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Calculation of Volume of Hot Water Storage Tank in Air Source Heat Pump System

Wang Jian[1, *], Jiang Ai Ling[1], Liu Jun[1], Wang Yiling[2]

[1]Architecture Design & Research Institute, Southeast University, Nanjing, China
[2]Department of Mathematics, Duke Kunshan University, Kunshan, China

Email address:

football_fan@sohu.com (Wang Jian)
[*]Corresponding author

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Abstract: Air source heat pump integrated with hot water storage tank may enhance the efficiency of heating, and the volume of hot water storage tank is closely related to the thermal efficiency of the hot water system. Referring to the relevant formulas of building water supply and drainage design standards, this paper simulates the operation conditions of heat pump, and combined with the measured annual data of hot water using in a hospital, systematically discusses the adaptability of heat pump water production and seasonal hot water usage, as well as the actual regulating volume of hot water storage tank. Assumed the heat pump is altered by the working condition of the vernal equinox, the daily storage and discharge of the hot water tank can be accurately calculated, the hot water tank should charge 2.94 times of average hourly water yield of air pump during the peak water usage period. considering the safety and economy of the air source heat pump system, it is strongly recommended that the volume of hot water storage tank can be designed as the 5 ~ 6 times of hourly average water yield of air source heat pump, which can meet the usage of hot water for most of the time and it is inspected under various accidental conditions.

Keywords: Air Source Heat Pump (ASHP), Hot Water Storage Tank (HWST), Volume Calculation

1. Introduction

Water heating is the fourth largest energy user in the commercial buildings sector [1], ASHP can use low-grade air energy to heat water, which can effectively reduce energy consumption and emissions of buildings [2]. The shortcomings of low heating efficiency in winter caused by frost in winter have gradually been overcome with the development of technology [3-5]. At present, low-temperature ASHP can still work stable even at an ambient temperature of -15°C [6], with the increasing adaptation to climate and environment [7, 8], ASHP has been widely used in construction projects [9].

The water production of ASHP is related to the inlet water temperature and ambient temperature, and has the same characteristics of seasonal variation as hot water consumption. In practice, the design is generally according to the average heat consumption of the spring and autumn equinox to match the water production of ASHP. The ASHP integrated with a HWST has significant energy-saving potential [2], which becomes an effective demand-side management tool and smooths the supply and demands of heat water. Storage tanks are commonly used to cope with peak demand for domestic hot water preparation in buildings [13]. Although the daily change in the hot water demand does not significantly affect the daily average system efficiencies [14], hot water storage tanks play a pivotal role in the transition to low carbon energy systems by increasing energy efficiency [15]. Since peak water consumption cannot be accurately estimated, the HWST is mainly used for water regulation between water production and consumption, as well as emergency water use. the volume of the water tank is generally calculated directly by applying the relevant formulas in the specification.

If the volume of HWST is too small, it can’t meet the peak water consumption; but if the volume is too large, HWST cannot be full used, which will affect the technical and economic performance of the whole system, optimal sizing of hot water storage capacity is an important consideration for reducing costs and increasing overall efficiency in many conventional heating systems [13]. In this paper, we will compare the simulated water production of the ASHP with the measured hot water consumption of a hospital in one year through simulating the working condition function of the ASHP, then the actual efficiency of the HWST will be analyzed. Actual regulating volume of HWST will be compared with the parameters recommended by the specification, so as to provide a reference basis for the accurate estimation of the volume of the HWST.

2. Calculated Volume of HWST

According to «Standard for design of building water supply and drainage» (2019) [10], The volume calculation formula of HWST is:

$$V_{\mathrm{r}} = k_1 \frac{\left(Q_{\mathrm{h}} - Q_{\mathrm{g}}\right) T_1}{\left(t_{\mathrm{r}} - t_1\right) C \cdot \rho_{\mathrm{r}}} \tag{1}$$

Where k_1=1.25~1.5, is the uniformity factor of water safety;

Q_h is heat consumption per hour;

Q_g is heat supply per hour;

T_1 is duration of hourly heat consumption, It often takes 2 ~ 4 hour in the full-time centralized hot water supply system.

Deform formula1:

$$\begin{aligned} V_{\mathrm{r}} &= k_1 T_1 \left(\frac{Q_{\mathrm{h}}}{Q_{\mathrm{g}}} - 1 \right) \frac{Q_{\mathrm{g}}}{\left(t_{\mathrm{r}} - t_1\right) C \cdot \rho_{\mathrm{r}}} \\ &= k_1 T_1 \left(\frac{Q_{\mathrm{h}}}{Q_{\mathrm{g}}} - 1 \right) \frac{C_v m q_{\mathrm{r'}}}{T_5} \end{aligned} \tag{2}$$

Which:

$$\frac{Q_{\mathrm{h}}}{Q_{\mathrm{g}}} = \frac{K_{\mathrm{h}} q_{\mathrm{r}} T_5}{q_{\mathrm{r'}} T} \tag{3}$$

Where q_r and q_r is hot water quota, q_r takes as the maximum daily water quota, $q_{r'}$ takes as the average daily water quota;

T_5 is working time of ASHP, takes 8~16h per day, T is the service time.

Consider $C_v m q_r / T_5$ as water production of ASHP (L/h), $k_1 T_1$ (Q_h/Q_g-1) as the coefficient A, so the HWST can store A times of the average water production.

Take the hospital ward building as an example, K_h takes 2.56, q_r takes 200 L/per·bed per·day, $q_{r'}$ takes 140 L/per·bed per·day, T takes 24 h, T_5 takes 16 h,

So Q_h/Q_g=2.438, A=3.60~8.63 h.

The value of A is mainly related to the uncertainty of design hourly heat consumption duration.

According to «Technical Code for Solar Energy and Air-source Heat Pump Water Heater System in Zhejiang Province» [11], When the duration of design hourly heat consumption cannot be determined, the volume calculation formula of HWST is:

$$\begin{aligned} V_{\mathrm{r}} &= k m q_{\mathrm{r'}} \left(1 - \frac{T_5}{24} \right) \\ &= \frac{k T_5}{C_v} \left(1 - \frac{T_5}{24} \right) \frac{C_v m q_{\mathrm{r'}}}{T_5} \end{aligned} \tag{4}$$

Where k_1=1.10~1.20, is the uniformity factor of water safety; m, $q_{r'}$, T_5 as the same.

Consider $kT_5(1-T_5/24)/C_v$ as the coefficient A, A takes 5.10~5.82, the value of A is smaller than in formula 1, which is in the middle of the calculation range in formula 1.

As Zhejiang Province is located in an area with a hot summer and cold winter, it is reasonable that the volume range of the HWST is relatively small. Therefore, how to accurately estimate the volume of the HWST and the regulating volume actually used is the key parameter to be studied. This paper will select the real-time online monitoring data of hot water consumption of a hospital in Nanjing with hot water system and monitoring conditions. The datum is collected every 5 minutes by the ultrasonic flowmeter for a whole year. At the same time, referring to the water production data of ASHP provided by the enterprise, water production under an inlet water temperature and ambient temperature is fitted by simulation function. The water consumption in one year is linearly transformed with the water production of the ASHP to simulate the actual working conditions. The adaptation of water usage and water supply, as well as real-time regulating volume of HWST is systematically analyzed.

3. Simulation of Operation of ASHP

The annual data of hot water usage is collected from a hospital in Nanjing, where is in the area with a hot summer and cold winter. It is assumed that ASHP is selected to be heat resource, which mode is determined to the vernal equinox monthly working condition and average daily water quota.

The test conditions of water production of ASHP are: inlet water temperature is 5, 9, 15, 20 and 29°C, air temperature is 2, 7, 10, 15, 20, 26, 30 and 35°C, and 40 operating conditions are obtained by combining any inlet water temperature with any air temperature. In order to analyze the suitability of water usage and water production, the water production of the heat pump is divided by the water production at the inlet temperature of 15°C and the air temperature of 26°C to obtain the coefficient of the ASHP operation condition [12]. Polynomial fitting is used to obtain the variation surface of working condition coefficient with water temperature and air temperature. The fitted polynomial is:

$$\begin{aligned} f(x, y) &= 0.3463\text{-}0.001314 * x + 0.02231 * y \\ &+ 0.0005043 * x^2 + 0.0003907 * x * y\text{-}0.000244 * y^2 \end{aligned} \tag{5}$$

As x is inlet water temperature, y is air temperature, f(x, y) is the coefficient of ASHP operation condition. The error sum of squares SSE is 0.0169, the coefficient of determination of R-square is 0.995, and the degree of approximation is relatively high.

Bring the measured monthly average water temperature and air temperature data of Nanjing in the past three years (2017, 2018, 2019) into the fitted polynomial, and simulate the one-year monthly average working condition coefficient curve of Nanjing (when the inlet water temperature is 13°C and the air temperature is 11.5°C, the coefficient of ASHP operation condition is 0.70), as shown in Figure 1. Since the mode of ASHP is determined to the vernal equinox monthly working condition (inlet temperature of 13°C, air temperature of 11.5°C), the obtained working condition coefficients are all divided by 0.70, so that the working condition coefficient of March working condition is 1, and finally the water supply coefficient and water consumption coefficient curve are shown in Figure 2.

In order to analyze the adaptation between the average daily water usage and the water production under the working condition of vernal equinox, we divide the measured daily water consumption of the hospital by Q (Q is the average daily water usage), quantify the average daily water usage as 1, and obtain the water usage coefficient of the hospital for one year (see Figure 2).

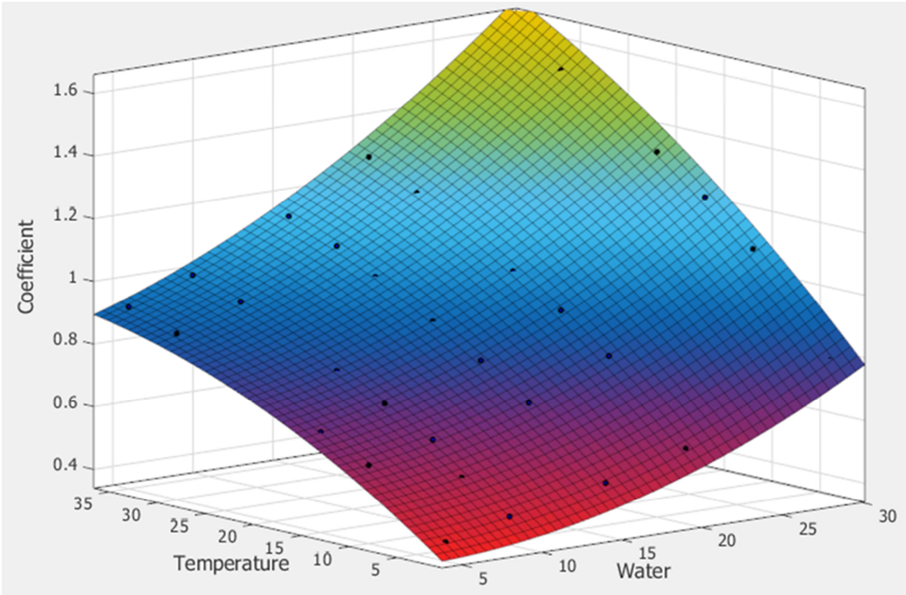

Figure 1. *Curve of ASHP operation condition.*

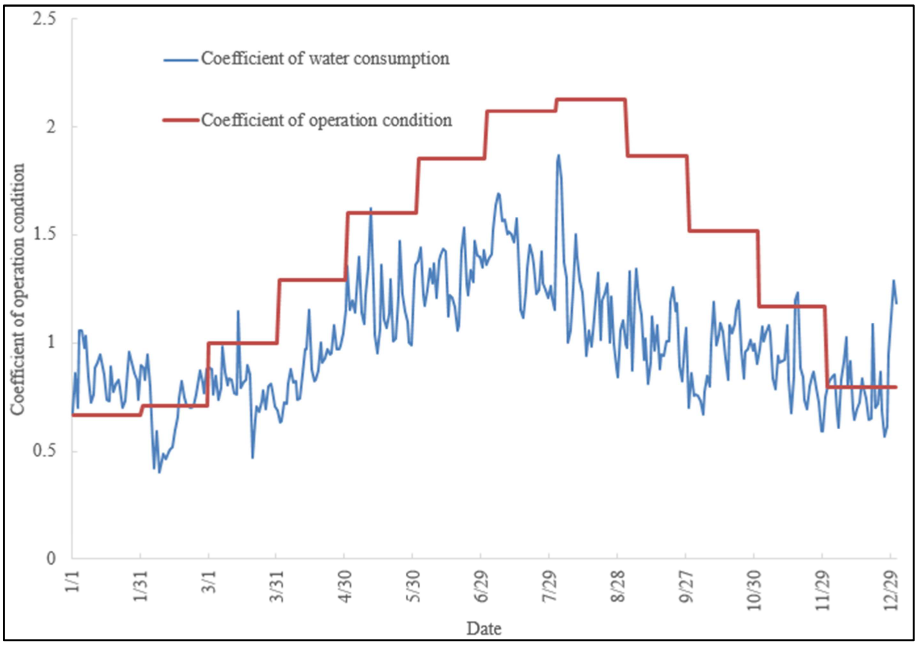

Figure 2. *Coefficient of hospital daily water usage and monthly average daily water production.*

From Figure 2, it can be seen that the daily water production of ASHP can't meet the daily water demand in January, February and December, in winter the demand of hot water can be supplied through the auxiliary heat source when it can't be wholly met by the heat pump. When in March, April, May and November the demand and supply of hot water have high matching degree. From June to October, the inlet water temperature and ambient temperature in the above months are high than other months, so the increase of heat pump water production in summer is greater than that of water consumption. Therefore, there will be some surplus of water production.

When the ASHP is altered by the working condition of the vernal equinox, in spring, summer and autumn the daily water usage can meet the demand of daily water consumption except on March 14, May 11 and November 18. From the perspective of the whole year, the water production is insufficient only 65 days, and the most unfavorable daily water consumption coefficient is 1.29, which is 49% greater than the working condition coefficient of 0.80 at the same time, that is, the water supply capacity of the auxiliary heat source can be half times of the ASHP. In the other 300 days, the heat pump water production is greater than the water usage, of which the water production is 1/3 higher than the water usage in 163 days, and the water production is 1/2 higher than the water usage in 106 days. Therefore, in most months of the year, the HWST is used to charge the surplus hot water produced by the ASHP, and is only used to supplement the hot water supply in a few months of the year. Then we will further discuss regulating volume of the HWST.

4. Regulating Volume of the HWST

4.1. Simulated Regulating Volume of HWST

The HWST in the ASHP water supply system is mainly used to adjust the hourly variation of water usage. Therefore, the maximum daily water usage is preferred to the calculation of water tank volume. The maximum daily water usage is 389.96 m^3/d, which is 1.87 time of the number of average daily water usage. The curve of the maximum daily operation condition coefficient and maximum daily discharge coefficient is shown in Figure 3.

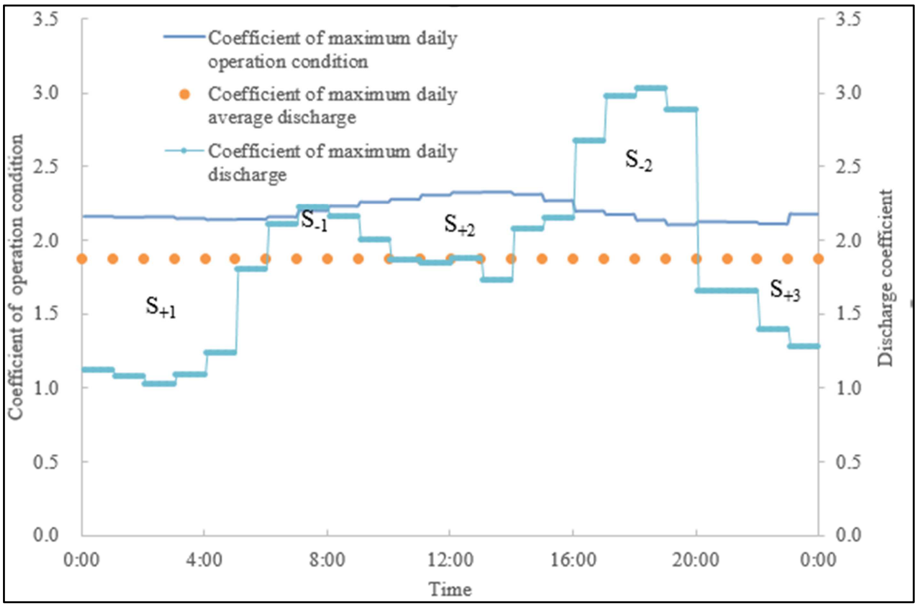

Figure 3. *Coefficient of maximum daily operation condition and maximum daily discharge.*

As can be seen, 20:00 ~ 7:00, 8:00 ~ 16:00 on the day are the water charging time of the HWST, and the rest are the water discharging time of the HWST. According to the integral formula of discrete function, the values of S_{+1}, S_{-1}, S_{+2}, S_{-2}, S_{+3} in Figure 3 (S is the area enclosed by the maximum daily operation condition coefficient curve and the maximum daily discharge curve, positive value represents hot water charge in water tank and negative value represents hot water discharge in water tank) are 5.61, - 0.02, 2.63, - 2.94 and 2.54 respectively. $S_{+1} + S_{+3}$ is 8.15, $S_{+1} + S_{+3} + S_{-1} + S_{+2}$ is 10.76. Therefore, it is necessary to store 2.94 times of average hourly water yield of AHSP in the water tank during the peak water usage period. Assuming that the production and usage of the hot water remains unchanged near the highest day, a total of 8.15 times of average hourly water yield of the heat pump can be charged at night.

As in Formula 2, the value range of key parameter A is 3.60 ~ 8.63 hours, which can meet the peak demand of hot water on that day. If the parameter takes the maximum, that is, A is 8.63, the average hourly hot water production (including the previous day) of 8.63 hours can be stored between 20:00~6:00. During the water peak of the next day, assuming that the water production of heat pump is broken off by the control system, the HWST can still provide 4.36 hours of peak hot water supply. If the hot water is charged in the water tank for more than a certain time, the heat loss of the water tank will affect the thermal efficiency of the whole system. Therefore, even considering the safety factor of the system, the high limit value of the water tank volume may still increase the investment and energy consumption, and then reduce the thermal efficiency of the hot water system. If the value of A is taken as the lower limit of 3.6, it can also meet most of the water regulation and charge of the next day. However, given the efficiency attenuation of heat pump equipment and the failure of some heat pump equipment during use, it may not be able to ensure the hot water supply in extreme cases, therefore, considering the water supply safety and system thermal efficiency, combined with figure 2, it is recommended to take 5-6 hours as A. In this way, the largest one-time water charge in the whole day can be met, and this value is roughly the same as the calculation formula of HWST in the local standard of Zhejiang Province, because this calculation formula is based on the balance of water production and water supply during the working period of the heat pump every day, and is more suitable for the actual operation of the heat pump in hot summer and cold winter areas.

4.2. Volume of HWST Inspection

In order to further analyze the regulation and charge of the HWST, further tests are taken in the vernal equinox, autumn equinox and March 14, May 11 and November 18, when the daily water production of the heat pump is lower than the daily water usage in spring, summer and autumn.

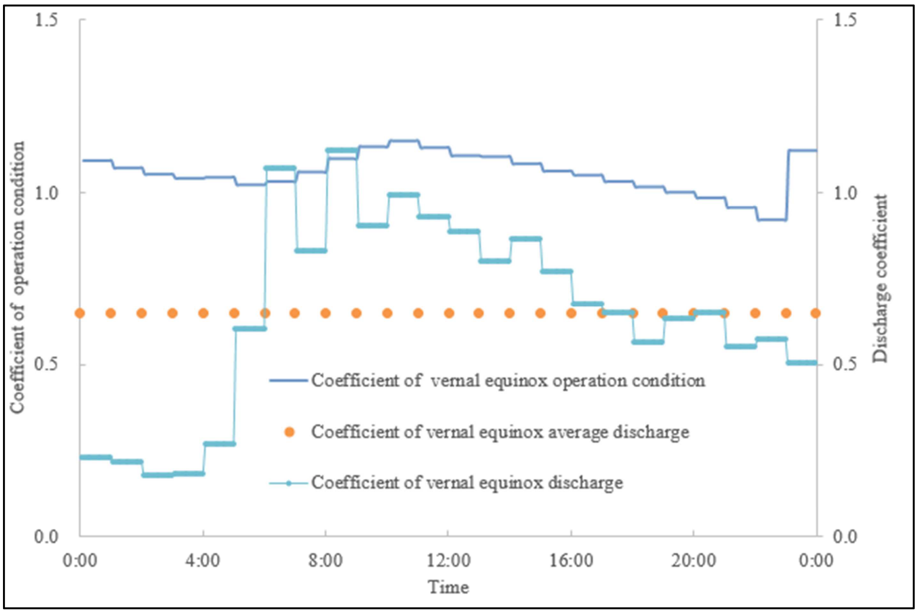

Figure 4. *Coefficient of vernal equinox operation condition and vernal equinox discharge.*

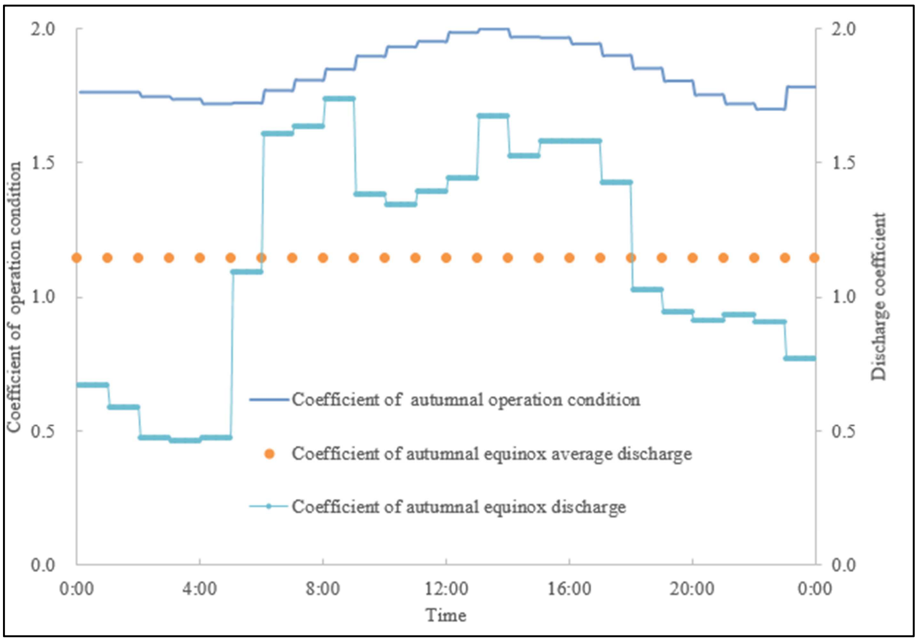

Figure 5. *Coefficient of autumnal equinox operation condition and autumnal equinox discharge.*

Figures 4 and 5 shows the operation condition coefficient of and discharge coefficient curves on the vernal equinox and autumn equinox respectively. Although the parameter of ASHP is designed according to the working condition of the vernal equinox, the daily water consumption on the vernal equinox and autumn equinox is lower than the annual average daily water consumption. The water tank is mainly used to charge the excess water production of the heat pump. The water tank on the vernal equinox charges 4.82 times of hourly hot water production and the water tank on the autumn equinox stores 6.46 times of hourly hot water production.

The curves of March 14, May 11 and November 18 are shown in figures 6, 7 and 8 respectively. It can be seen from Figure 6 that the water production is lower than the water consumption during 6:00 ~ 20:00 on March 14, and 4.75 times of hourly ASHP water production needs to be supplemented; It can be seen from Figure 7 that the water production during 5:00 ~ 9:00 and 14:00 ~ 21:00 on May 11 is lower than the water consumption, and 1.03 times or 3.79 times of the hourly water production of ASHP needs to be supplemented respectively. It can be seen from figure 8 that the water production is lower than the water consumption during 0:00 ~ 10:00 and 17:00 ~ 20:00 on November 18, so it is necessary to supplement the hourly water production of 5.57 hours and 1.43 hours respectively. Therefore, if effective volume of the HWST is designed according to the hourly water production of 5 ~ 6 hours, it can basically meet the regulation demand for water during peak hours at all times of the year.

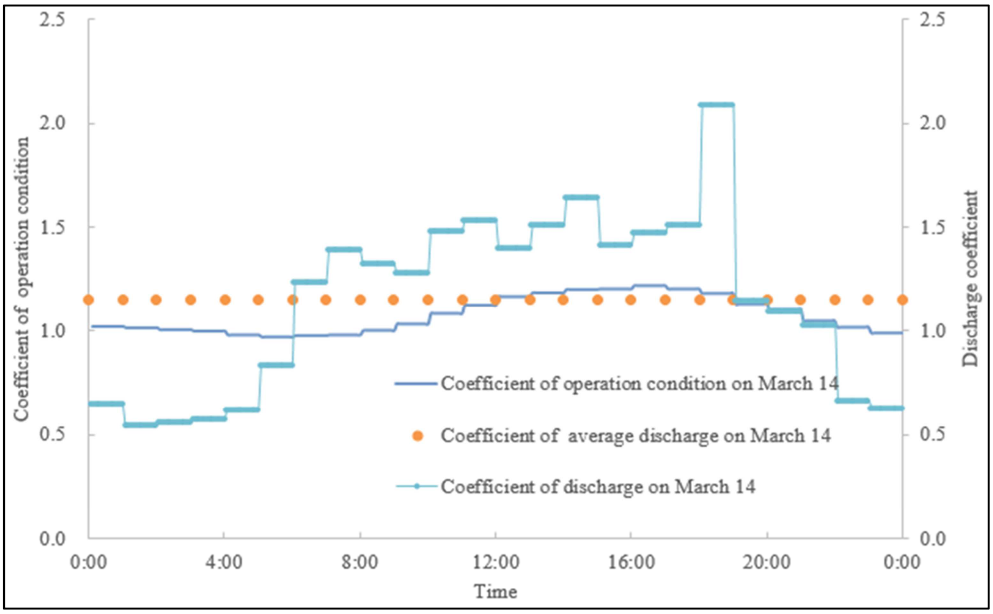

Figure 6. *Coefficient of operation condition and discharge on March 14.*

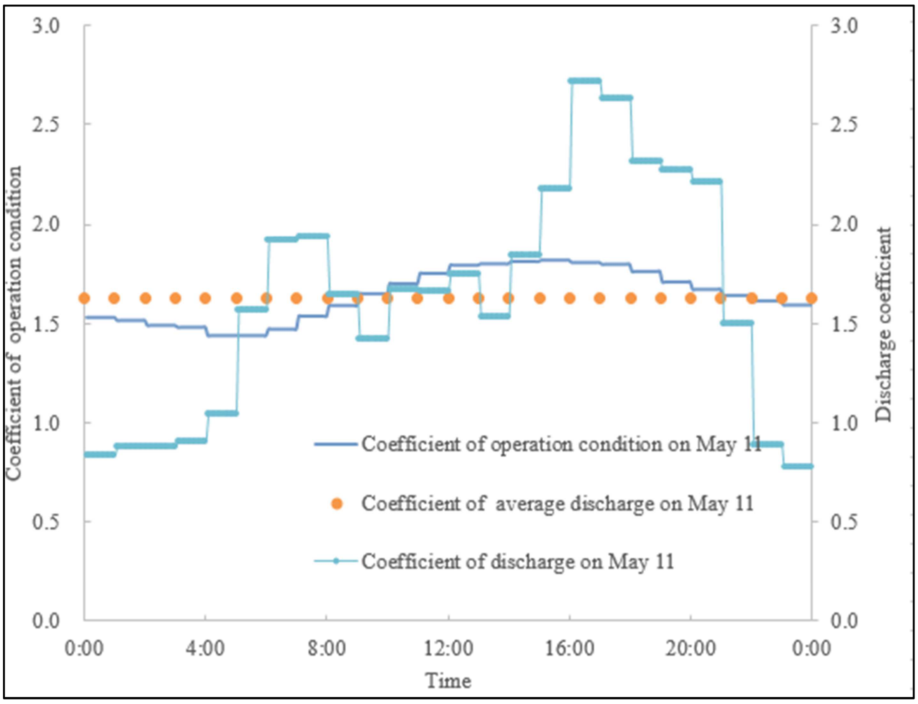

Figure 7. *Coefficient of operation condition and discharge on May 11.*

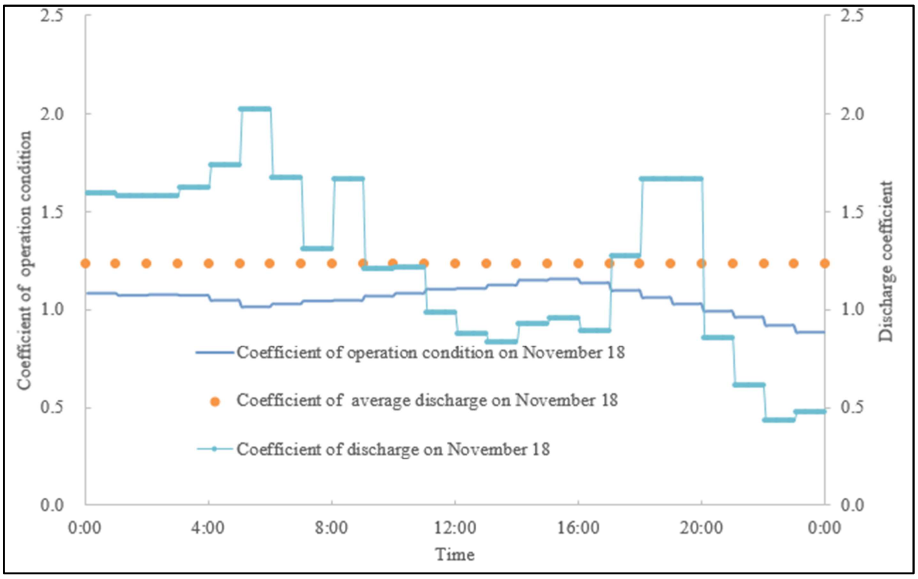

Figure 8. *Coefficient of operation condition and discharge on November 18.*

For further faulty water supply inspection, the heat pump system unit adopts dual-use and one-standby configuration generally. Assuming that one of the heat pump units fails, the water production of the heat pump will be reduced by 50%. If the value of A is taken as 5.5 hours, the HWST can still ensure faulty water supply of more than 4 hours for the day with the highest water usage. Similarly, on vernal equinox (24 hours), autumn equinox (19 hours), March 14 (11 hours) and May 11 (10 hours), and November 18 (5 hours), the HWST can ensure the hot water supply for more than 5 hours.

5. Conclusion

This paper studies the volume calculation of the HWST of the ASHP hot water system. Through the measured data of hot water use in a hospital in Nanjing and the simulation comparison of the ASHP, it is found that in the hot summer and cold winter areas, even considering the fault water supply during the extreme period of the system, the volume of the HWST can still be designed according to the median value of the continuous hourly heat consumption range provided by the specification, that is, the 5 ~ 6 times of hourly average water yield of ASHP is recommended strongly. Although the hot water system in hospital is representative, the conclusions still need to be verified in more scenarios, and the determination of value in cold or other areas may need further improvement of relevant research under conditions of sufficient effective data collection such as in dormitory or apartment.

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