneration section, the inlet temperature was set to 55 ℃, and the L/G ratio was set to 4, based on the applied model.

To save energy in the LD system, renewable energy is applied to improve the solution, in accordance to the set temperature. Cooling towers were used on the cooling side of the solution for water-side free cooling when the system was implemented. China's district heating capacity is second in the world and continues to increase at a rapid rate. In China, which has many coal resources, the use of coal as district heating source has considerable advantages in terms of energy saving (Odgaard 2015). It is also expected that energy consumption will be reduced in regenerating the solution concentration needed on the regeneration side of the LD system.

After the hot and humid air is dehumidified by the LD unit, it exits the LD unit and passes through the IEC and DEC parts located in the subsequent evaporative cooling stage. As the humidity of the air passing through the IEC does not change, the humidity ratio of air from the IEC is the same as that from LD. In the IEC, the air temperature is cooled and the outlet temperature of the IEC is predicted based on Equation (10). Given the DEC efficiency and the set point of the air from the DEC, the wet-bulb temperature of the IEC is also obtained using Equation (11).

$$\varepsilon_{IEC} = \frac{(T_{LD.out} - T_{IEC.out})}{T_{LD.out} - WBT_{IEC.in}} \quad (10)$$

$$\varepsilon_{DEC} = \frac{(T_{IEC.out} - T_{DECout})}{T_{IEC.out} - WBT_{IEC.out}} \quad (11)$$

All the processes mentioned above are applied to the simulation using the EES (Klein and Alvarado 2008), and the energy performance analysis is performed.

RESULTS

OPERATIONAL MODE COMPARISON

The operational mode is selected in accordance to the outside conditions of the three regions selected in this study. The simulation of the proposed system was carried out on an annual basis to confirm how the regions having different climatic characteristics are structured in the operational mode. In the psychrometric chart, four seasonal areas correspond to the four modes of the proposed system. Comparison of the outside temperature and the target set temperature, and the comparisons of the humidity ratios and enthalpies, are the important criteria for distinguishing the operational mode. If the outside temperature is lower than the set target temperature, the system operates in mode 4, that is, the heating seasonal mode. If the outside temperature is higher than the set temperature, the system operates in the first mode, that is, the LD operational mode. When the outdoor air temperatures are higher than the set temperature of the supply air, mode 3 is entered if the outside enthalpy is lower than that of the enthalpy of the set point. Alternatively, if the outside enthalpy is larger than the enthalpy of the set supply air, mode 2 is entered. Considering the office occupant's work schedule, the total number of hours applied for the simulation was 4800.

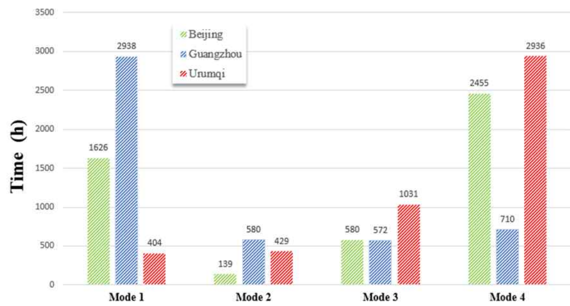


Figure 8. Distribution of the driving mode in each studied region

Analysis of Figure 8 shows that in the LD system driving mode, Guangzhou, which exhibits hot and humid outdoor air conditions, is the most occupied city. Beijing, which is a bit drier than Guangzhou, is a city that needs to be operated by the second LD system. The driest city, Urumqi, was found to be operated in mode 1 for the least amount of operational time. In Urumqi, it was judged that the evaporative cooling system was adequate to handle the cooling load in the summer. Therefore, even when the LD-IDECOAS is used, it is possible to save energy given that the LD system is not operational. The operating modes shown in this figure correspond to the different climatic characteristics of each region.

COMPARISON OF ENERGY CONSUMPTION IN DIFFERENT ZONES

When comparing the simulation results, all the energy values are converted to the same primary energy to obtain a more accurate comparative result. In addition, the simulation results are compared with the city in China where the most coal energy is used. Energy transformation into primary energy in China complies with the standard GB/T2589–2008.

In this standard, the transfer factor is defined as 0.1229 kgce / KWh when the electrical energy is converted into coal energy. Correspondingly, the transfer factor is defined as 0.03412 kgce / KWh when the thermal energy of the district heating is converted. The unit kgec refers to the kilogram of coal equivalent. When the thermal energy was converted to the appropriate units, it was changed to 0.009485 kgec/KWh. The results of the conversion of the energy consumption into primary energy for coal are shown in Table 2.

Table 2. Coal energy conversion factor

Energy type	Transfer factor （kgce / KWh）
Electrical energy	0.1229
Thermal energy （district heating）	0.009485

In this study, the energy consumption and energy saving potential of the LD-IDECOAS and the conventional VAV systems were compared and analyzed. Figure 10 shows the energy consumption of each component when the two systems are applied in the three studied cities during the summer.

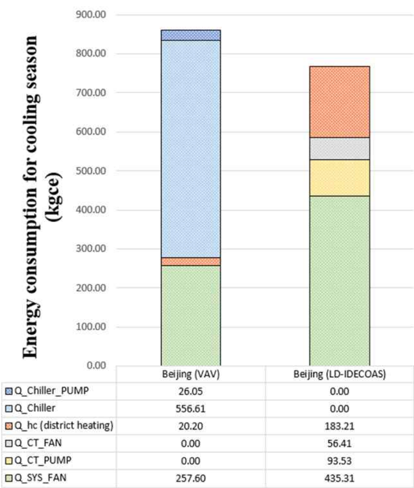


Figure 9. Comparison of energy consumption during summer in Beijing

In Figure 9, the proposed and the VAV systems compare the energy consumption of each component through simulations for the Beijing region. Figure 9 shows that the VAV system has higher energy consumption in the summer than the proposed system. This is mainly because in the proposed system, the cooling coil is replaced by the IEC and DEC to achieve the cooling effect. As the processed air must be dehumidified in the LD part of the proposed system, the energy consumption of the heating coil is much higher than that of the VAV in regenerating the used liquid desiccant. However, because it was applied to district heating, it can be used as waste heat or residual heat, so it uses less energy. Overall, the proposed system saves approximately 10.69% the energy consumption of the VAV system. In conclusion, the comparison shows that LD-IDECOAS is more profitable.

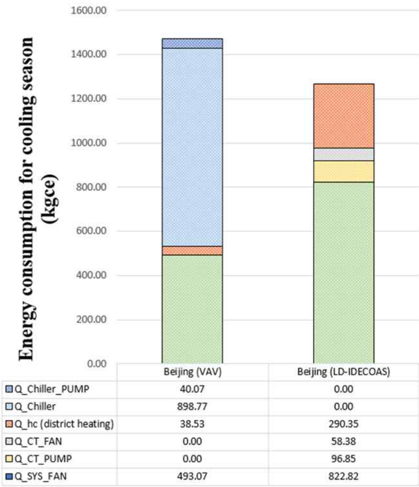


Figure 10. Comparison of energy consumption during summer in Guangzhou

Figure 10 shows the comparison of energy consumption in the hot and humid area of the city of Guangzhou, where the LD system operates more frequently. Under these circumstances, the figure shows that the energy consumption of the VAV system is slightly higher than the proposed system, similar to the Beijing area. Regarding the fan energy section, it is half of the fan energy consumption of the LD-IDECOAS. This reflects the fact that all of the air introduced during operation of the LD-IDECOAS system has introduced fresh air outside. As a result, the proposed system consumes less energy, and has reduced overall energy consumption compared to the VAV system by approximately 13.74%.

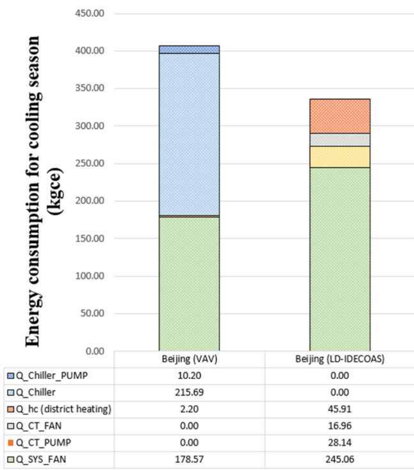
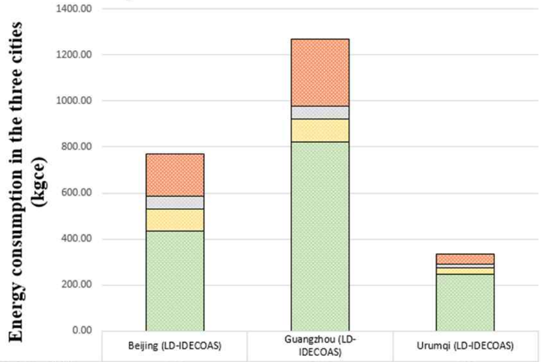


Figure 11. Comparison of energy consumption during summer in Urumqi

Figure 11 shows the energy performance analyses results in the Urumqi area. It is shown that the VAV system needs to consume approximately 17.36% more energy than the proposed system in this area. This energy saving result is owing to the replacement of the cooling coil with the LD and evaporative cooling. In this region, district heating is used in the same way as before, and the main reason for the higher operating energy in the conventional VAV system is the large load of the cooling coil.



	Beijing (LD-IDECOAS)	Guangzhou (LD-IDECOAS)	Urumqi (LD-IDECOAS)
Q_Chiller_PUMP	0.00	0.00	0.00
Q_Chiller	0.00	0.00	0.00
Q_hc(district heating)	183.21	290.35	45.91
Q_CT_FAN	56.41	58.38	16.96
Q_CT_PUMP	93.53	96.85	28.14
Q_SYS_FAN	435.31	822.82	245.06

Figure 12. Comparison of energy consumption during summer in the three studied cities

Figure 12 shows the energy consumption status when the proposed system is applied to all three regions designated as the comparison target during the cooling season. This figure shows that the consumption of the operating mode of the proposed system in Guangzhou, which has the highest humidity, is the highest computed, and the smallest in the driest region. The total energy consumption in Guangzhou is nearly three times that of the driest city Urumqi.

CONCLUSIONS

LD-IDECOAS, a non-vapor compression air-conditioning system that is more environmentally friendly, with increased capacity for further improvements in energy-saving under various environmental conditions, and a conventional VAV system, were analyzed through detailed simulations. One of the biggest advantages of the proposed system is that it uses 100% outdoor air, thereby improving indoor comfort. The operating energy consumptions of the proposed system in the three selected cities, Beijing, Guangzhou, and Urumqi, were respectively 10.69%, 13.74%, and 17.36% lower than the energy consumption of the VAV system during the cooling season. In the proposed system, the heat required to regenerate the liquid desiccant for the operation of the dehumidifier is high, an issue that can be solved using waste heat or various renewable energy sources. In this study, only summer data were analyzed, and further research is needed to analyze data recorded throughout the year.

ACKNOWLEDGEMENT

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