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Applicability of a heat-pump-driven liquid-desiccant air-conditioning system in energy-efficient buildings

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Applicability of a heat-pump-driven liquid-desiccant air-conditioning system in energy-efficient buildings

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Abstract. Building trend is toward energy-efficiency by reducing building sensible load, while neglecting latent load. A heat-pump-driven liquid-desiccant (HPLD) air-conditioning system has emerged for effectively handling building latent load in energy-efficient buildings with low indoor sensible heat ratio. However, previous studies only investigated one building type, failing to account for the increase in building energy-efficiency. This study estimates building thermal loads of four different energy-efficient high latent load buildings, simulating building trend. Then, as energy-efficiency of buildings increases, the changes in indoor thermal comfort and energy consumption of the HPLD air-conditioning system and reference vapour compression system are compared. Simulation results show that in building with the highest energy-efficiency, the reference system can only maintain thermal comfort for 43.3% and 24% of summer operating hours when primarily meeting supply-air target temperature and humidity, respectively. Contrastingly, the proposed system can maintain thermal comfort in all building types for almost 100% of summer operating hours due to decoupled control of air temperature and humidity. Additionally, the proposed system saves up to 33.2% of operating energy when both systems achieve the same thermal comfort satisfaction. In conclusion, the HPLD air-conditioning system with decoupled control is more applicable as energy-efficiency of buildings increases.

1. Introduction

The sector of energy-use accounts for 73.2% of global greenhouse gas emissions, while the sector of energy-use in buildings, especially in space cooling, accounts for even 17.5% of total energy-use [1]. Hence, the current building focus is on enhancing energy efficiency through a reduction in space cooling energy consumption and accordingly has primarily focused on lowering the building sensible load in summer. Improving thermal performance of the building envelope and using high-efficiency lighting and equipment, considerable reductions in building sensible load and energy consumed to control indoor temperature in air-conditioning systems have been achieved. On the other hand, the building latent load due to occupants and their metabolic activities has not been reduced. That is, in buildings with high energy-efficiency, the indoor sensible heat ratio (SHR) is decreased. Hence, optimal energy efficiency in buildings highlights the importance of air-conditioning systems in effectively treat building latent load and sustain a comfortable building humidity level during indoor cooling. [2].

On the other hand, the vapour compression system, widely employed as a conventional air-conditioning system, has often overlooked controlling the air humidity and focused only on controlling the air temperature. Otherwise, the vapour compression system has required overcooling the air to eliminate water vapour from the air, referred to as condensation dehumidification process [3]. The thermodynamic inefficiency of air-conditioning process in this mechanism highlights drawbacks in the conventional vapour compression system, hindering its ability to effectively and efficiently treat building latent load. As an alternative to traditional air-conditioning systems, emerging technologies efficiently treat building latent load through decoupled control of building sensible and latent loads. Examples include dedicated outdoor air systems, solid or liquid desiccant systems, and membrane dehumidifiers. [4].

Previous researches on emerging air-conditioning technologies briefly introduced the building trend, specifically the improvement in energy efficiency of buildings. They did not directly simulate the building trend, leading to an absence of analysis on the changes in applicability of emerging technologies with increasing energy efficiency in buildings. That is, the analysis of applicability of emerging technologies has been limited to a single building type, potentially lacking representation of an energy-efficient building characteristic.

Hence, this study simulates building thermal loads for four distinct energy efficiency levels in buildings with high latent loads, such as commercial building, to model the evolving building trend. Subsequently, this study explores variations in the operation performance as well as energy-use of both traditional air-conditioning system and emerging technologies, examining their response to increasing energy efficiency in buildings. As a representative of conventional air-conditioning systems, the vapour compression system is selected. A heat pump integrated with liquid-desiccant (HPLD) system, exhibiting workability and feasibility previously, is chosen as a representative of emerging technologies. With increasing energy efficiency in buildings., the changes in operating frequency of satisfying the thermal comfort zone based on indoor air conditions and energy consumed for operation of the two systems during summer operating hours are investigated. Utilizing EES software, both systems are modelled through the integration of theory interpretation and the effectiveness-NTU model. This study contributes quantitatively demonstrating that with increasing energy efficiency in buildings, the conventional air-conditioning system becomes obsolete. Only the proposed system, utilizing decoupled control, remains applicable, resulting in improved indoor thermal comfort and reduced energy consumed to operate the system during the summer.

2. System overview

2.1. Reference system

The reference system chosen is the conventional vapour compression system, comprising a vapour compression cooling cycle. (Fig. 1). This study categorizes the operating strategy into two cases: Case A focuses on removing building sensible load by controlling the evaporator to achieve the supply-air target temperature. In contrast, Case B prioritizes the removal of building latent load by adjusting the evaporator to meet the supply-air target humidity through the overcooling air below dew point temperature and dehumidification. While capable of entirely eliminating building latent load, the approach of Case B may induce indoor thermal discomfort by excessively cooling the room.

2.2. Proposed system

The HPLD air-conditioning system, representing emerging technologies, comprises a liquid-desiccant unit and a heat pump. (Fig. 2). The process air is supplied to absorber and then dried due to the difference in vapour pressure with the liquid-desiccant solution which is initially cooled in the solution-side evaporator. The process air is cooled to meet the target supply-air temperature (i.e., 15 °C) without humidity change in the air-side evaporator. The liquid-desiccant solution undergoes initial heating in the solution-side condenser, subsequently releasing moisture to the scavenging outdoor air to enhance its concentration in the regenerator.

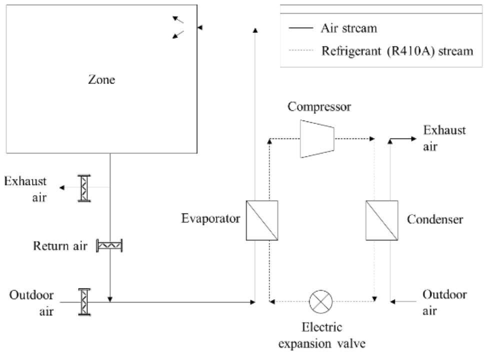


Figure 1. Vapour compression system (reference system)

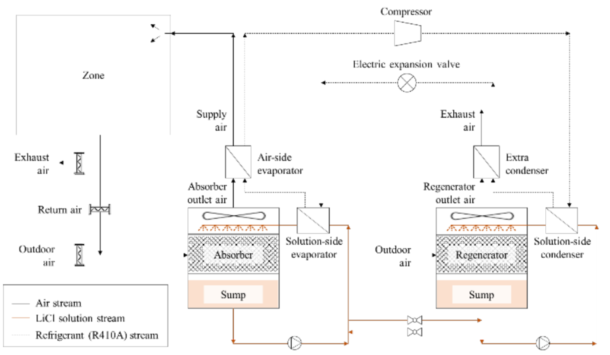


Figure 2. HPLD air-conditioning system (proposed system)

3. Simulation overview

3.1. Estimation of building thermal loads

A 10 m × 10 m × 4 m high latent load commercial building (i.e., occupant density of 40 people per 100 m^2 [5]) in Seoul was selected as a model space. Advanced Energy Design Guides (AEDGs) specified in ASHRAE were employed to acquire load data for energy-efficient buildings [6]. AEDGs consist of three design guides: Types 1 and 2 target energy savings of 30% and 50%, respectively, compared to ASHRAE Standard 90.1's minimum requirements. Type 3 targets zero energy buildings. Hourly estimates of building thermal loads were computed for energy-efficient buildings (Types 1, 2, and 3) and a reference building complying with ASHRAE Standard 90.1.

3.2. Vapour compression system (Reference system)

The evaporator of vapour compression system in both cases A and B, operates in wet-coil mode. An, evaporator effectiveness (ε_{evap}) can be expressed as Eq. (1) with saturated air enthalpy at evaporating temperature ($h_{evap,sat,a}$) in the wet-coil. The actual cooling capacity of evaporator ($\dot{Q}_{evap}$) is calculated using Eq. (2), and the required refrigerant flow rate ($\dot{m}_{ref}$) to accommodate $\dot{Q}_{evap}$ is calculated also using Eq. (2). The input power of compressor ($\dot{W}_{comp}$) can be calculated using Eq. (3) [7].

$$\varepsilon_{evap} = \frac{h_{evap,i,a} - h_{evap,o,a}}{h_{evap,i,a} - h_{evap,sat,a}} \tag{1}$$

$$\dot{Q}_{evap} = \dot{m}_{sa,target} \times \left(h_{evap,i,a} - h_{evap,o,a}\right) = \dot{m}_{ref} \times (h_{evap,o,ref} - h_{evap,i,ref}) \tag{2}$$

$$\dot{W}_{comp} = \dot{m}_{ref} \times (h_{comp,o,ref} - h_{comp,i,ref}) \tag{3}$$

3.3. Heat-pump-driven liquid-desiccant system (Proposed system)

In this study, effectiveness-NTU model [8] was adopted for the LD unit modelling. Lithium Chloride (LiCl) solution is used in this study. The overall number of mass transfer unit (NTU_m) is defined by Eq. (4) utilizing the mass flow rate of inlet air ($\dot{m}_{i,a}$), entire packing volume (V_p), effective contact-area per unit packing volume (a), and overall mass transfer coefficient (k_m). Additionally, the heat capacitance ratio (m^*), the ratio of air heat capacitance to solution heat capacitance, is represented by Eq. (5).

$$NTU_m = \frac{k_m \times a \times V_p}{\dot{m}_{i,a}} \tag{4}$$

$$m^* = \frac{\dot{m}_{i,a} \times Cp_{eq,i,a}}{\dot{m}_{i,s} \times Cp_{i,s}} \tag{5}$$

The enthalpy effectiveness of LD unit (ε_h) is defined by Eq. (6). The actual enthalpy of outlet air ($h_{o,a}$) is determined using ε_h, as outlined in Eq. (7). An "effective" heat and mass transfer process characterizes an ideal scenario where the solution conditions remain constant across the whole contact surface with air. The actual humidity ratio of outlet air ($\omega_{o,a}$) can be obtained using Eq. (8) with the "effective" equilibrium humidity ratio of the inlet air ($\omega_{eff,eq,i,a}$). The process of calculating heat pump is similar as the vapour compression system described in Section 3.2. In both systems, R410 refrigerant is used, and economizer and set point reset control are applied during part load operation.

$$\varepsilon_h = \frac{1-e^{-NTU_m \times (1-m^*)}}{1-m^* \times e^{-NTU_m \times (1-m^*)}} \tag{6}$$

$$h_{o,a} = h_{i,a} + \varepsilon_h \times (h_{eq,i,a} - h_{i,a}) \tag{7}$$

$$\omega_{o,a} = \omega_{eff,eq,i,a} + \left(\omega_{i,a} - \omega_{eff,eq,i,a}\right) \times e^{-NTU_m} \tag{8}$$

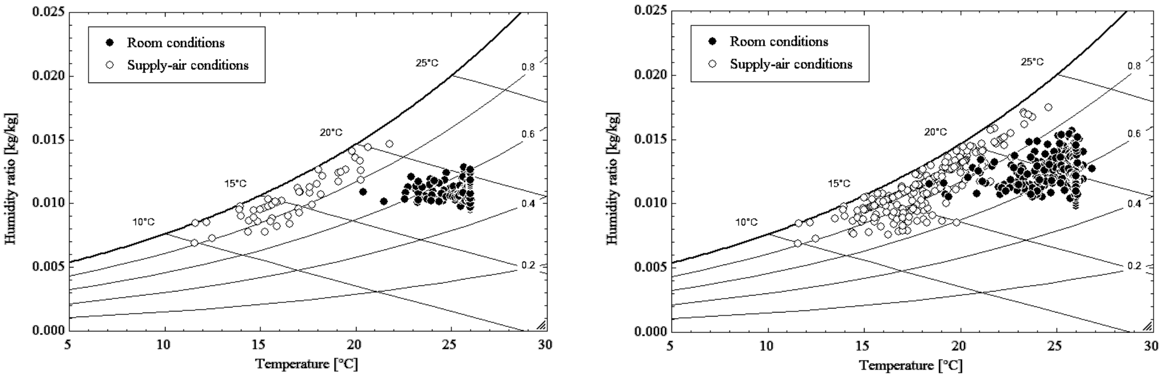
4. Results and discussion

4.1. Building thermal loads profile

Estimations are conducted for the building thermal loads and indoor SHR for all building types including reference building type. With increasing energy efficiency in buildings, the building sensible load steadily decreases, with the building latent load remaining constant across all building types. Consequently, the indoor SHR also experiences a continual decrease. The average indoor SHR sequentially decreases to 0.8, 0.75, 0.71, and 0.64, respectively, for the type of reference building and types 1, 2, and 3 of energy-efficient building.

4.2. Reference system

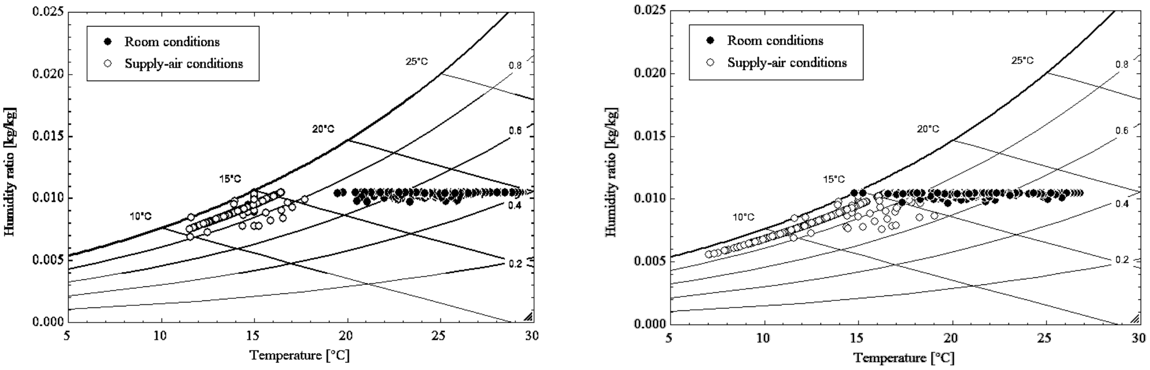
Figure 3 presents the indoor and supply air conditions distribution in the reference system's case A during the summer. As energy-efficiency of buildings increases, the supply-air temperature is increased due to the low sensible load. The supply-air humidity is also increased because the higher the air temperature, the higher the humidity of saturated air. Hence, the latent load remains incompletely eliminated, leading to a gradual rise in indoor humidity with the increasing energy efficiency of buildings. Based on the thermal comfort of ASHRAE standard 55 [9], the frequency of satisfying the thermal comfort zone of the reference building and the energy-efficient building type 3 in case A is 97.8% and 43.3%, respectively.



(a) Reference building (b) Most energy-efficient building (i.e., Type 3)

Figure 3. Indoor and supply-air actual conditions: reference system - case A

Figure 3 presents the indoor and supply air conditions distribution in the reference system's case B during the summer. As energy-efficiency of buildings increases, the supply-air flow rate is decreased due to the low building sensible load, thus the supply-air humidity should instead be decreased to remove the building latent load. Accordingly, the overcooled supply-air temperature is also decreased, leading to a gradual reduction in indoor temperature with the increasing energy efficiency of buildings. The frequency of satisfying the thermal comfort zone of the reference building and the energy-efficient building type 3 in case B is 65.3% and 24.0%, respectively.

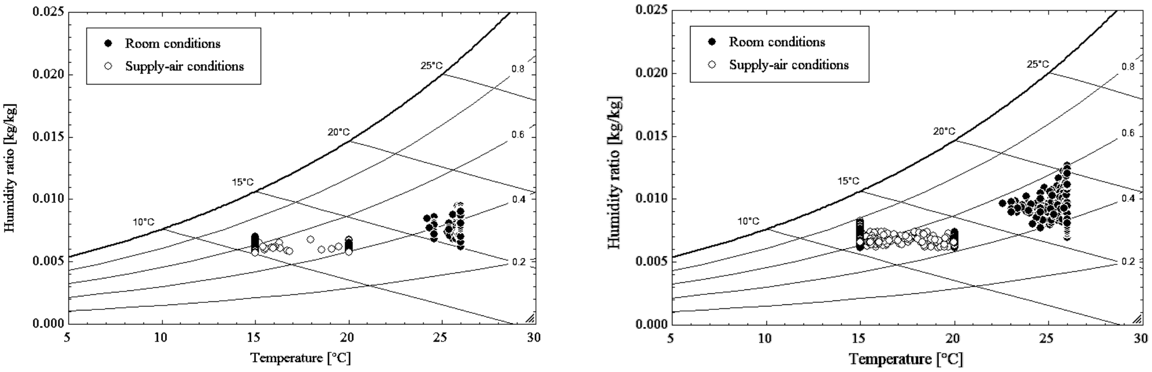


(a) Reference building (b) Most energy-efficient building (i.e., Type 3)

Figure 4. Indoor and supply -air actual conditions: reference system - case B

4.3. *Proposed system*

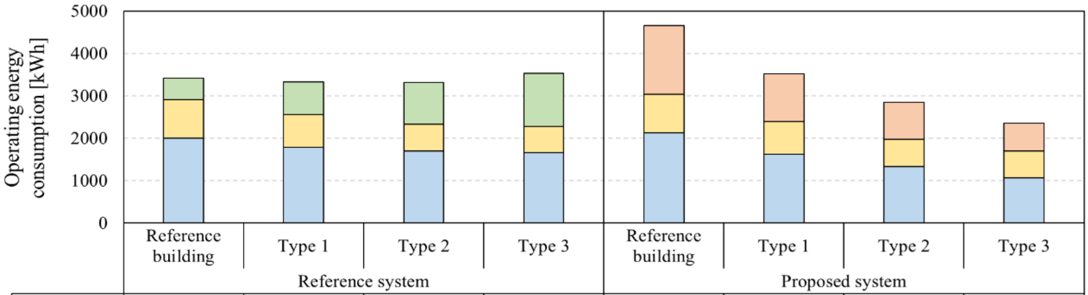
Figure 5 presents the indoor and supply-air conditions distribution in the proposed system during the summer. The proposed system consistently attains the targeted supply-air temperature and humidity, facilitated by the independent control of air temperature and humidity. The supply-air temperature higher than 15 °C is resulted from the economizer and setpoint reset control. Consequently, the proposed system is capable of sustaining room temperature and humidity within the range of 23–26 °C and 0.006–0.013 kg/kg in all buildings. Meanwhile, the room humidity is slightly increased as energy-efficiency of buildings increases due to the difference in NTU_m between buildings during the part load operation. Nevertheless, the proposed system consistently ensures a comfortable indoor environment across all buildings throughout almost all summer operating hours.



(a) Reference building (b) Most energy-efficient building (i.e., Type 3)

Figure 5. Indoor and supply-air actual conditions: proposed system

For comparable thermal comfort satisfaction to the proposed system, the reference system's case B is enhanced with a reheat-coil to warm the subcooled air. Then, the operating energy consumptions between the two systems are compared as energy-efficiency of buildings increases, as shown in Fig. 6. In the reference system, as energy-efficiency of buildings increases, compressor energy consumption cannot be decreased significantly to meet the target humidity, but the reheat-coil energy consumption is increased to meet the target temperature. Contrastingly, in the proposed system, the operating energy consumptions is gradually decreased as energy-efficiency of buildings increases. Finally, in the most energy efficient building type, 33.2% saving in operational energy use compared to the reference system was derived from the proposed system.



	Reference building	Type 1	Type 2	Type 3	Reference building	Type 1	Type 2	Type 3
🟩 Reheat coil	504	779	981	1244	0	0	0	0
🟧 Pumps	0	0	0	0	1626	1125	875	667
🟨 Fans	904	769	641	625	910	770	641	625
🟦 Compressor	2001	1781	1693	1658	2124	1624	1330	1065

Figure 6. Operating energy consumption comparison between reference and proposed systems

5. Conclusion

This study estimates building thermal loads for both the reference building type and energy-efficient building types with high latent load to model building trend. Examining the impact of increasing building energy efficiency, this study investigates the variations in indoor thermal comfort satisfaction and operating energy for both the reference system (vapour compression system) and the proposed system. The reference system can only maintain thermal comfort for a limited time during summer operating hours in high energy-efficient buildings (i.e., 43.3% in case A and 24% in case B). However, the proposed system, employing decoupled control, ensures thermal comfort across all building types throughout nearly all summer operating hours. The proposed system attains nearly 100% thermal comfort satisfaction while concurrently achieving up to a 33.2% reduction in operating energy consumption. Hence, the proposed system, utilizing decoupled control, is deemed more suitable with increasing energy efficiency in buildings.

Acknowledgments

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