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Optimized control strategies for an integrated heat pump environment control unit with outdoor air in different climate zones

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Abstract

An integrated heat pump environment control unit with outdoor air (IHPECU), as a key environmental control device for nearly zero-energy buildings (NZEBs), can achieve multiple functions such as heating, cooling, and ventilation; however, its complex operational mode switching often leads to high energy consumption. Therefore, the present study proposes and evaluates optimized control strategies tailored to the climatic characteristics of different regions in China, aiming to enhance the operational energy efficiency of IHPECUs. Based on the TRNSYS dynamic simulation platform, a coupled model of the building and the unit was established, with a key focus on analyzing demand-controlled outdoor air strategies based on indoor CO_2 concentration during the heating season and free cooling utilization strategies based on the electronic enthalpy method during the cooling season. The results show that: during the heating season, adopting CO_2 demand-controlled outdoor air strategies, while ensuring indoor air quality, can reduce the total system electricity consumption in cities such as Harbin, Beijing, and Wuhan by over 10%; during the cooling season, optimizing electronic enthalpy control parameters and outdoor air volume for natural cooling source utilization can reduce total energy consumption by 2%-5% in severe cold and cold regions. Furthermore, in severe cold regions, proper window opening behavior can additionally reduce cooling season energy consumption by approximately 16.8%. These findings offer theoretical insights and quantitative support for the energy-efficient design and intelligent control of IHPECUs across diverse climate zones and demonstrate strong potential for engineering application.

Keywords: integrated heat pump environment control unit; DCV; free cooling; TRNSYS; energy efficiency; climate zones;

1. Introduction

In the context of the "dual carbon" strategy, nearly zero energy buildings (NZEBs) impose stringent demands on building energy performance. Integrated Heat Pump Environment Control Units with Outdoor Air (IHPECUs), which combine heat pump functions with outdoor air treatment, are a promising solution for NZEBs due to their high integration and multifunctionality [1–2].

Despite these advantages, the energy-saving potential of IHPECUs is highly dependent on their control strategies, which must adapt to diverse climatic conditions. However, systematic studies on such tailored strategies, particularly for residential applications across China's major climate zones, are still lacking.

However, the high degree of integration in IHPECUs introduces complexity in control logic. Poorly designed strategies can prevent the system from achieving its intended efficiency. This challenge is exacerbated by China's diverse climate zones, which require tailored control strategies [3].

Key energy-saving strategies include demand-controlled ventilation (DCV) based on CO_2 levels and the use of free cooling. While these methods are known in [4], systematic studies are lacking for residential

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IHPECUs across China's varied climate zones, especially considering the coupled operation of multiple functions.

This study uses the TRNSYS 18 platform to model an IHPECU in a nearly zero energy residential building across four typical Chinese climate zones. We propose and evaluate a CO_2-based DCV strategy for heating and an optimized electronic enthalpy-based free cooling strategy for cooling. The goal is to provide practical guidance for energy-efficient design and intelligent control in different regions.

2. Methods

A coupled simulation model was developed using TRNSYS 18, integrating building loads, system operation, and control strategies.

2.1. Building and system model

A representative 122 m^2 nearly zero energy residential building (GB/T 51350-2019) was modeled. Four representative metropolitan cities were selected: Harbin (severe cold), Beijing (cold), Wuhan (hot summer and cold winter), and Guangzhou (hot summer and warm winter).

The IHPECU model simulates a multifunctional unit integrating ventilation, air purification, and heat pump cooling/heating. The system's operating modes are summarized in Table 1, and the key performance parameters, which vary by climate zone, are shown in Table 2.

Table 1. Operating modes of the IHPECU

Operating mode	Season	Heat pump status	Outdoor air status	Outdoor air volume(m^3/h)
Outdoor Air Mode	Winter/Summer	Off	On	120
Bypass Mode	Spring/Summer/Fall	Off	On	120-960
Mixed Air Mode	Summer/Winter	On	On	120
Recirculation Mode	Winter/Summer	On	Off	0

Table 2. Performance parameters of IHPECU for representative cities in different climate zones

City	Heating capacity/W	Rated heating COP	Cooling capacity/W	Rated cooling EER
Harbin	5036	3.32	5409	3.69
Beijing	1918	3.32	2059	3.69
Wuhan	2655	3.32	2850	3.69
Guangzhou	2336	3.32	2508	3.69

2.2. IHPECU system

The IHPECU is modelled in TRNSYS (version 18) as a set of coupled sub-modules representing the main system functions. The heat pump is simulated using Type 119, while the supply/exhaust fans are modelled with a constant specific fan power of 0.273 W/(m^3/h). Total heat recovery is represented using Type 667. The key modelling assumption is that the heat-recovery operation is governed by a season-dependent control logic: during the heating season, total heat recovery is continuously enabled for the outdoor air stream to reduce heating demand. During the cooling season, total heat recovery is enabled only when the exhaust-air enthalpy is at least 0.4 kJ/kg lower than the outdoor-air enthalpy, to ensure net cooling benefit while accounting for the potential temperature rise introduced by the fans.

2.3. Control strategies

2.3.1. Outdoor air control strategy during the heating season

Two strategies were compared: Conventional Strategy: A constant minimum outdoor air volume of 120 m^3/h is supplied during occupancy when heating is required. Demand-Controlled Strategy: The outdoor air supply (120 m^3/h) is activated only when the indoor CO_2 concentration exceeds a predefined threshold. Otherwise, the system operates in recirculation mode. The hourly variation in indoor CO_2 concentration is calculated using a mass balance equation:

$$C_i = \frac{C_{i-1} \cdot V + N \cdot V_{CO_2} \cdot 1000000 \cdot t + C_1 \cdot Q_{xf} \cdot t}{V + Q_{xf} \cdot t} \quad (1)$$

Where:

C_i is the indoor CO_2 concentration at time step i;

C_{i-1} is the indoor CO_2 concentration at time step $i-1$;

V is the room volume (m^3);

N is the number of occupants;

V_{CO_2} is the CO_2 generation rate per person (m^3/h, set to 0.018m^3/h in this study);

t is the time step (h, set to 0.125 h in this study);

C_1 is the outdoor CO_2 concentration (ppm, set to 420 ppm in this study [5]);

Q_{xf} is the outdoor air volume (m^3/h).

2.3.2. Outdoor air control strategy during the cooling season

The free-cooling strategy is based on the electronic enthalpy method proposed in [6–7]. The control logic is evaluated every 5 min. At each control step, outdoor air (OA) conditions are checked against an allowable region defined by fixed thresholds, i.e., T_{oa} < 26 °C and h_{oa} < 49.79 kJ/kg [8–9]. The OA enthalpy (h_{oa}) is calculated from dry-bulb temperature and relative humidity using the TRNSYS psychrometric model under a constant-pressure assumption. To prevent frequent mode switching, a ±1 °C hysteresis band is applied around the temperature threshold.

If the OA conditions are unsuitable, free cooling is disabled; the heat pump is activated to meet the cooling demand, while the OA flow rate is maintained at the minimum ventilation rate (120 m^3/h). If the OA conditions are suitable, the system prioritizes free cooling by supplying a variable OA flow rate up to 960 m^3/h. If free cooling was active in the previous control step but the cooling demand persists, the system supplies the maximum OA flow rate and enables the heat pump to cover the remaining load. Here, "cooling demand persists" is identified when either the zone temperature or the zone humidity condition does not satisfy the corresponding control requirements (i.e., T_{zone} and the humidity metric, such as RH_{zone}, are checked, and a violation of either criterion triggers supplemental cooling).

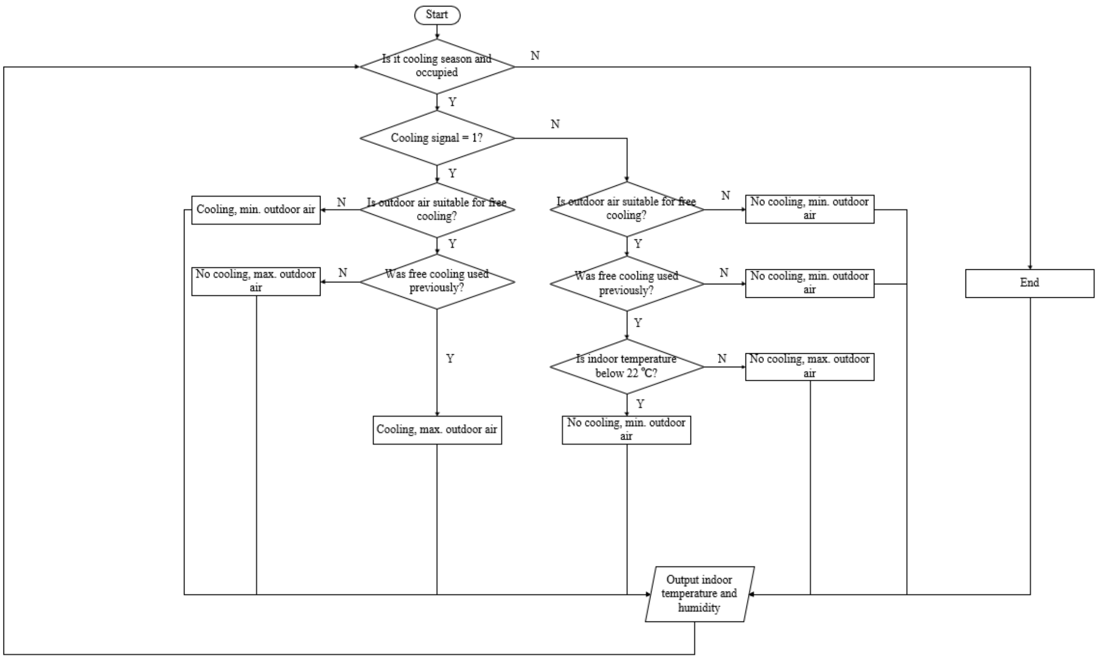

Figure 1. Outdoor air control strategy during the cooling season.

2.3.3. Window opening behavior patterns

The impact of natural ventilation from occupant window-opening was also analyzed. Ventilation rates are calculated using a model that incorporates both stack and wind pressure effects based on a typical schedule and model from [10].

Table 3. Window opening schedule

Room	Window opening duration
Bedroom (Whole Week)	7:00-9:00; 17:00-19:00
Living Room (Weekdays)	7:00-9:00; 17:00-19:00
Living Room (Weekends)	8:00-16:00

3. Results and discussion

3.1. Outdoor air control strategies for the heating season

The impact of different CO_2 control thresholds on system energy consumption and indoor air quality in Beijing was analyzed (Figure 2.). As the threshold increases from 500 ppm to 1000 ppm, the electricity consumption of the heat pump and fans declines steadily due to reduced outdoor air intake.

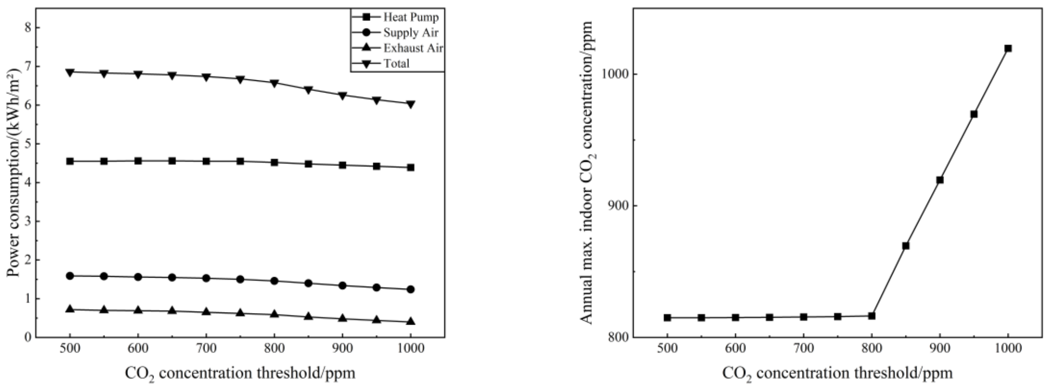

Figure 2. (a) Variation of heating season power consumption with CO_2 threshold; (b) Variation of maximum indoor CO_2 concentration with CO_2 threshold.

At 950 ppm, the system maintains the maximum hourly average indoor CO_2 concentration below the 1000 ppm standard while reducing total electricity consumption by up to 10.5% compared to the conventional strategy. This demonstrates an optimal balance between energy savings and air quality.

This DCV strategy showed significant regional variation. In Harbin (severe cold), total savings reached 11.82%. In Wuhan (hot summer and cold winter), the percentage savings were similar (approx. 11.8%), but the absolute savings were smaller due to lower heating demand. In Guangzhou (hot summer and warm winter), the heating demand is minimal, and the DCV strategy offered negligible energy-saving potential.

Therefore, CO_2 sensor-based DCV is strongly recommended for severe cold, cold, and hot summer–cold winter regions.

3.2. Outdoor air control strategies for the cooling season

A key finding was that using a high outdoor air volume (e.g., 960 m^3/h) for free cooling increased total energy consumption. The significant rise in fan energy outweighed the savings from the heat pump.

Therefore, the outdoor airflow rate for free cooling was optimized using a parametric sweep. For each climate, the outdoor airflow rate was varied from 120 to 960 m^3/h with an increment of 120 m^3/h (i.e., 120, 240, 360, …, 960 m^3/h). For each candidate airflow rate, the cooling-season simulation was repeated and the objective function was defined as the total cooling-season electricity consumption. The airflow rate that minimized this objective was selected as the optimum, subject to the constraint that the indoor parameters (temperature and humidity) satisfy the control requirements. Using this procedure, the minimum total cooling-season electricity consumption occurred at 240 m^3/h in Harbin and Beijing.

As shown in Figure 3, the optimal airflow rate varies by climate. In Harbin, the optimal rate was 240 m^3/h, achieving a 4.3% reduction in total cooling-season electricity consumption. In Beijing, the optimal rate was also 240 m^3/h, yielding a 2.0% saving. For Wuhan and Guangzhou, the hot and humid climate limits free cooling potential, and the energy savings were minimal (0.7% and 0.01%, respectively).

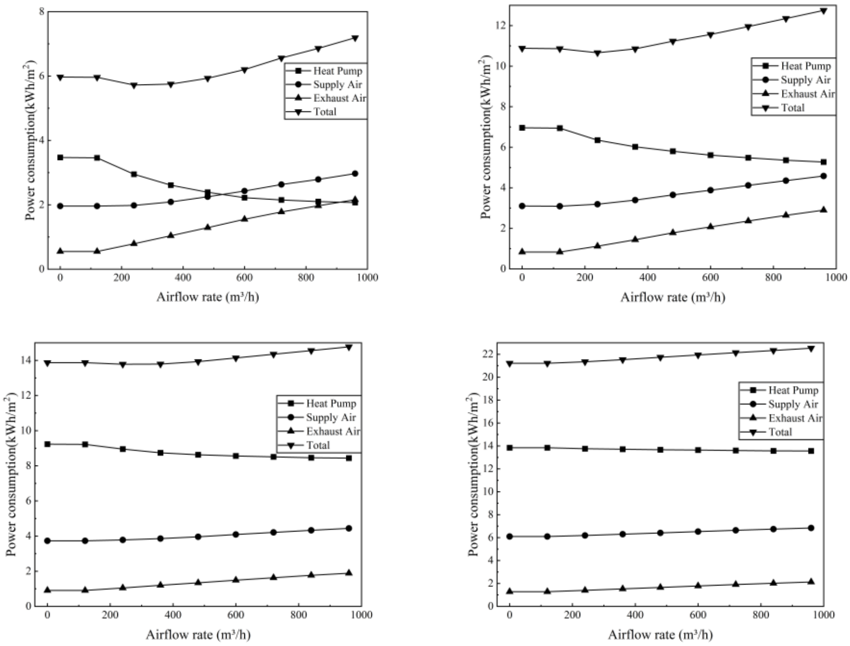

Figure 3. (a) Variation of cooling season power consumption with outdoor airflow rate in Harbin; (b) Variation of cooling season power consumption with outdoor airflow rate in Beijing; (c) Variation of cooling season power consumption with outdoor airflow rate in Wuhan; (d) Variation of cooling season power consumption with outdoor airflow rate in Guangzhou.

This indicates that free cooling must be carefully optimized. In Harbin and Beijing, an optimized flow rate (240 m^3/h) with appropriate enthalpy settings is beneficial. In hot and humid regions, mechanically driven free cooling offers little benefit.

3.3. Impact of window opening behavior on cooling

Window opening behavior also shows strong regional variation. In severe cold (Harbin) and cold (Beijing) regions, opening windows during favorable conditions significantly reduced cooling energy consumption by 16.8% and 6.3%, respectively. Conversely, in hot summer–cold winter (Wuhan) and hot summer–warm winter (Guangzhou) regions, window opening increased energy use by introducing hot and humid outdoor air, adding to the cooling load.

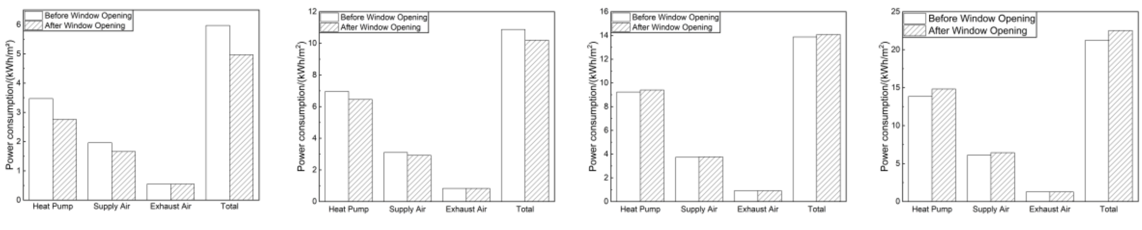

Figure 4. (a) Variation of cooling season power consumption in Harbin before and after window opening; (b) Variation of cooling season power consumption in Beijing before and after window opening; (c) Variation of cooling season power consumption in Wuhan before and after window opening; (d) Variation of cooling season power consumption in Guangzhou before and after window opening.

4. Conclusion

This study evaluated optimized control strategies for IHPECUs in NZEBs across four representative Chinese climate zones. The main conclusions are:

1. During the heating season, CO_2-based demand-controlled ventilation (with a 950 ppm threshold) is highly effective, reducing total system electricity consumption by over 10% in severe cold, cold, and hot summer–cold winter regions while maintaining IAQ standards.
2. During the cooling season, free cooling must be carefully applied. High airflow rates are counterproductive. An optimized, lower airflow rate (e.g., 240 m^3/h) can achieve 2%–5% energy savings in severe cold and cold regions, but the strategy is ineffective in hot and humid regions.
3. Window opening behavior has a major, regionally-dependent impact. It provides significant savings (up to 16.8%) in colder regions but increases energy consumption in hot-humid regions in cooling season. Intelligent control systems should account for this behavior.

These findings provide practical, quantitative guidance for the energy-efficient design and intelligent control of IHPECUs tailored to specific climate zones.

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