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Study on Regional Suitability of Heat-Source Tower Heat Pump

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Abstract. To address the regional applicability of heat-source tower heat pumps (HSTHPs), a mathematical model of HSTHPs was established and experimentally verified. In different thermal zones, the seasonal operation characteristics of HSTHPs were investigated in winter and summer conditions. The results showed that, the heating seasonal performance factor (HSPF) value of HSTHPs in cold zone is the lowest, but it can reach 2.40 in the winter, and the HSPF values of HSTHPs in hot-summer and warm-winter (HSWW) zone A, hot-summer and cold-winter (HSCW) zone and mild zone are all greater than 2.70. The seasonal energy efficiency ratio (SEER) values for the HSTHPs in four thermal zones are above 4.70 in summer. Except for the severe cold zone, HSTHPs have good prospects in the other four thermal zones, particularly in mild zone, with a high HSPF value of 2.77 and a high SEER value of 5.43, respectively.

Keywords. Regional suitability, seasonal energy efficiency, heat-source tower heat pump

1. Introduction

With regard to building air conditioning, the cooling and heating source technologies include air-source heat pumps (ASHPs), ground-source heat pumps (GSHPs) and chillers & boilers (CBs). Chillers are efficient in the summer, but they are dormant in the winter and must be equipped with boilers to provide the heating requirement, resulting in pollution [1]. ASHPs are commonly used because to their ease of installation and maintenance, although their performance is more highly influenced by outdoor air factors, particularly the frost problem in winter. Frost on the surface of evaporator fin increases heat transfer resistance, greatly decreasing ASHP performance [2]. Furthermore, ASHPs have a poorer energy efficiency in the summer than chillers. GSHPs are effective both in summer and winter, however they are limited by geographic constraints, soil environment, and high initial cost [3]. HSTHPs, a new cooling and heating source scheme, were proposed to alleviate the aforementioned difficulties. Furthermore, HSTHPs solve the frosting problem essentially, and are easy to install without being constrained by topographic conditions [4].

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In recent years, research in the field of heat source towers has focused on the economic and regional applicability problem. Li et al. [5] conducted an economic analysis of HSTHPs and found that compared with ASHPs, HSTHPs have the advantages of low initial investment, low annual comprehensive operating cost, and stable operation and high efficiency of comprehensive energy utilization, which are more suitable for application in low temperature and high moisture regions in winter. Xu et al. [6] observed the operation of HSTHPs in Tianjin, China, during the heating season, and found that the HSPF was 2.35. Some researchers [7-9] developed mathematical models for HSTHPs and ASHPs and discovered that HSTHPs have a higher energy efficiency than ASHPs. Xie et al. [9] also compared HSTHPs and CBs in terms of technical and economic performance. The annual operating performance factor of HSTHPs was found to be 10-23 percent higher than that of CBs in HSCW zone, as well as in cold zone. Huang et al. [10] investigated the global applicability of HSTHPs, dividing them into three categories: warm zone, cool zone, and mixed zone. They discovered that HSTHPs functioned better in the warm and mixed areas than in the cool area.

The majority of the above-mentioned studies on the applicability of HSTHPs are conducted with experiments or theoretical simulations in a specific city or thermal zone in China, with only a few studies on the applicability of HSTHPs in various thermal zones. Therefore, it is necessary to propose a method for evaluating the performance of HSTHPs and carry out a study on the regional applicability of HSTHPs in different thermal zones in China.

In this study, a mathematical model of HSTHPs is developed and empirically verified, and the seasonal operation features of HSTHPs in winter and summer in key Chinese cities are investigated, providing theoretical direction for HSTHPs promotion.

2. HSTHPs Model

2.1. Principle of HSTHPs

The HSTHPs mainly include the heat pump and the heat source tower, as shown in Figure 1. The HSTHPs had two operating modes: summer cooling mode (open valves V1, V2, V3, V4) and winter heating mode (open valves V5, V6, V7, V8).

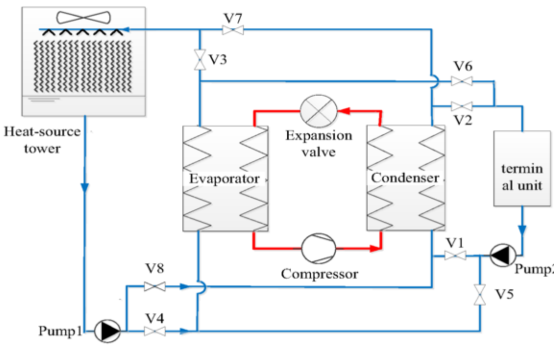


Figure 1. Schematic diagram of HSTHPs.

2.2. System Model

In this section, the model of each component for heat pump system, such as compressor, condenser, throttle valve and evaporator, and the model of heat source tower are established first, and then the devices are connected to form the system model.

2.2.1. Compressor Model

The refrigerant flow rate, m_r, and compressor power consumption, P_e, can be expressed as follows.

$$m_{\mathrm{r}} = \frac{\eta_v V_h r}{60 v_1} \tag{1}$$

$$P_e = \frac{m_{\mathrm{r}} \times (h_1 - h_2)}{\eta} \tag{2}$$

where η_v, r, V_h, v_1 and η are the volumetric efficiency, speed, discharge volume and specific suction volume, and efficiency for the compressor. h_1 and h_2 represent the refrigerant enthalpy in the inlet and outlet of compressor.

2.2.2. Condenser Model

The heating capacity of condenser, Q_c, is calculated as follows.

$$Q_c = m_r (h_2 - h_3) \tag{3}$$

where h_3 is the refrigerant enthalpy of the compressor outlet.

The heating capacity of the condenser can also be expressed in terms of the heat taken away by the cooling water, which is calculated as follows.

$$Q_c = c_w m_{cw} (T_{cw\_out} - T_{cw\_in}) \tag{4}$$

where c_w, m_{cw}, T_{w_out} and T_{w_in} are the specific heat capacity of water, mass flow rate of cooling water, cooling water temperature in condenser.

2.2.3. Throttle Valve Model

The refrigerant flow rate in the throttle valve, m_r, can be expressed as follows.

$$m_r = C_D A \sqrt{2\rho (p_1 - p_2)} \tag{5}$$

where C_D and A are the mass flow coefficient constant and the geometric area of the throat of throttle valve.

2.2.4. Evaporator Model

Similar to the heating capacity of condenser, the cooling capacity of evaporator, Q_e, can also be indicated according to refrigerant and chilled water respectively.

$$Q_e = m_r(h_1 - h_4) \tag{6}$$

where h_4 is the refrigerant enthalpy of the evaporator inlet.

$$Q_e = c_w m_{ew}(T_{ew\_in} - T_{ew\_out}) \tag{7}$$

where m_{ew}, T_{ew_in} and T_{ew_out} are the mass flow rate of chilled water and chilled water temperature in evaporator

2.2.5. Heat Source Tower Model

The energy balance in the heat source tower is as follows.

$$\frac{1}{K} \times G_w \times c_w \times dT_w = K_{dv} \times (h - h_w) dV \tag{8}$$

where G_w, T_w, K and K_{dv} are the solution mass flow rate, solution temperature, coefficient of heat taken away by water evaporation and mass transfer coefficient.

The conservation of mass in the heat source tower is as follows.

$$G_a \times d(d_a) = K_{dv} \times (d_w - d_a) \times V = dG_w \tag{9}$$

where G_a, d_a and d_w are the air mass flow rate, air moisture content and air moisture content of solution interface.

2.2.6. Unit Energy Efficiency

The coefficient of performance of the HSTHPs, COP, is calculated as follows.

$$COP = \frac{Q}{P_e} \tag{10}$$

where Q is heat (Q_e for summer conditions and Q_c for winter conditions).

The system coefficient of performance (SCOP) of HSTHPs, is calculated as follows.

$$SCOP = \frac{Q}{P_e + P_1 + P_2 + P_f} \tag{11}$$

where P_1, P_2 and P_f are the Pump 1 power, Pump 2 power and fan power of heat source tower.

2.3. Model Validation

In order to verify the accuracy of the HSTHPs model, a heat source tower heat pump test bench was established in Qingdao. The comparison of the simulation and experimental results is shown in Figure 2. As seen in Figure 2, the simulation and experimental results are in good agreement.

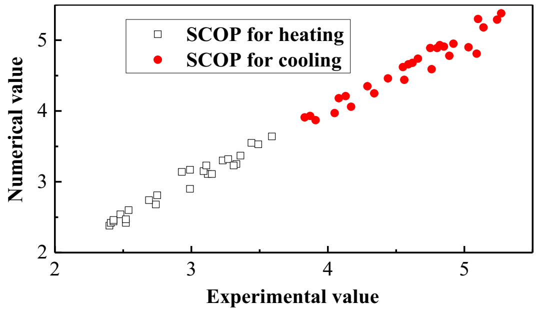


Figure 2. Model verification of the HSTHPs.

2.4. Thermal Zone

In China, there are five thermal zones, such as severe cold zone, cold zone, HSCW zone, HSWW zone and mild zone. The monthly average temperature in the severe cold region is lower than -10°C, and HSTHPs cannot operate normally or operates with lower energy efficiency in this region [11]. According to the standards, buildings in HSWW zone A should meet the winter heating demand, and buildings in Zone B may not consider heating in winter [12]. Therefore, the applicability of HSTHPs in the severe cold zone and HSWW zone B is not considered.

Some typical cities were selected as simulation objects from each of the remaining thermal zones, mainly in the provincial capital cities, and other cities can refer to the calculated data of the provincial capital cities, as shown in Table 1. The meteorological parameters of each city are found on the website (http://climate. onebuilding.org/).

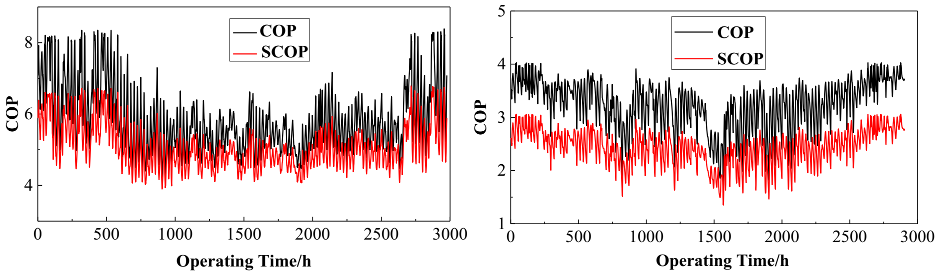
Table 1. Typical cities of the thermal zones in China.

Thermal zone	**Cold zone**	**Hot-summer and cold-winter zone**	**Hot-summer and warm-winter zone A**	**Mild zone**
Typical cities	Beijing, Dalian, Jinan, Lhasa, Lanzhou, Qingdao, Shijiazhuang, Taiyuan, Tianjin, Xi'an, Yinchuan, Zhengzhou	Chengdu, Hangzhou, Hefei, Nanchang, Nanjing, Shanghai, Wuhan, Changsha, Chongqing	Fuzhou, Longyan, Hechi, Liuzhou	Guiyang, Dushan, Kunming, Lijiang, Dali

3. Results and Discussion

In this section, the annual operational energy efficiency diagrams of HSTHPs in Beijing are displayed, and the seasonal operation characteristics of HSTHPs in the above four thermal zones are analyzed.

Figure 3 shows the annual operational energy efficiency diagrams of HSTHPs in Beijing. As can be seen from Figure 3a, the energy efficiency of the middle zone system is lower, and that of the two-end zone system is higher. This is due to the fact that the two-end zone is the time when the heat pump system is running in May or September. At this time, the dry bulb temperature of the outside air is low, which reduces the condensation temperature of heat pump and leads to a higher value of COP and SCOP for HSTHPs. In the middle area, the heat pump system operates in summer, generally between June and August. The dry bulb temperature of the outside air is high, and the condensation temperature of heat pump is also increased accordingly, which may lower the energy efficiency of the unit. Therefore, the COP of unit and the SCOP of heat pump system are low. The operating conditions in winter are similar to those in summer. The energy efficiency of the system in the middle area is low and the energy efficiency of the system at both ends is high, as shown in Figure 3b. This is because: in the middle area, the heat pump system operates in winter, and the outside air dry bulb temperature is very low, generally lower than 0℃. The evaporation temperature of the unit is also reduced accordingly, resulting in the decline of unit energy efficiency. Therefore, the values of COP and SCOP are very low in the middle area.



(a) Cooling conditions in summer (b) Heating conditions in winter

Figure 3. Seasonal operation energy efficiency of HSTHPs in Beijing.

The seasonal operating characteristics of heat pump can be expressed by HSPF and SEER, which are calculated as follows.

$$HSPF = \frac{\sum Q_c}{\sum (P_e + P_1 + P_2 + P_f)} \tag{12}$$

$$SEER = \frac{\sum Q_e}{\sum (P_e + P_1 + P_2 + P_f)} \tag{13}$$

The values of HSPF and SEER of HSTHPs in Beijing are 2.37 and 4.98, respectively. The results of HSPF and SEER of HSTHPs in Other cities are displayed in Table 2. As shown in Table 2, most of the HSPF values of HSTHPs operating in these above typical cities are between 2.1 and 2.9, and the SEER values of HSTHPs operating in the typical cities mentioned above is mostly between 4.6 and 5.59.

Table 2. Typical cities of the thermal zones in China.

Thermal zone	Typical cities	HSPF	SEER	Thermal zone	Typical cities	HSPF	SEER
Cold zone	Beijing	2.37	4.98	Hot-summer and cold-winter zone	Chengdu	2.8	5.01
	Dalian	2.29	5.29		Hangzhou	2.74	4.79
	Jinan	2.55	4.8		Hefei	2.68	4.79
	Lhasa	2.42	6.01		Nanchang	2.76	4.69
	Lanzhou	2.28	5.42		Nanjing	2.68	4.78
	Qingdao	2.54	5.17		Shanghai	2.73	4.84
	Shijiazhuang	2.46	4.89		Wuhan	2.73	4.66
	Taiyuan	2.28	5.31		Changsha	2.75	4.78
	Tianjin	2.37	4.95		Chongqing	2.86	4.76
	Xi'an	2.55	4.91				
	Yinchuan	2.12	5.34				
	Zhengzhou	2.59	4.87				
Mild zone	Guiyang	2.74	5.12	Hot-summer and warm-winter zone a	Fuzhou	2.82	4.71
	Dushan	2.74	5.08		Longyan	2.8	4.88
	Kunming	2.78	5.59		Hechi	2.85	4.68
	Lijiang	2.75	5.82		Liuzhou	2.8	4.73
	Dali	2.82	5.56				

The seasonal operation data of HSTHPs in the above typical cities, averaged according to the thermal zone, are indicated in Figure 4. As seen in Figure 4, the HSPF and SEER values of HSTHPs in the cold zone, HSCW zone and HSWW zone A show the opposite trend, with the HSPF values gradually increasing from 2.40 to 2.82 and the SEER values gradually decreasing from 5.16 to 4.75. This is related to the latitude of the above three thermal zones. The higher the latitude, such as the cold zone, the lower the outdoor air temperature, which is conducive to lowering the condensation temperature of the unit and improving the energy efficiency of the unit in summer. Therefore, the SEER value of HSTHPs in cold zone is higher. On the contrary, in winter, the lower outside air temperature will lower the evaporation temperature and reduce the energy efficiency of the unit, resulting in a lower HSPF value. The climatic characteristics of mild zone are cool in summer and warm in winter, so the HSPF and SEER values of HSTHPs in mild zone are higher, 2.77 and 5.43 respectively, and it maintains efficient operation throughout the year.

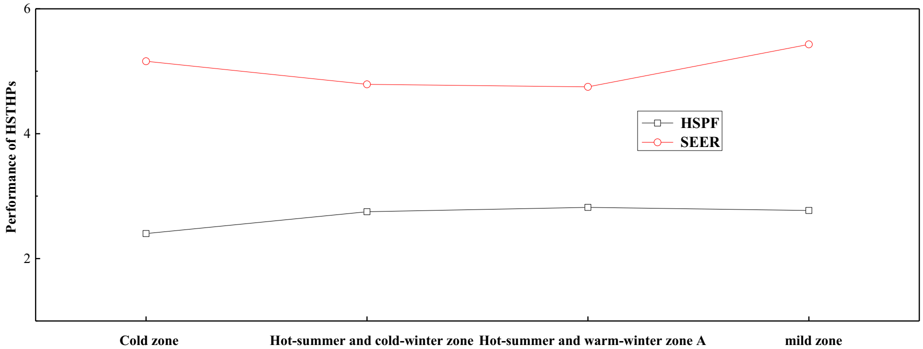


Figure 4. Seasonal operation performance of HSTHPs in the thermal zones in China.

In summary, the HSTHPs are suitable for application in cold zone, HSCW zone, HSWW zone A and mild zone, especially in mild zone with a higher energy efficiency.

4. Conclusion

In this paper, the mathematical model of HSTHPs was established and experimentally verified, and then the seasonal operation characteristics of HSTHPs in winter and summer conditions in major cities across China were studied to provide theoretical guidance for the promotion of HSTHPs. The main conclusions are as follows.

(1) The HSPF values of HSTHPs working in the cold zone, HSCW zone and HSWW zone A gradually increase from 2.40 to 2.82, while the SEER values of HSTHPs in the above zones show the opposite trends, with the SEER values gradually decreasing from 5.16 to 4.75.

(2) The HSTHPs maintain high efficiency in winter and summer working in mild zone, with a higher HSPF and SEER value, 2.77 and 5.43 respectively.

(3) There are still some deficiencies in the study of regional adaptability for HSTHPs, such as the small number of urban samples, which will be improved in the future work.

References

[1] Wen XT, Liang CH, Zhang XS. Experimental study on heat transfer coefficient between air and liquid in the cross-flow heat-source tower. Building and Environment. 2012 Nov;57:205-13.

[2] Guo XM, Chen YG, Wang WH, Chen. Experimental study on frost growth and dynamic performance of air source heat pump system. Applied Thermal Engineering. 2008 Dec;28(17-18):2267-78.

[3] Huang SF, Lv ZY, Liang CH, Zhang XS. Experimental study of heat and mass transfer characteristics in a cross-flow heating tower. International Journal of Refrigeration. 2017 May;77:116-27.

[4] Liang CH, Wen XT, Liu CX, Zhang XS. Performance analysis and experimental study of heat-source tower solution regeneration. Energy Conversion and Management. 2014 Sep;85:596-602.

[5] Li NP, Zhang D, Cheng JL, He ZM, Chen Q. Economic analysis of heat pump air conditioning system of heat-source tower. Journal of Shenzhen University Science and Engineering. 2015 Jul;32(4):404-10.

[6] Xu YD, Lu WP, Zheng WD. Experimental study on energy-tower heat pump system during heating season in Tianjin. Journal of Salt Science and Chemical Industry. 2017 Sep;46(9):46-9.

[7] Huang SF, Zuo WD, Lu HX, Liang CH, Zhang XS. Performance comparison of a heating tower heat pump and an air-source heat pump: a comprehensive modeling and simulation study. Energy Conversion and Management. 2019 Jan;180:1039-54.

[8] Liu MZ, Jiang LF, Zhang H, Zheng XJ, You SJ, Wei S. An exploration on the applicability of heating tower heat pump and air source heat pump systems in different climatic regions. Journal of Cleaner Production. 2019 Nov;238:117889.

[9] Xie LY, Huang SF, Ye YY, Zhang XS. Regional suitability of heating tower heat pumps based on technical and economic performance maps. Energy and Buildings. 2021Aug;245:111048.

[10] Huang SF, Ye YY, Han X, Zuo WD, Zhang XS, Jiang L. Performance evaluation of heating tower heat pump systems over the world. Energy Conversion and Management. 2019 Apr;186:500-15.

[11] China Academy of Building Research. CECS362-2014, Technical Specification for Heat-Source-Tower Heat Pump System. China Planning Press. 2014.

[12] China Academy of Building Research. JGJ75-2012, Design Standard for Energy Efficiency of Residential Buildings in Hot Summer and Warm Winter Zone. China Architecture & Building Press. 2012.