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Dynamic Operating Characteristics of Air-Source Heat Pump System in Public Buildings#

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ABSTRACT

Air-source heat pump, as an efficient and clean heating methods, have significant potential in the electrification of energy terminals within public buildings. This study delves into the suitability of air-source heat pumps for use in public buildings located in severe cold, cold, and hot-summer and cold-winter regions. Considering the performance adjustments required under defrosting and low-temperature conditions, the heating system is constructed using the TRNSYS software. The hourly operational characteristics and dynamic control strategies of heat pump clusters are simulated and analyzed across various climate regions and public building types. The results reveal a positive correlation between the COP of heat pump systems and outdoor temperature, with COP values of 1.64 (Harbin), 2.57 (Beijing), and 2.81 (Shanghai), alongside average operation numbers of 16.6 (Harbin), 7.5 (Beijing), and 2.6 (Shanghai). Notably, the COP remains unaffected by the type of public building. This study aims to offer valuable insights for the application and regulation of air-source heat pumps in public buildings.

Keywords: air-source heat pump, public building, heating, coefficient of performance, control strategy

NONMENCLATURE

Abbreviations	
COP	*Coefficient of performance*
Symbols	
a	*Fitting coefficients*
t	*Temperature*
K	*Correction coefficient of heat produced*

1. INTRODUCTION

According to the statistics from Tsinghua University building Energy Conservation research Center, the total energy consumption of buildings in China accounts for approximately 21% of the total energy consumption, with public building energy consumption comprising 34.8% of the total building operational energy consumption. The electrification of energy terminals in buildings is an important measure to achieve the "dual-carbon" goals, especially for public buildings where energy-saving retrofitting of heating systems is crucial [1].

Air-source heat pump, as an efficient and clean heating method, have been widely adopted in hot-summer and cold-winter zones, as well as in some low-temperature regions [2, 3]. With the gradual maturity of ultra-low temperature heat pump technology, heat pumps can operate even at outdoor temperatures as low as -25°C, making them suitable for use in low-temperature regions such as Northeast China. Ji et al. [4] conducted the economic calculations and analysis of low-temperature air source heat pumps in a large office building in Zhangjiakou City. The results indicated that the heating costs for buildings using air source heat pump heating systems are more economical and energy-efficient compared to new centralized heating systems. Currently, researchers predominantly focus on the operational characteristics of air-source heat pumps in residential and small-scale buildings [5,6], with insufficient studies on the parallel operation characteristics of heat pump clusters, which are necessary for guiding the design of heat pump systems in commercial buildings. Additionally, there exist significant differences in the operational characteristics of heat pumps across different climatic regions.

Therefore, this study focuses on the adaptability of air-source heat pumps in public buildings located in severe cold, cold, hot-summer and cold-winter zones. Considering the performance adjustments of air-source heat pumps under defrosting and low-temperature conditions, the heating systems are constructed using

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the TRNSYS software. Then, the hourly operation characteristics and dynamic control strategies of heat pump clusters are simulated and analyzed in different climate zones and commercial buildings. The findings are expected to provide guidance for the application and promotion of heat pump systems in public buildings.

2. MODEL AND METHODS

2.1 Air source heat pump system

The air source heat pump heating system constructed on the TRNSYS platform in this study is illustrated in Fig. 1. The system consists of an air source heat pump collection loop and a heating/cooling loop, including components such as the air source heat pump, circulating water pump, buffer tank, heating terminals, thermal pipes, and control feedback modules.

Divide your article into clearly defined and numbered sections. Subsections should be numbered 1.

$$K_1 = a_1 + a_2 t_a + a_3 t_{out,a} + a_4 {t_a}^2 + a_5 t_a t_{out,a} + a_6 {t_{out,a}}^2 \quad (1)$$

where K_1 denotes the correction coefficient of heat produced by heat pump under low temperature condition; a_1 ~ a_6 represent the fitting coefficients; t_a denotes the outdoor temperature, ℃; $t_{out,a}$ denotes the condenser outlet water temperature, ℃.

b) Defrosting correction for air source heat pump heating capacity: Defrosting of an air source heat pump typically involves the reverse cycle of the heating cycle, which can lead to a decrease in the variable condition heating capacity Q_h of the heat pump. When ta is below 7°C and above 7°C, the defrosting heating capacity correction coefficients for the air source heat pump [7] are calculated by Equations (2) and (3), respectively.

$$K_2 = 1 + 0.0027(t_a - 7) - 0.1801\exp(-{t_a}^2/5) \quad (2)$$

$$K_2 = 1 - 0.1801\exp(-{t_a}^2/5) \quad (3)$$

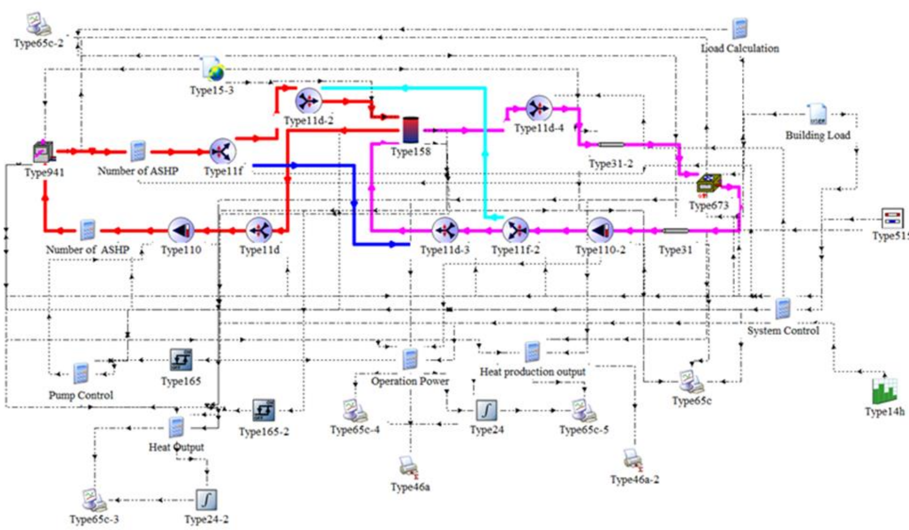


Fig. 1 The air source heat pump heating system.

2.2 Correction method for low temperature and defrosting of air source heat pumps

Regarding the analysis of the variable condition performance of air source heat pumps, this paper adopts a performance fitting equation and considers corrections for low temperature and defrosting on the heat pump heating capacity decay.

a) Low temperature correction for air source heat pump heating capacity: The heating capacity Q_n of air-source heat pump under variable conditions increases with the outdoor temperature t_a, and decreases with the increase of outlet temperature tout, a of the condenser water. The fitting equation for the variable condition Q correction coefficient surface is as following:

where K_2 is the correction coefficient of heat produced by heat pump under defrosting condition.

2.3 Section of material and methods

Provide sufficient detail to allow the work to be reproduced. Methods already published should be indicated by a reference: only relevant modifications should be described.

2.4 Section of of air source heat pumps

Considering the magnitudes of the building loads in severely cold, cold, and hot-summer and cold-winter zones, the variable frequency heat pump from Midea, with the model of LSQWRF160/R2(D)T, is chosen. The performance parameters of heat pump are shown in

Table 1. Based on the sample data provided by the manufacturer for heating capacity and input power under variable conditions, the correction coefficients for low temperature and defrosting are determined with the equations (1)-(3).

Table 1 The performance parameters of air-source heat pump

Nominal heating mode	Nominal heating capacity	kW	110
	Nominal Heating power	kW	41.98
	Water flow rate	m^3/h	18.90
	COP		2.62
Low-temperature heating mode	Low-temperature heating capacity	kW	90
	Low-temperature heating power	kW	50.1
	Water flow rate	m^3/h	18.6
	COP		1.8
Rated heating mode	Rated heating capacity	kW	165
	Rated heating power	kW	44.35
	Water flow rate	m^3/h	28.5
	COP		3.72

3. MATERIAL AND METHODS

3.1 Section of result Operation characteristics of air-source heat pump in different climate zones

Using commercial buildings as examples, the typical daily operational performance of air-source heat pump systems in Harbin, Beijing, and Shanghai were compared and analyzed. The selection of typical days is based on outdoor temperature, with the coldest and hottest days selected during the periods when the heat pump system operates. According to design standards, the working hours for commercial buildings are from 8:00 to 21:00, and a temperature of 5°C needs to be maintained during non-working hours. Therefore, the heat pump heating system were dynamically adjusted based on the building heat load for 24 hours. Moreover, there are variations in the standards for heat pump outlet water temperature across the three regions. Specifically, during heating operations, the minimum outlet water temperature was set at 38°C for Harbin, 41°C for Beijing, and 45°C for Shanghai.

3.1.1 Severe cold area-Harbin

Figure 2 illustrates the operational characteristics of the air-source heat pump system on the coldest day in Harbin. The daily average temperature and average heat load are -23.56°C and 1099.65 kW, respectively, with average number of heat pump and COP at 16.6 and 1.64, respectively. The building load at night is maintained at a relatively low level, with the maximum load occurring at the beginning of the working hours. As the outdoor temperature rises, the daytime load significantly decreases, stabilizing between 12:00-18:00. The variation in the number of heat pump follows a similar trend to that of the heat load. In addition, the COP variation of the heat pump system resembles the trend of outdoor temperature, reaching its maximum when the outdoor temperature peaks.

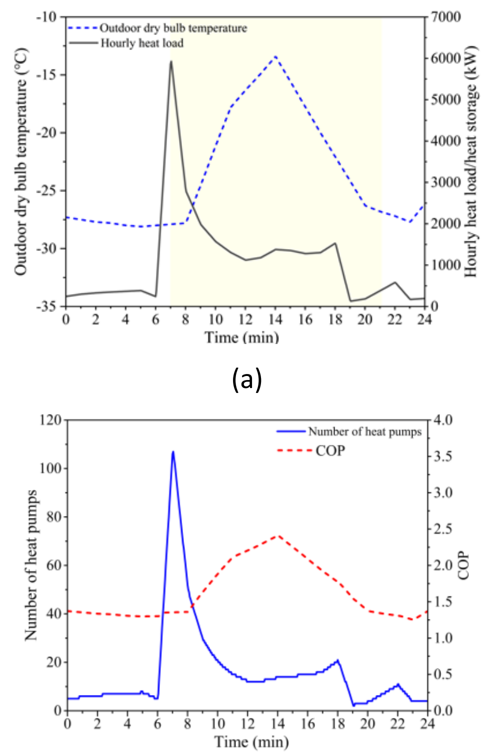
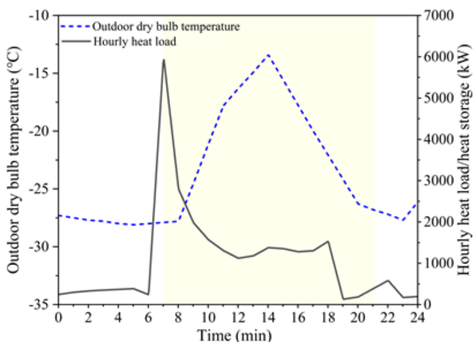


Fig. 2 (a) Hourly variations in outdoor dry bulb temperature and heat load; (b) Hourly variations in the number of heat pump and COP.

3.1.2 Cold area-Beijing

As shown in Fig. 3, the daily average temperature and average heat load on the coldest day in Beijing are -7.7°C and 764.18 kW, respectively. On average, 7.5 heat pumps are in operation, boasting an average COP of 2.57. The heat load at night is relatively small, and the heating demand can be met by relying on the heat storage in the tank from the previous day. Thus, the heat pump does not need to operate during non-working hours. During the system operation, the number of heat pump starting up aligns with the trend of heat load variation, and the COP of heat pump changes relatively smoothly.



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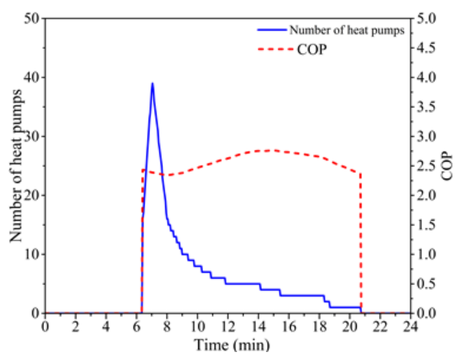

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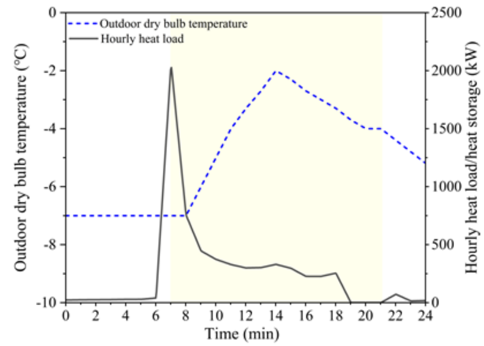
Fig. 3 (a) Hourly variations in outdoor dry bulb temperature and heat load; (b) Hourly variations in the number of heat pump and COP.

3.1.3 Hot-summer and cold-winter zone-Shanghai

The operational characteristics of air-source heat pump system on the coldest day in Shanghai are depicted in Fig. 4. The daily average temperature and average heat load are -4.57°C and 235.91 kW, respectively. The average number of heat pump is 2.6, with a corresponding average COP of 2.81. Heat load at night requires one heat pump to operate from 21:00 to 4:00. The number of heat pumps in operation during working hours fluctuates with the heat load. In contrast, there is minimal variation in COP, with the overall COP during working hours higher than that of the heat pump system during the night, primarily due to lower nighttime temperatures.



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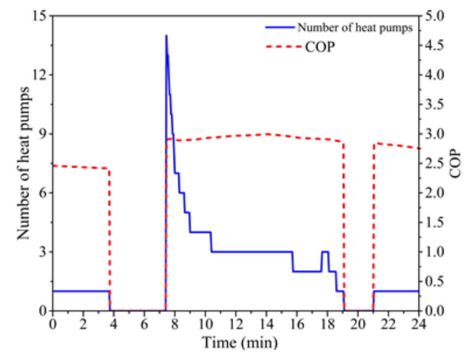

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Fig. 4 (a) Hourly variations in outdoor dry bulb temperature and heat load; (b) Hourly variations in the number of heat pump and COP.

3.2 Operation characteristics of air-source heat pump in different public building

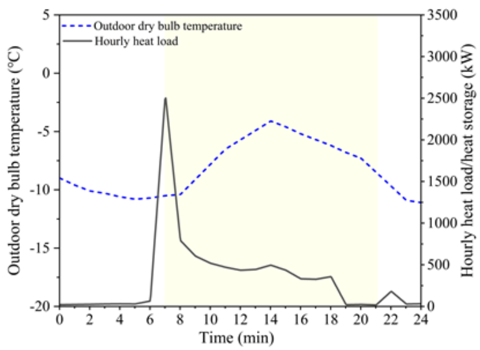
To explore the influence of public building types on the operational characteristics of heat pumps, the operation characteristics of air-source heat pump on the moderate-temperature day in Harbin are analyzed for commercial, hotel, and office buildings. The selection of moderate temperature day is based on the average temperature of the hottest and coldest days.

3.2.1 Commercial building

The typical daily operation results of air-source heat pump for commercial buildings are shown in Fig. 5. On the moderate temperature day, the heat pump system in Harbin operates almost all day. With the increase in thermal storage capacity of the tank, the heating demand can be met without the need for the heat pump system to operate from 6:30 to 7:10. The COP of heat pumps in commercial buildings varies minimally.

3.2.2 Hotel building

The operational hours for hotel buildings are from 1:00 to 24:00, and a temperature of 22°C needs to be maintained during non-working hours. Therefore, the heat pump heating system adjusts dynamically based on the building heat load for 24 hours. Fig. 6 depicts the typical daily operational performance curves of air source heat pump systems in office buildings. Compared to the other two building types, the dynamic control of heat pumps in hotel buildings is more frequent, primarily due to the significant hourly fluctuations in its heat load. Additionally, the heat stored in the tank can meet the heating demand for partial periods, resulting in the heat pump systems being shut down for 1 hours.



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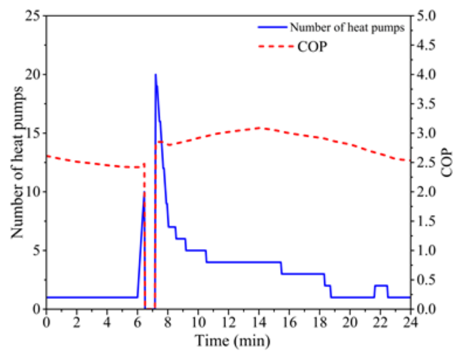

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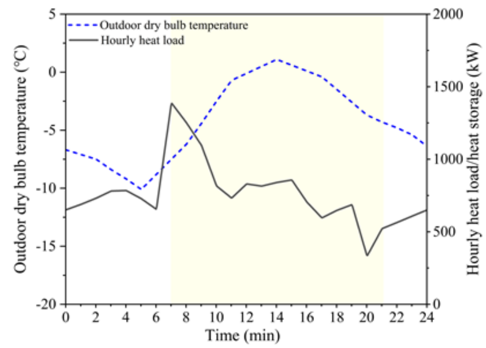
Fig. 5 (a) Hourly variations in outdoor dry bulb temperature and heat load; (b) Hourly variations in the number of heat pump and COP.

3.2.3 Office building

The operational hours for office buildings are from 7:00 to 18:00, and the indoor temperature of 5°C needs to be maintained during non-working hours. Therefore, the heat pump heating system is adjusted dynamically based on the building heat load for 24 hours. Fig. 7 depicts the typical daily operational performance of air-source heat pump systems in the office building. The hourly results indicate that the office building has a small heat load. The thermal storage tank can accommodate a portion of heat load, resulting in reduced heat pump number and shorter operating times, with minimal fluctuations in COP.

The operation characteristics of air-source heat pump system in the public building for Harbin are listed in Table 2. When the outdoor temperature is similar, the deviations of COP among the three building types within the same region are minimal. However, variations in heat load across different regions lead to differences in the number of heat pump. Therefore, it can be considered that the influence of building type on the COP of air-source heat pump system can be ignored, while the dynamic control strategy of the heat pump system is influenced by both building type and outdoor temperature.



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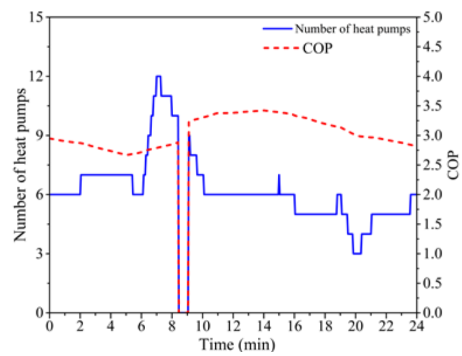

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Fig. 6 (a) Hourly variations in outdoor dry bulb temperature and heat load; (b) Hourly variations in the number of heat pump and COP.

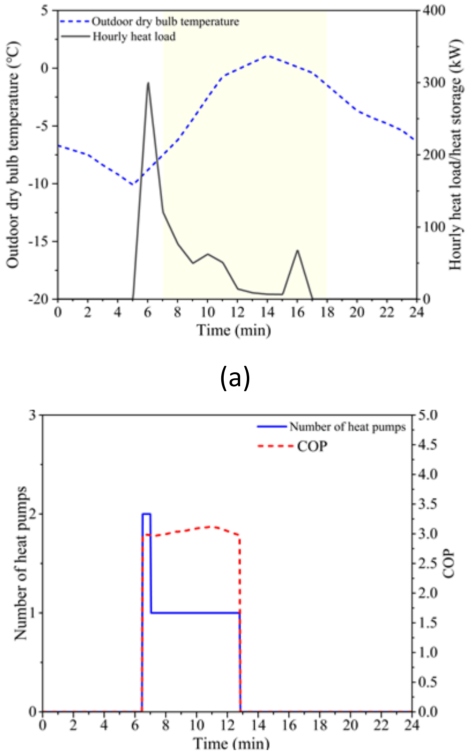

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Fig. 7 (a) Hourly variations in outdoor dry bulb temperature and heat load; (b) Hourly variations in the number of heat pump and COP.

Table 2 Operation characteristics of air-source heat pump system in different public buildings

Building types	**Commercial**	**Hotel**	**Office**
Average outdoor temperature/°C	-8.1	-4.13	-3.43
Heat load/ kW	294.42	752.02	64.7
Number of heat pump	3.0	6.2	1.1
COP	2.77	3.06	3.04

4. CONCLUSIONS

This study developed a TRNSYS model of air-source heat pump heating system to explore the typical daily operational characteristics under different climatic regions and public commercial building types. The simulation results demonstrate a positive correlation between the COP of heat pump systems and outdoor temperature. Taking commercial buildings as an example, the COP of heat pump systems are 1.64 (Harbin), 2.57 (Beijing), and 2.81 (Shanghai), respectively, with average heat pump operation number of 16.6 (Harbin), 7.5 (Beijing), and 2.6 (Shanghai). Additionally, the correlation between the average COP of heat pump systems and commercial building types is relatively small, with hourly variations influenced by changes in building loads.

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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.

REFERENCE

[1] Chen H, Qi S, Tan X. Decomposition and prediction of China's carbon emission intensity towards carbon neutrality: From perspectives of national, regional and sectoral level[J]. Science of The Total Environment, 2022, 825:153839.

[2] Huang S, Yu H, Zhang M, Qu H, Wang L, Zhang C, Yuan Y, Zhang X. Advances, challenges and outlooks in frost-free air-source heat pumps: A comprehensive review from materials, components to systems. Applied thermal engineering, 2023; 234. 121163.

[3] Ma S, Liu W, Dong J, Liu J, Wang Z. Indoor thermal environment in a rural dwelling heated by air-source heat pump air-conditioner. Sustainable energy technologies and assessments. 2022; 51: 101948

[4] Ji S, Liu Y, Xu H X, Yang Y W, Chen J, Xue K L, Sun Y. Application and Analysis of Air-Source Heat Pump Heat Supply System in Cold Areas. Journal of Physics: Conference Series, 2022; 2186(1): 012017.

[5] Kelly N, Cockroft J. Analysis of retrofit air source heat pump performance: results from detailed simulations and comparison to field trial data, Energy and Buildings, 2011; 43: 239-245.

[6] Minglu Q, Tianrui L, Shiming D, Yanan F, Zhao L. Improving defrosting performance of cascade air source heat pump using thermal energy storage based reverse cycle defrosting method. Applied Thermal Engineering, 2017; 121: 728-736

[7] Loïc Cabrol, Rowley P. Towards low carbon homes -A simulation analysis of building-integrated air-source heat pump systems. Energy & Buildings, 2012; 43(1):127-136.