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Feasibility investigations on utilizing deep eutectic solvent ethaline for energy saving and indoor CO_2 concentration regulation in air-conditioning systems

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ABSTRACT

The rapid urbanization has led to a significant increase in building energy consumption, with air-conditioning systems being a major contributor. Liquid desiccant air-conditioning systems (LDAS) have been proposed as an effective solution for energy saving. In this study, the feasibility of using a deep eutectic solvent, ethaline, in LDAS is investigated for its energy-saving benefits and CO_2 concentration (C_{CO2}) regulation. Results show that LDAS using ethaline exhibits higher coefficient of performance (COP) than conventional systems by over 16%, particularly at low fresh air ratios. However, the effect of ethaline on C_{CO2} control is not significant due to limited absorption with insufficient ethaline flow rate, and the regulation of C_{CO2} indoors still heavily depends on the inclusion of fresh air. Thereafter, an advanced air-conditioning system that coordinates energy-saving, CO_2 capture, and energy recovery is proposed. The findings of this study can contribute to the further integration and design of air-conditioning systems, particularly for sustainable buildings in urban areas.

Keywords: liquid desiccant, ethaline, indoor CO_2 concentration, air-conditioning, energy-saving

NOMENCLATURE

Abbreviations	
CAS	Conventional air-conditioning system
COP	Coefficient of performance
IEC	Indirect evaporative cooling
LDAS	Liquid desiccant air-conditioning system
Symbols	
C_{CO2}	CO_2 concentration, ppm
COP	Coefficient of performance
FAR	Fresh air ratio
V_{sa}	Supply air flow rate, m^3/h
τ	Time, s

1. INTRODUCTION

Nowadays, reducing energy consumption is a hotspot with the rapid development of society and the appealing of CO_2 neutrality. According to International Energy Agency, the energy consumption of buildings accounted for around 30% of the totality [1]. In humid tropical regions, consumption for air-conditioning constituted the proportion of 40-60% of building energy consumption, since both sensible and latent loads should be handled [2].

Liquid desiccant air-conditioning system (LDAS) is favorable by researchers because of its energy saving potential of up to 50% compared with conventional air-conditioners [2]. Moreover, liquid desiccant has other advantages such as microorganism filtering. However, existing liquid desiccants (e.g., LiBr) has severe drawbacks, including crystallization risk and metal corrosiveness. The accompanying device wear-out and shortening service life result in the waste of material and resources.

In order to improve system stability, various kinds of liquid desiccant candidates are proposed to replace LiBr. In our recent studies, deep eutectic solvent ethaline was raised as liquid desiccant for air-conditioning, and comparative operation energy efficiency was obtained against LiBr [1, 2]. However, these studies did not take crowdedness and indoor CO_2 concentration variation into consideration, which greatly affects thermal comfort in practical applications.

Ethaline is a kind of deep eutectic solvent made up with choline chloride and ethylene glycol with a mole fraction of 1:2, and it is liquid at room temperature with freezing point of -66 ℃. Therefore, crystallization risk can be prevented. In addition, the corrosion of ethaline on either steel or stainless steel was also found one of the lowest among all the liquid desiccant candidates [1].

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Moreover, the price of ethaline was only 18.4 USD/kg, which was cheaper than LiBr [1].

Ethaline was also raised for CO_2 capture [3]. Li et al. [4] experimentally found that 34-mol CO_2 can be absorbed by 1-ton ethaline at atmospheric pressure and 20 ℃. However, CO_2 absorption of ethaline was neglected in existing studies on LDAS, while the respiratory CO_2 from occupants is always an important factor to be considered for indoor air quality control.

In this paper, a systematic evaluation is numerically simulated for a LDAS using ethaline, while the effects of crowdedness and fresh air ratio on energy efficiency and indoor CO_2 concentration are studied. The simulation results in this paper provide a quantitative reference for the effects of ethaline on both energy saving and CO_2 control in LDAS, which contributes to further integrated design of air-conditioning systems.

2. MODELING AND CALCULATION

2.1 System description

Since this study is raised to analyze the influence of ethaline as a new liquid desiccant, the configuration of LDAS is not changed in aspect of working principle. In other words, ethaline is a drop-in alternative to LiBr to be used in LDAS. The schematic diagram of a typical LDAS is shown in Fig. 1.

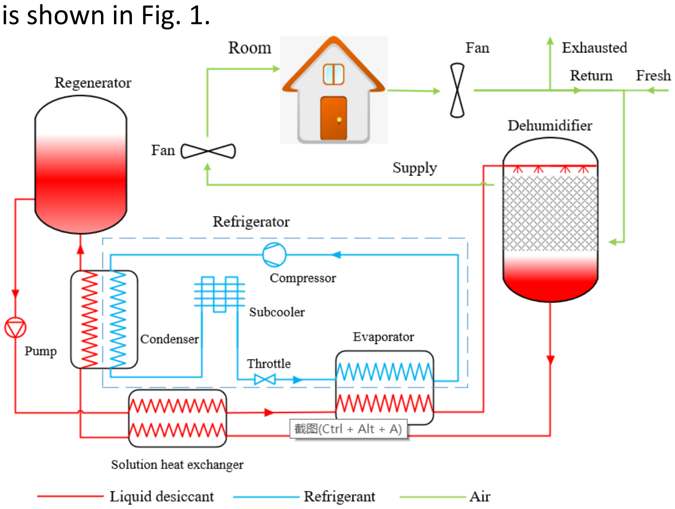

Fig. 1. Schematic diagram of LDAS

This LDAS has been detailly introduced in Ref. [1]. Generally, an adiabatic dehumidifier is adopted for both cooling and dehumidification to deal with sensible and latent load of air-conditioned space, and the liquid desiccant entering dehumidifier is precooled by a refrigerator. Meanwhile, this refrigerator also provides the heating capacity for desiccant regeneration before entering regenerator. A solution heat exchanger is adopted to recover heat and improve energy efficiency.

It can be found that the return air and fresh air is mixed before being processed in the dehumidifier. And if ethaline is adopted as a liquid desiccant, part of CO_2 can be expected to be absorbed. In this study, both LiBr and ethaline are adopted for comparison.

Meanwhile, a conventional air-conditioning system (CAS) is also used for comparison, whose configuration and working principle are introduced in Ref. [1] as well. In CAS, the latent load is handled by reducing processing air to a temperature lower than its dew point.

2.2 Indoor and outdoor conditions

Firstly, the environmental conditions are specified. For ambient air, its temperature and relative humidity are set as 35 ℃ and 80%, and its CO_2 concentration (C_{CO2}) is 400 ppm. The indoor environment is controlled with temperature of 26 ℃ and relative humidity of 50%, while the initial C_{CO2} is set as 500 ppm.

Secondly, the cooling load is dependent on both indoor and outdoor conditions [5]. In this study, ten identical rooms with size of 8m*8m*3m (length*width*height) per room are adopted. 70 W sensible heat and 45 W latent heat are assumed to generated for a single occupant [5]. In addition, 1 kg CO_2 is exhaled by an occupant per day [6]. The sensible heat generated by other indoor devices (e.g., light) is assumed as 10.7 W/m^2 [5]. Moreover, the heat transfer through roof, floor, window and wall is determined according to Ref. [5].

Therefore, cooling load and CO_2 generation varied with crowdedness can be determined.

Meanwhile, specific constraints are also defined for practical applications: 1) For a person, the lower limit of required fresh air rate is 30 m^3/h to supply oxygen. 2) For an air-conditioning room, the minimum air change rate is set as 4, i.e., the lower limit of supply air flow rate is 800 m^3/h per room. 3) The threshold of C_{CO2} is set as 1000 ppm in consideration of human health, i.e., if C_{CO2} is higher than 1000 ppm, additional approaches to reduce C_{CO2} should be exerted (i.e., increasing fresh air ratio).

2.3 Performance calculation

The governing equations of each component in LDAS or CAS can be found in Ref. [1]. Generally, the model of dehumidifier is established with correlated *Le*-NTU method, while the regenerator is modelled with specified effectiveness. The effectiveness of heat exchangers is fixed as 0.7, and their models are established based on mass and energy conservation. The thermophysical properties of ethaline are determined with fundamental models with experimental data. The modeling of LDAS and CAS is conducted using MATLAB and Energy Engineering Solver.

COP is used to evaluate the operating energy efficiency of air-conditioning systems as follows.

$$\mathrm{COP} = (Q_{\mathrm{sen}} + Q_{\mathrm{lat}})/(W_{\mathrm{refrig}} + W_{\mathrm{fan}} + W_{\mathrm{p}}) \quad (1)$$

In Eq. (1), Q_{sen} is sensible heat of an air-conditioned room, which is generated by occupants, devices and heat transfer with outdoors, and it is calculated according to section 2.2. Q_{lat} is latent heat of air-conditioned room, which is generated by occupants and calculated according to section 2.2. W_{refrig}, W_{fan} and W_p are the power consumptions of refrigerator, fan and pump, which represent the total power consumption of LDAS. They are calculated according to Ref. [1].

In addition, indoor CO_2 concentration is determined by mass conservation as follows.

$$V\int_{\tau(i)}^{\tau(i+1)} C_{\mathrm{CO2,in}} d\tau = V_{\mathrm{sa}} C_{\mathrm{CO2,sp}}\big|_{\tau(i)} - V_{\mathrm{ex+re}} C_{\mathrm{CO2,in}}\big|_{\tau(i)} + V_{\mathrm{oc}} \quad (2)$$

In Eq. (2), the difference of C_{CO2} between two time steps is decided by the net CO_2 variance of supply air inclusion, indoor air exhaustion, and occupant activity. Here the step size of time is set as 1 s. V is the volume of room, i.e., 192 m^3. V_{oc} is CO_2 volume generated by occupants in 1 s, m^3. V_{sa} and V_{ex+re} are air flow volumes of 'supply air' and 'exhausted air + return air' in 1 s, m^3. The subscripts of C_{CO2} 'in' and 'sp' represents 'indoor' and 'supply air'. It should be mentioned that $C_{CO2,sp}$ is influenced by the ratio of fresh air flow rate (i.e., FAR) and the CO_2 absorption effect of LDAS.

From section 2.2 and 2.3, it can be found that the crowdedness of air-conditioned room (i.e., occupant number indoors) has a direct influence on both cooling load and indoor C_{CO2}. In this study, the cooling load is primarily handled by LDAS, and C_{CO2} is controlled by both liquid desiccant absorption and fresh air dilution.

2.4 Validation

According to the models in sections 2.2 and 2.3, two important indicators of air-conditioning system can be determined, i.e., COP and C_{CO2}. The validations on these two aspects (i.e., energy and environment) have been conducted in our previous studies. In Ref. [1], the accuracies of dehumidification performance and COP were illustrated, with deviations of less than 10% against experimental data. In Ref. [6], the accuracy of C_{CO2} variation with time was illustrated, with deviations of less than 3% against experimental data.

3. RESULTS AND DISCUSSIONS

3.1 Results of room with low crowdedness

In this section, the results of room with low crowdedness are depicted, where 4 occupants live in this 64-m^2 room. Fig. 2 shows the variation of C_{CO2} with time at different ventilation conditions. The pink area denotes that C_{CO2} is higher than the threshold of 1000 ppm.

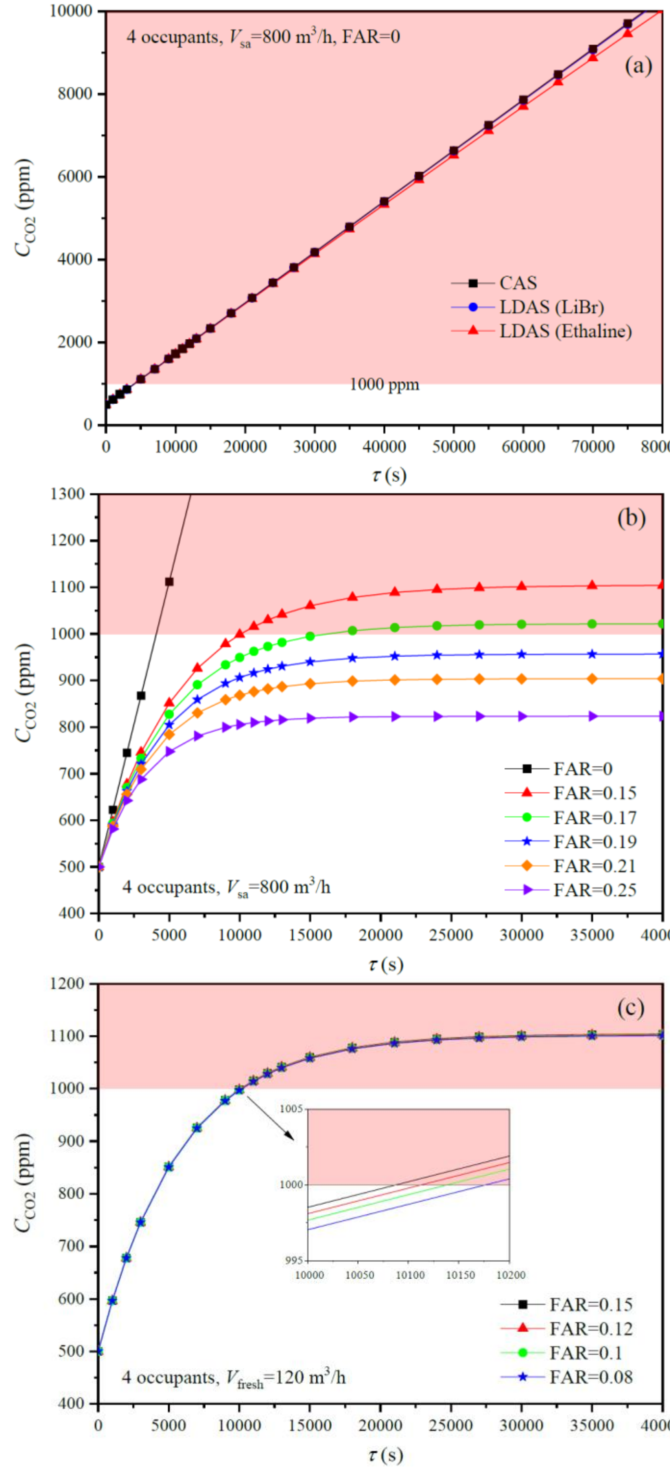

Fig. 2. C_{CO2} variation with time at different FAR for LDAS using ethaline for 4 occupants per room

In Fig. 2(a), the circumstance without fresh air is firstly analyzed. Without fresh air, indoor C_{CO2} increases linearly. Different systems exhibit a tiny difference in C_{CO2}

variation. For all the systems, C_{CO2} reaches the threshold of 1000 ppm at around 4000 s. Only the time scale reaches more than 50000 s can the curves in Fig. 2(a) exhibit certain difference. It indicates that even though ethaline is able to absorb CO_2, this effect is not significant in LDAS applications. In existing studies on CO_2 capture from exhausted air at atmospheric pressure in the air-conditioning field, the amount of sorbent is required to reach the magnitude of ton (i.e., 10^3 kg) for a room with area of 60 m^2 [6]. In this study, ethaline is used as liquid desiccant to deal with latent loads primarily, and the absorption of CO_2 is just auxiliary. Only 2 kg/s ethaline is needed here, so its CO_2 capture is quite mild and has nearly no influence on indoor C_{CO2} control.

It is well known that the inclusion of ambient fresh air is helpful for indoor C_{CO2} control. As shown in Fig. 2(b), at specific FAR, gradually increases and finally reaches a plateau, where the generated CO_2 by human can be diluted by introduced fresh air. Therefore, it is certain that higher FAR results in lower plateau of C_{CO2}. As shown in Fig. 2(b), when FAR reaches 0.19, indoor C_{CO2} can be kept lower than 1000 ppm.

Fig. 2(c) depicted the influence of supply air flow rate at fixed fresh air flow rate. It can be found that when provides certain amount of fresh air, the change of overall supply air flow rate has little influence on C_{CO2} control. With fresh air of 120 m^3/h, if supply air flow rate varies from 800 m^3/h to 1500 m^3/h (i.e., FAR from 0.15 to 0.08), the equilibrium C_{CO2} is unchanged while the time reaching 1000 ppm delays for just 83 s, negligible compared with time scale in Fig. 2(c).

From Fig. 2, the conclusion can be drawn. Since ethaline is proposed as liquid desiccant to primarily handle latent load (i.e., absorb moisture in air), it is not enough to remove CO_2 and control C_{CO2} within comfort range. For such a LDAS, its influence on C_{CO2} control is tiny, while introducing enough fresh air is still the most effective way to keep C_{CO2} within 1000 ppm.

However, the inclusion of fresh air increases the cooling load for refrigerator, since ambient air has higher temperature and humidity than the return air. Fig. 3 presents COP of different configurations varied with FAR. The pink area denotes that C_{CO2} is higher than the threshold of 1000 ppm. It can be found that with the increase of FAR, both CAS and LDAS show a decreasing trend of COP. LiBr and ethaline show little COP difference at each FAR. Moreover, the COP advantage of LDAS using ethaline against CAS also reduces with FAR increase. When FAR is 0.19, the advantage of LDAS using ethaline is 89.3%. To this end, LDAS is suitable for the circumstance with lower FAR.

In addition, it should be noted that keeping fresh air flow rate and increasing total supply flow rate (as Fig. 2(c)) is also ineffective for energy performance. With fresh air of 120 m^3/h, if supply air flow rate varies from 800 m^3/h to 1500 m^3/h (i.e., FAR from 0.15 to 0.08), COP of LDAS using ethaline reduces from 1.101 to 0.822.

In brief, for LDAS using ethaline, increasing supply air flow rate and increasing FAR are both unfavorable to emerge its superiority.

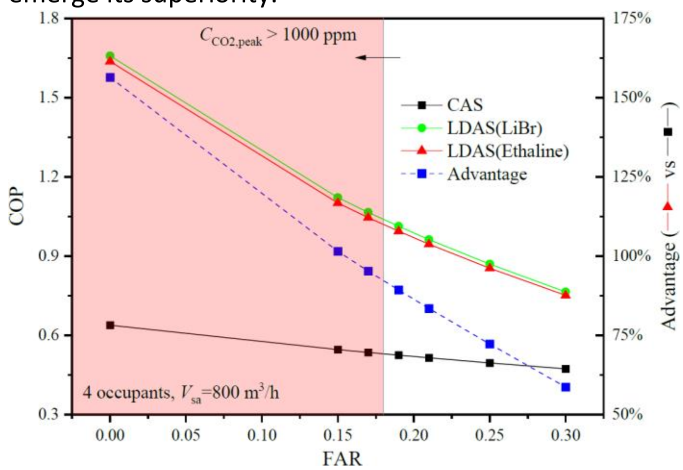

Fig. 3. Variation of COP with FAR for different configurations for 4 occupants per room

3.2 Results of room with medium-crowdedness

In this section, the results of room with medium crowdedness are depicted, where 10 occupants live in this 64-m^2 room. Fig. 4 shows the variation of C_{CO2} with time at different ventilation conditions, and COP of CAS and LDAS at FAR of 0.44 are also shown. The pink area denotes that C_{CO2} is higher than the threshold of 1000 ppm.

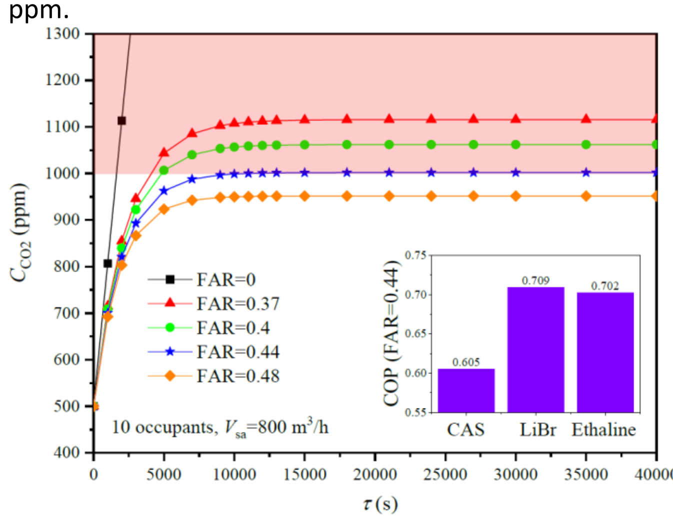

Fig. 4. C_{CO2} variation with time at different FAR for LDAS using ethaline for 10 occupants per room

The curves in Fig. 4 is similar with those in Fig. 2(b), and the only difference is that more fresh air is required to maintain C_{CO2} within an acceptable range for more occupants. For 10 occupants, C_{CO2} reaches the threshold of 1000 ppm at around 1600 s, much faster than the circumstance with 4 occupants. To this end, more fresh air is appealed. As shown in Fig. 4, FAR of 0.44 is needed to satisfy comfort requirement, i.e., the equilibrium C_{CO2} is lower than 1000 ppm. And for FAR of 0.44, COP advantage of LDAS using ethaline is 16.1% (0.702 vs 0.605). Compared with the results in section 3.1, the advantage is significantly reduced, which is attributed to high fresh air requirement and thus high FAR.

3.3 Discussions

In sections 3.1 and 3.2, the performances of LDAS using ethaline at different crowdedness are analyzed in terms of COP and C_{CO2}. On one hand, LDAS using ethaline exhibits higher COP than CAS, so it can be a kind of energy-saving alternative applied for air-conditioning. On the other hand, because of the low flow rate of ethaline, its CO_2 absorption effect on C_{CO2} control is not significant, and the regulation of C_{CO2} indoors mainly depends on the inclusion of fresh air.

However, with the increase of occupants (e.g., LDAS applied in classroom), the required fresh air increases, resulting in the deterioration of the COP superiority of LDAS. To this end, an advanced scheme of air-conditioning system is designed as shown in Fig. 5, which is integrated by three subsystems, in order to realize energy saving and C_{CO2} control simultaneously.

Firstly, LDAS using ethaline exhibits superiority on operating energy efficiency, but its advantage decreases with the increase of fresh air. Therefore, LDAS is installed in Fig. 5 to handle the load of return air, through which the humidity and temperature of return air can be effectively reduced, without the influence of fresh air.

Secondly, additional CO_2 capture subsystem should be adopted in tandem. For LDAS in Fig. 1, the partial pressure of CO_2 is reduced before entering dehumidifier due to the mixing of fresh air. And in Fig. 5, the CO_2 capture subsystem removes CO_2 from indoors directly, so the mass transfer potential can be enlarged. Moreover, compared with liquid absorption, solid adsorption for CO_2 capture is more favorable because of the avoidance of pumping liquid absorbent. However, existing solid absorbents are sensitive to humidity that, moisture outcompetes CO_2 in coordinating absorption sites [7, 8]. In other words, high humidity results in the decline of CO_2 capture capacity of absorbent. Therefore, installing CO_2 capture subsystem after LDAS is favorable for improving adsorption performance and prolong service life. Also, thanking to the reduction of C_{CO2} of processed return air, required fresh air can be reduced to control indoor C_{CO2}, which is beneficial for improving energy efficiency of the whole system.

Thirdly, even though the return air is processed in aspects of temperature, humidity and C_{CO2}, the introduced fresh air should be also processed before supplying. According to our previous study, indirect evaporative cooling (IEC) is an efficient approach for recovering energy from exhausted air [9]. However, it was demonstrated that IEC was incompetent to handle latent load, while it did show promising energy recovery performance during cooling the supply air [9]. In the advanced system in Fig. 5, the proportion of fresh air is reduced because of the capture of CO_2 in return air, so the cooling load to be handled in IEC is reduced. The function of IEC is actually cooling the processing air to required supply air temperature.

In brief, these three subsystems coordinate with each other, so that their advantages can be better utilized and their drawbacks can be bypassed to some extents, as shown in Table 1. And the performance of advanced air-conditioning system will be quantitatively analyzed in our follow-up studies.

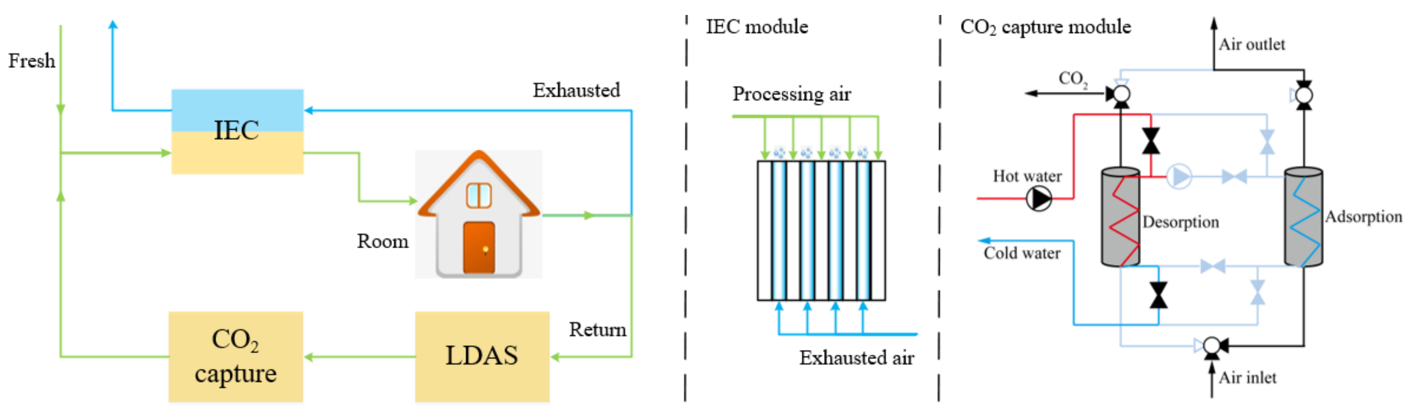

Fig. 5. Schematic diagram of advanced air-conditioning system for enregy saving and CO_2 concentration control

Table 1. Explanation on the coordination of subsystems of the advanced air-conditioning system in Fig. 5.

Subsystem	LDAS	CO_2 capture	IEC
Advantage	High energy efficiency	Regulating C_{CO2} effectively	Recovering energy from exhausted air
Weakness	Efficiency decline at high FAR	Influenced by moisture	Incompetent in handling latent load
Solution	Adopting CO_2 capture to reduce FAR	Adopting LDAS to reduce moisture	Adopting CO_2 capture to reduce FAR, adopting LDAS to reduce latent load

4. CONCLUSIONS

Rapid urbanization has resulted in the dramatic increase in building energy consumption, making air-conditioning systems a potential area for energy savings. In this paper, a systematic evaluation is conducted for a LDAS using ethaline, while the effects of crowdedness and fresh air ratio on energy efficiency and indoor CO_2 concentration are studied.

LDAS using ethaline exhibits higher COP than CAS by over 16%, so it can be a kind of energy-saving alternative applied for air-conditioning. The COP advantage is more noticeable at low FAR. However, the effect of ethaline on C_{CO2} control is not significant, and the regulation of C_{CO2} indoors still mainly depends on the inclusion of fresh air. Thereafter, an advanced air-conditioning system is proposed, in which energy saving, CO_2 capture and energy recovery are coordinated.

The results in this paper provide a quantitative reference for the effects of ethaline on both energy saving and CO_2 control in LDAS, thereby contributing to further integrated design of air-conditioning systems.

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DECLARATION OF INTEREST STATEMENT

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper. All authors read and approved the final manuscript.

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