ISSN 2004-2965 Energy Proceedings, Vol. 22, 2021

International Conference on Applied Energy 2021
Nov. 29 - Dec. 5, 2021, Thailand/Virtual
Paper ID: 192

Long-term Energy Performance Evaluation and Improvement of Heat Pump Water Heating Systems in Shanghai

Deliya Kezier[1], Yue-Ming Lu[1], Jia-Hao Cheng[1], Chun-Lu Zhang[1*]
School of Mechanical Engineering, Tongji University, Shanghai 201804, China
E-mail address: chunlu_zhang@tongji.edu.cn Tel.: +86-136-71825-133

ABSTRACT

The energy performance of air source heat pump water heaters decays with increasing time due to improper operation and maintenance. In this paper, a quantitative study is conducted on the energy performance decay of air source heat pump water heaters and the potential improvement of long-term energy performance. First, the energy performance decay of five heating systems in Shanghai was studied on site. The results showed that the Annual Performance Factor of the air source heat pump water heaters decayed by 5%-6% per year during the first six years of operation. Then, a Service Life Cycle Performance Factor model was proposed for further evaluation of the long-term energy performance. Case studies combined with simulations showed that the Service Life Cycle Performance Factor could be improved by 8.0% to 12.2%.

Keywords: air source heat pump water heaters, long-term energy performance, energy performance decay, field test, optimization

NOMENCLATURE

Abbreviations	
APF	annual performance factor
ASHPWH	air source heat pump water heater
COP	coefficient of performance
F	time frequency of temperature
MCOP	monthly coefficient of performance
Q	heating capacity (kWh)
SCOP	seasonal coefficient of performance
SLCPF	service life cycle performance factor
W	power consumption (kWh)
Greeks	
α	APF decay factor
ε	correlation factor of hot water load

1. INTRODUCTION

Air source heat pump water heaters (ASHPWH) are energy-efficient and environmentally friendly, and are widely used in areas such as domestic hot water supply. To make ASHPWH more efficient, a large amount of research has been conducted on energy performance improvement. Most of these studies, whether experimental or theoretical, focus on specific operating conditions [1-8]. Some studies have also noticed the complexity of the actual operating conditions of ASHPWH and optimized operating strategies [9-11]. More related details are given in the reviews by Willem et al. [12] and Song et al.[13].

For further long-term energy savings, it is necessary to pay attention to the multi-year operational energy performance of ASHPWH, considering its service life is often 10 years and more. However, there is a lack of research in this area. On the one hand, only a few studies have considered or pointed out the decay of the APF of ASHPWH with operating time [14, 15]. On the other hand, there is a lack of evaluation indexes for the long-term energy performance of ASHPWH. The energy performance indexes specified in the existing standards [16-18] are used to evaluate the laboratory test results of new ASHPWH, which involve only one or several operating conditions; even the indexes commonly used in the literature, such as SCOP [9, 10] and APF [15], involve a maximum operating time of only one year. Therefore, these existing energy performance indexes cannot be directly used to evaluate the long-term energy performance of ASHPWH, much less to guide its improvement.

In this paper, the decay of energy performance of ASHPWH and the potential improvement of long-term energy performance are quantitatively studied. First, five air source heat pump water heating systems were selected in Shanghai for field research. After that, a Service Life Cycle Performance Factor (SLCPF) model was developed for long-term energy performance evaluation. Finally, the improvement of SLCPF was quantified in combination with simulation.

2. LONG-TERM ENERGY PERFORMANCE FIELD RESEARCH

2.1 Research samples

For the field research on the long-term energy performance of ASHPWH, five air source heat pump water heating systems installed in a student apartment complex in Shanghai were selected as research samples. One is shown in Fig. 1. These systems serve different apartments independently, but their operation modes are similar, thus avoiding the contingency of single energy performance study results.

Fig. 1. Picture of the air source heat pump water heating system

2.2 Data collection

A field study on the ASHPWH was conducted, including testing structural and operational parameters of the ASHPWH, as well as collecting the historical operating data records, as shown in Table 1. These data will be used to quantify their performance decay and for subsequent simulation modeling.

2.3 Data analysis

Based on the collected data, two levels of energy performance decay results were derived, the decay of Monthly Coefficient of Performance (MCOP) and APF.

The MCOP of ASHPWH is defined as the ratio of monthly heating capacity to monthly power consumption, and its decay over time is shown in Fig. 2. As can be seen, the year-to-year decline in MCOP varies slightly from month to month, due to the fluctuations in both climate and hot water load.

The APF of ASHPWH is defined as the ratio of annual heating capacity to annual power consumption, and its decay over time is shown in Fig. 3, where the vertical coordinate is the ratio of APF of the k^{th} year to that of the first year. It can be seen that the APF of five samples declined year by year, with an annual decay of 5%-6%.

Table 1. Historical operating data of ASHPWH

Parameters	Accuracy
Number of breakdowns and maintenance	--
Hourly power consumption	±3%
Hourly water consumption	±3%
Inlet/Outlet water temperature	±1°C

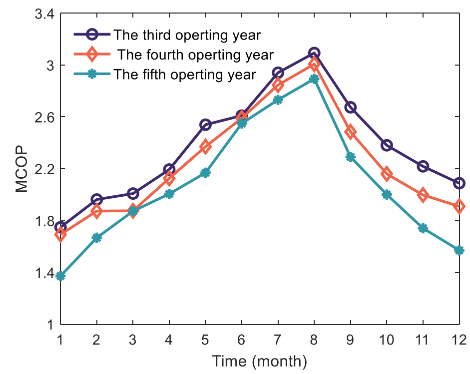

Fig. 2 Decay of MCOP of ASHPWH

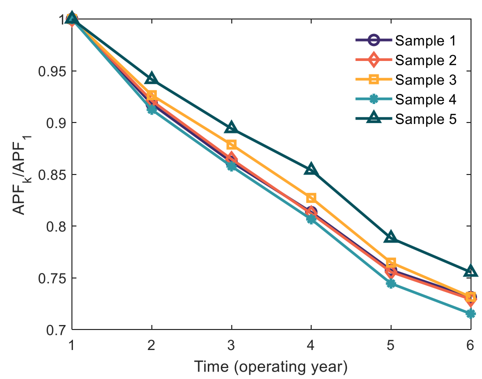

Fig. 3. Decay of APF of ASHPWH

3. LONG-TERM ENERGY PERFORMANCE MODEL

3.1 Evaluation model

SLCPF (Service Life Cycle Performance Factor) model is proposed in this section. It is defined as the energy performance of an ASHPWH over the service life cycle, which represents the period from when the equipment is put into service to when phased out.

The SLCPF is defined as actual and predicted here. First, the actual SLCPF can be calculated as the ratio of the total heating capacity Q_{life} to the total power consumption W_{life}, i.e.,

$$\mathrm{SLCPF_{Actual}} = \frac{Q_{\mathrm{life}}}{W_{\mathrm{life}}} = \frac{\sum_{k=1}^{n} Q_{\mathrm{annual},k}}{\sum_{k=1}^{n} W_{\mathrm{annual},k}} \tag{1}$$

Next, the predicted SLCPF is derivated using the BIN-hour method. To do that, APF is first calculated as follows. More details can be found in our previous paper [15].

$$\mathrm{APF} = \frac{Q_{\mathrm{annual}}}{W_{\mathrm{annual}}} = \left(\sum_{j=1}^{N} \frac{\varepsilon_j F_j}{\mathrm{COP}_j} \right)^{-1} \tag{2}$$

where, F_j and ε_j are the time frequency of temperature and correlation factor of hot water load in the j^{th} temperature interval.

Here, the APF decay factor α is introduced, which reflects the effect of performance degradation of the components of the ASHPWH on the APF. α_k is the ratio of the APF of the k^{th} year to that of the first year, and its value can be obtained from actual data or from the calibrated simulation model of ASHPWH. Then the APF in the k^{th} year can be calculated as

$$\mathrm{APF}_k = \mathrm{APF}_1 \cdot \alpha_k \tag{3}$$

Assuming that the operating conditions of ASHPWH and its annual heating capacity Q_{annual} remain unchanged each year, then the prediction model of SLCPF can be derived according to Eq.(1)~(4) as follows.

$$\mathrm{SLCPF_{Predicted}} = \frac{Q_{\mathrm{life}}}{W_{\mathrm{life}}} = \frac{n\mathrm{APF}_1}{\sum_{k=1}^{n} \frac{1}{\alpha_k}} \tag{4}$$

Since the SLCPF combines the initial value of the APF and its decay over the years, it is a comprehensive multi-year operational energy performance index of ASHPWH.

3.2 Simulation model of ASHPWH

3.2.1 Simulation modeling

For the improvement study of the SLCPF, a simulation model of ASHPWH was developed, considering the long operation time involved and the difficulty of real experiments. The simulation is based on GREATLAB, a well-validated vapor-compression system modeling tool [19, 20]. The quasi-steady-state simulation model of ASHPWH in GREATLAB is shown in Fig. 4, and the details can be found in the literature [15, 19, 20].

3.2.2 Model Validation

The simulation model of ASHPWH was validated at three levels, short-term operating parameters, MCOP, and SLCPF. The validation of short-term operating parameters of an ASHPWH is shown in Table 2, and the absolute error between the test and simulation values does not exceed ±0.4°C. The validation of MCOP of an ASHPWH in its 5th operating year is shown in Fig. 5, with a maximum error of less than 7% between the simulated and actual values. The validation of SLCPF of five ASHPWHs is shown in Table 3, and the maximum relative error between the actual and simulation values does not exceed ±4%. The validation results show that the simulation model is accurate and reliable, and can be used for the improvement study of the SLCPF.

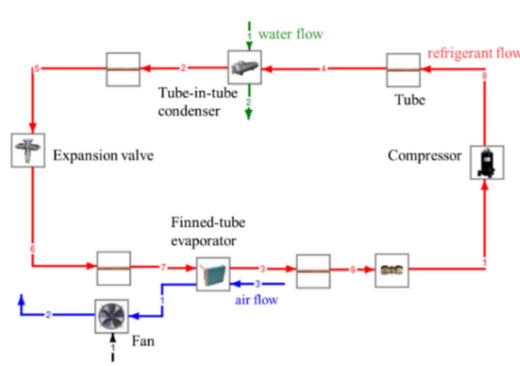

Fig. 4. Simulation model of ASHPWH in GREATLAB

Table 2. Verification of the operating parameters of an ASHPWH

Parameters	Test	Simulation	Error
Suction temperature /°C	10.5	10.6	-0.1
Discharge temperature /°C	89.3	89.5	-0.2
Condensing temperature/°C	54.5	54.9	-0.4
Evaporating temperature /°C	8.5	8.8	-0.3
Outlet water temperature /°C	50.6	50.2	0.4

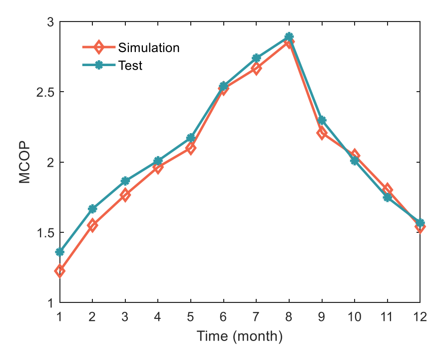

Fig. 5 Verification of MCOP of an ASHPWH

Table 3. Validation of SLCPF of five ASHPWHs

Sample	Test	Simulation	Relative error
1	2.24	2.16	-3.8%
2	2.23	2.17	-2.9%
3	2.30	2.37	3.3%
4	2.27	2.35	-3.5%
5	2.37	2.43	2.7%

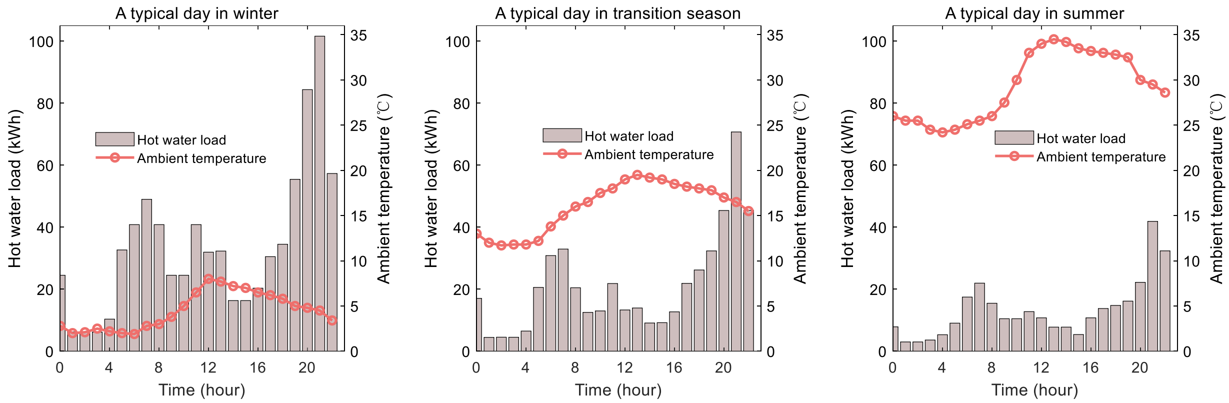

Fig. 6 Ambient temperature and hot water load on typical days

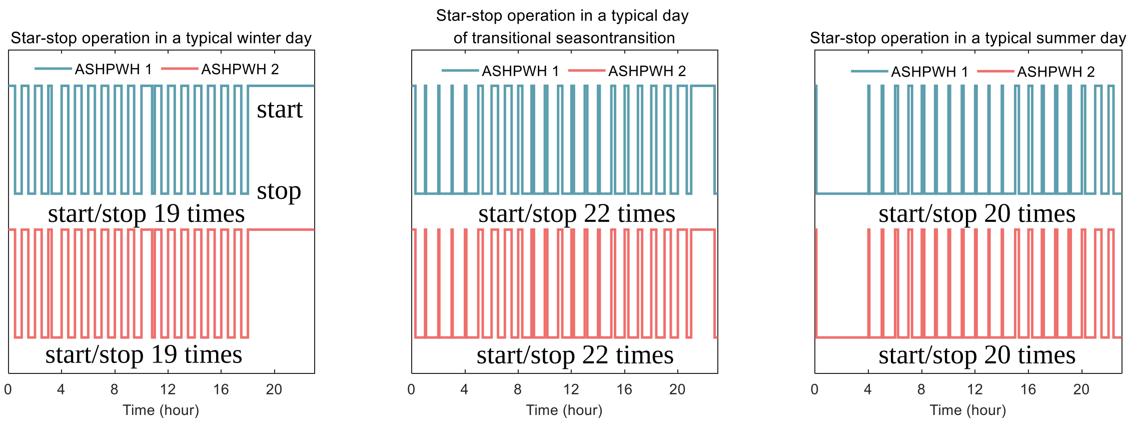

Fig. 7 Original start-stop operation of ASHPWH

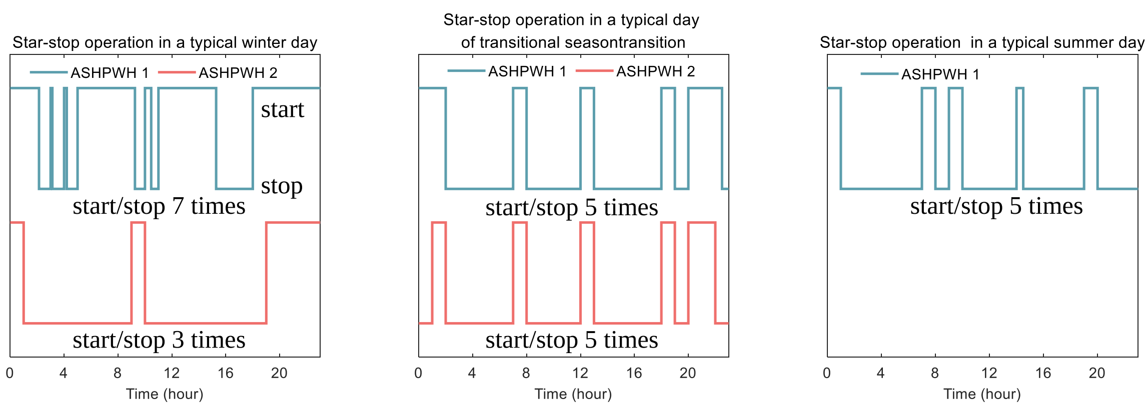

Fig. 8 Optimized start-stop operation of ASHPWH

4 IMPROVEMENT OF LONG-TERM ENERGY PERFORMANCE

4.1 Optimization of control strategy

In the field research, we found that some ASHPWH start and stop frequently, and this phenomenon leads to an increase in start-stop power consumption and a decrease in energy performance [21]. To address this problem, we optimized the control strategy of ASHPWH for water heating and quantified the resulting improvements.

The ambient temperature and hot water load on typical days is shown in Fig. 6. Since the system provides domestic hot water for student apartments, the hot water load is generally peaked in the morning, midday, and evening hours due to the students' work and rest.

The original start-stop operation of the ASHPWH on typical days is shown in Fig. 7. It can be seen that the ASHPWH starts and stops too frequently, generally more than 20 times a day during the transition season and summer. This phenomenon is the result of an unreasonable scheme. The two ASHPWH in the system were set to start and stop simultaneously, and the heating capacity of the units, hot water load, and set water temperature were poorly matched.

The control strategy for water heating was optimized in several ways, including running the two ASHPWH independently, resetting the upper and lower water temperature limits, and storing hot water in advance at night. The optimized start-stop operation of the two ASHPWH on typical days is shown in Fig. 8. Compared with the original scheme, the number of starts and stops was reduced by more than 60%.

The improvement was further quantified. The start-stop power consumption was calculated according to the standard [22] and incorporated into the optimized SLCPF, and then the operating costs were calculated based on the peak and valley electricity prices for student apartments in Shanghai. The results showed that the SLCPF of the ASHPWH for 5 years of operation increased from 2.24 to 2.42, an improvement of 8.0%; the total operation cost decreased from RMB 712,200 to RMB 659,800, a decrease of 7.4%. This result can be explained by the fact that the optimization of the control strategy has resulted in fewer starts and stops of the ASHPWH, thus reducing the start-stop power consumption and improving the SLCPF.

4.2 Heat exchanger cleaning

The ASHPWH studied in this paper are installed on open roofs, and the heat exchangers are fouling seriously due to improper operation and maintenance. In this section, we investigate the improvement of SLCPF by heat exchanger cleaning in combination with field tests and simulations.

We cleaned the air-cooled finned tube heat exchangers of ASHPWH, as shown in Fig. 9, and tested the operating parameters before and after cleaning. The results show that the evaporating temperature of one system increased by 1.6°C and the COP increased from 2.51 to 2.62. The evaporating temperature of the other system increased by 1.4°C and the COP increased from 3.12 to 3.24.

Keeping the heat exchanger of ASHPWH clean helps to slow down its energy performance decay and significantly improves its SLCPF. The simulation results show that the SLCPF of two ASHPWH operating for 5 years increased from 2.30 and 2.23 to 2.58 and 2.48, with an improvement of 12.2% and 11.2%.

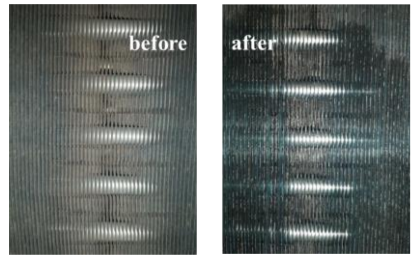

Fig. 9. The heat exchanger before and after cleaning

5 CONCLUSIONS

In this paper, we conducted a field study on the energy performance decay of ASHPWH, proposed an evaluation model for the long-term energy performance of ASHPWH, and conducted a quantitative study on its improvement. The main conclusions are as follows.

1) The APF of five ASHPWH samples studied in this paper decays by 5%-6% per year, which is detrimental to the long-term energy savings of ASHPWH.

2) The SLCPF model was proposed, which is an ASHPWH long-term energy performance evaluation model that integrates the initial values of APF and its annual decay magnitude.

3) The improvements of SLCPF were quantified using simulation, and the results showed that optimizing the control strategy for water heating could improve the SLCPF by 8.0%; keeping the heat exchanger clean could improve the SLCPF by 12.2%.

Finally, it should be noted that the energy performance decay and improvement of ASHPWH can be influenced by a variety of factors, such as system scheme and local climate, and changes in each factor may lead to numerical differences in the results. Further research is needed in this area.

REFERENCE

[1] Cao X, Zhang C-L, Zhang Z-Y. Stepped pressure cycle - A new approach to Lorenz cycle. International Journal of Refrigeration. 2017;74:283-94.

[2] Sun S, Guo H, Lu D, Bai Y, Gong M. Performance of a single-stage recuperative high-temperature air source heat pump. Applied Thermal Engineering. 2021;193:116969.

[3] Xiao B, Huang T, He L, Yan Y, Sun Y, Wang W. Experimental study of an improved air-source heat pump system with a novel three-cylinder two-stage variable volume ratio rotary compressor. International Journal of Refrigeration. 2019;100:343-53.

[4] Sim J, Lee H, Jeong JH. Optimal design of variable-path heat exchanger for energy efficiency improvement of air-source heat pump system. Applied Energy. 2021;290:116741.

[5] Ju F, Fan X, Chen Y, Wang T, Tang X, Kuang A, et al. Experimental investigation on a heat pump water heater using

R744/R290 mixture for domestic hot water. International Journal of Thermal Sciences. 2018;132:1-13.
[6] Guo H, Gong MQ, Qin XY. Performance analysis of a modified subcritical zeotropic mixture recuperative high-temperature heat pump. Applied Energy. 2019;237:338-52.
[7] Wang F, Wang Z, Zheng Y, Lin Z, Hao P, Huan C, et al. Performance investigation of a novel frost-free air-source heat pump water heater combined with energy storage and dehumidification. Applied Energy. 2015;139:212-9.
[8] Qu M, Li T, Deng S, Fan Y, Li Z. Improving defrosting performance of cascade air source heat pump using thermal energy storage based reverse cycle defrosting method. Applied Thermal Engineering. 2017;121:728-36.
[9] Pospisil J, Spilacek M, Kudela L. Potential of predictive control for improvement of seasonal coefficient of performance of air source heat pump in Central European climate zone. Energy. 2018;154:415-23.
[10] Wu P, Wang Z, Li X, Xu Z, Yang Y, Yang Q. Energy-saving analysis of air source heat pump integrated with a water storage tank for heating applications. Building and Environment. 2020;180:107029.
[11] Fang A, Hou Y, Wang F. Feasibility of Domestic Hot Water Regulation for Power Grid Peak and Valley Balance: Hotel-Building Case Study. Journal of Energy Engineering. 2017;143:05017002.
[12] Willem H, Lin Y, Lekov A. Review of energy efficiency and system performance of residential heat pump water heaters. Energy and Buildings. 2017;143:191-201.
[13] Song M, Deng S, Dang C, Mao N, Wang Z. Review on improvement for air source heat pump units during frosting and defrosting. Applied Energy. 2018;211:1150-70.
[14] Song M, Wang K, Liu S, Deng S, Dai B, Sun Z. Techno-economic analysis on frosting and defrosting operations of an air source heat pump unit applied in a typical cold city. Energy and Buildings. 2018;162:65-76.
[15] Liang X-Y, Cheng J-H, He Y-J, Wang L, Li H, Shao L-L, et al. Study on annual energy performance of transcritical CO2 heat pump water heating systems in Shanghai. International Journal of Refrigeration. 2019;107:174-82.
[16] ASHRAE. ANSI/ASHRAE Standard 206-2013 Method of Test for Rating of Multi-Purpose Heat Pumps for Residential Space Conditioning and Water Heating. 2017.
[17] CEN. EN 16147- Heat pumps with electrically driven compressors - Testing, performance rating and requirements for marking of domestic hot water units. 2017.
[18] Standardization Administration of the People's Republic of China. GB/T 21362-2008 Heat pump water heater for commercial & industrial and similar application. 2008.
[19] Zhang C-L. Fundamentals of vapor-compression refrigeration and air-conditioning system modeling. Beijing: Chemical Industry Press; 2012.
[20] Zhang C-L, Yang L, Shao L-L. Refrigeration and air-conditioning system modeling and analysis using GREATLAB. Beijing: Chemical Industry Press; 2015.
[21] Bagarella G, Lazzarin R, Noro M. Sizing strategy of on-off and modulating heat pump systems based on annual energy analysis. International Journal of Refrigeration. 2016;65:183-93.
[22] Standardization Administration of the People's Republic of China. GB/T 17758-2010 Unitary air conditioners. 2010.