STUDY ON THE OPTIMIZATION OF HEAT LOSS DURING OPERATION OF AIR SOURCE HEAT PUMP BASED ON ENTRANSY THEORY

Fang Ruan[a],*, Dingye Qin[a], Saisai Xu[a], Pengxu Chen[a], Shun Li[a]

[a]College of Civil Engineering, Xiangtan University, Xiangtan, Hunan, China

Corresponding author: E-mail: rufa2002@163.com

Existing research on the analysis heat pump operation generally focuses on the efficiency of doing work while ignores heat loss in the transfer process. Hence, heat pumps are often studied based on theory of minimum entropy production. However, this theory is rarely applied to optimizing heat transfer process without heat work conversion. Taking the air source heat pump hot water supply system of a hotel building as an example, this paper simulates the heat production, power and coefficient of performance of the air source heat pump during operation based on the theory of entransy and entransy dissipation proposed by Professor Zengyuan Guo. The findings show that heat pump operates best at inlet water temperatures of 293K and 298K, with a coefficient of performance of 4.8. In the water at a temperature of 298K, water temperature can be adjusted by the function of heating capacity between 30 kW and 40 kW to minimize the system's entransy dissipation, where the system's unit power consumption reaches its minimum at 9 kW, corresponding to an entransy dissipation of 245.4 kJ·K. This study provides a good research idea to optimize the thermal power conversion process using the theory of entransy and entransy dissipation.

Keywords: *entransy theory; ASHP; COP*

1 Introduction

With sustainable economic development and improvement of people's living standards, energy and environmental issues are becoming increasingly prominent. In recent years, building heating has been consuming more and more energy, with the energy consumption of heating, ventilation and air conditioning systems accounting for more than 40% of the total building energy consumption [1]. In 2020, China set a development target of "peak carbon by 2030 and carbon neutral by 2060" [2] to gradually reduce the use of traditional energy sources. Therefore, renewable and clean energy sources [3], especially air energy, should be introduced to replace traditional energy sources to reduce the use of traditional energy sources and carbon emissions.

Air-source heat pump (ASHP) has the advantages of high efficiency, energy conservation, and environmental benefits [4],[5]. In particular, hot water can be prepared using air sources [6]. According to the regression analysis of energy consumption variables, its energy saving can be up to 40% compared to traditional boiler [7]. and the electrical energy required to prepare hot water using heat pumps is about half of that required by traditional electric water heaters, so ASHP can be used in large quantities in the market, making its optimization one of the research priorities. The water supply temperature is an important factor affecting the heat transfer efficiency of ASHP [8], and an adaptive water supply temperature control method has been proposed for water temperature regulation, which is able to predict the optimal setting value of feed water temperature and achieve the adaptive identification of parameters [9]. Zhang et al. used EnergyPlus to model the energy consumption of heating system and established an optimal control method for water temperature [10]. There have been studies combining ASHP with solar energy (SHW) [11] or ground-source heat pump(GSHP) [12], using air source heat pump as the auxiliary heat system and designing a variety of operation modes to improve energy efficiency and optimize performance. Various theories for optimizing heat pumps have also been proposed by many scholars, most of which have been applied to water source heat pump (WSHP), GSHP, and other devices. Likewise, it is possible to consider selecting and applying appropriate theory to the operation of ASHP.

For the performance analysis and optimization of heat exchangers, researchers have proposed a variety of methods, and entropy generation analysis is one of the more commonly used methods. Entropy is a physical quantity that reflects the inequality of heat and power and measures the ability to do work in a closed-port system, however, the heat exchanger heat transfer process does not always involve work, and there are some problems in optimizing the heat transfer process. It has been pointed out that entropy analysis alone cannot fully determine the irreversibility of heat transfer processes that do not contain heat work conversion, but rather reduces heat transfer performance [13].

Aiming at this type of problem, Professor Zeng-Yuan proposed a new physical quantity entransy, the physical meaning of which is the ability of an object to transfer heat in a time period. It is mainly used for the optimization of heat transfer processes that do not contain heat work conversion [13]. Entransy theory was initially applied to heat conduction, heat convection, heat radiation, and heat exchangers [15], while later it is used for thermodynamic processes for systems with heat work conversion [16]. To enhance heat transfer, heat transfer optimization analysis was carried out on heat exchangers mainly based on entransy theory [17]. Some studies combine entransy theory with other theories to optimize heat transfer systems [18] and explore the controversies of entransy theory in heat transfer, its significance and its development in detail [19]. In addition, entransy theory can be used for the evaluation of thermodynamic performance of heat pump systems, especially suitable for heat flow into high temperature heat sources [20]. As well as analyzing hybrid absorption-compression heat pump cycles to reduce the irreversibility of heat exchange [21]. These studies have proved that the theory can be used for the optimization of heat pumps with favorable results.

In this study, entransy theory is applied to ASHP, and numerical simulation is used as the main method to analyze the heat transfer process, to obtain the inlet temperature, heating capacity, and unit power consumption of the air source heat pump with optimal performance after the application of entransy theory, and experiments are carried out to ensure the reliability of the results.

It is worth mentioning that although the entransy theory is highly controversial in the international arena, it is still studied by many scholars at home and abroad, and the authors believe that this is not only a proof and promotion of the entransy theory, but also a refinement of heat transfer science.

2 Physical model

Fig.1 shows that ASHP works according to the principle of the inverse Carnot cycle, in which heat exchange occurs between the liquid mass in the evaporator and surrounding air, hot water is heated in the condenser, and then the pressure is reduced and cooled back to the evaporator so that heat exchange continues. The inlet water temperature fluctuates with outdoor temperature, so heating cycle was set to heat water to 323K and the refrigerant used in the experiment is R134a.

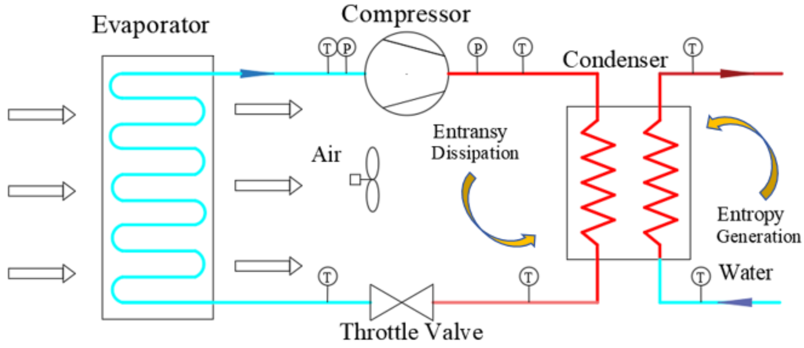

Figure 1. Simplified model of air source heat pump water heater

3 Materials and Methods

3.1 Numerical Calculation Model

The most central role of ASHP in hot water supply system is to transfer heat from air to water, and the core of the present study is heat transfer rather than heat work conversion. Analogous to the potential energy, the object's entransy that can be transferred out of the thermal potential energy, heat transfer is an irreversible process. Although the energy is conserved, it will be dissipated in the process of heat transfer due to the existence of thermal resistance, which is called entransy dissipation. In the evaporator, it is the air that exchanges heat with R134a, while in the condenser R134a exchanges heat with water, and tap water is heated. In this study, ASHP heats tap water at different temperatures up to 323K. In the whole heat transfer process, most of the heat is used to heat tap water, and heat pump unit will suffer heat dissipation, which is negligible.

Entransy equation can be expressed as:

$$G = \frac{1}{2} Q_h T = \frac{1}{2} \int q_h dT \qquad (1)$$

The entransy dissipation model on the condenser side is expressed as:

$$G_{con} = \int_{T_c}^{T_h} q_{con} dT = q_{con} \ \Delta T_{con} \qquad (2)$$

Since there is a thermodynamic relationship between system entransy dissipation and heat pump heat production, heat gain from the tap water on the condenser side should be firstly calculated by:

$$Q = c_p m \Delta t \qquad (3)$$

Then the entransy of the system is quadratically related to the heating capacity of the heat pump. Considering the influence of system heat dissipation and environmental factors, the quadratic function is assumed to be:

$$G = aQ_h^2 + bQ_h + c \qquad (4)$$

In addition, comparing the entransy dissipation rate and entropy yield of the heat transfer process, Where C_{min} is the smallest value in the cold and heat capacity flow;

Maximum efficiency of heat exchangers:

$$\varepsilon = \frac{c_h \left(T_{h,in} - T_{h,out}\right)}{C_{\min} \left(T_{h,in} - T_{c,in}\right)} \qquad (5)$$

entransy dissipation rate analysis:

$$\Phi_g = c_{p,h} m_h \left(T_{h,in} - T_{c,in}\right)^2 \left[\varepsilon - \frac{1}{2} \varepsilon^2 \left(1 + \frac{c_{p,h} m_h}{c_{p,c} m_c} \right) \right] \qquad (6)$$

In addition, to better represent the advantages of entransy dissipation analysis, entropy generation analysis is also performed on the system:

$$S_g = m_h c_{p,h} \ln \left[1 - \frac{c_{p,h} m_h \left(T_{h,in} - T_{c,in}\right)}{c_{p,h} m_h T_{h,in}} \varepsilon \right] + m_c c_{p,c} \ln \left[1 + \frac{c_{p,h} m_h \left(T_{h,in} - T_{c,in}\right)}{c_{p,c} m_c T_{c,in}} \varepsilon \right] \qquad (7)$$

3.2 Simulation and Validation

The structure and operation diagram of the system was established in TRNSYS, and some high-rise rooms were mainly selected to prepare for hot water circulation. The model of the system is shown in fig.2.

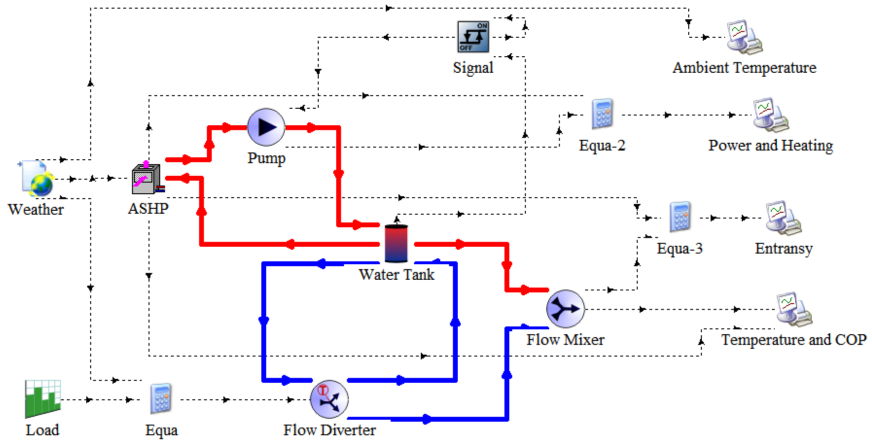

Figure 2. ASHP system simulation model

3.3 Simulation settings

The temperature of tap water in life is basically between 278K and 298K, (eq.(1)) is used in Equ-3, and the relevant parameters of heat pump, water tank and pump in TRNSYS are shown in tab.1.

Table 1. Parameter Setting

Parameters	Value	278K	283K	288K	293K	298K
Design Heating Capacity	(kW)	58.06	51.61	45.16	38.71	40.73
ASHP Heating Capacity	(kW)	73.31	65.16	57.02	48.88	40.73
ASHP Rated Power	(kW)	24.44	21.72	19.01	16.29	13.58
Water Tank	(m^3)	1.40	1.24	1.09	0.93	0.78
Pump Rated Flow	(m^3/h)	4990	4430	3880	3330	2770
Pump Rated Power	(kW)	0.2265	0.2014	0.1762	0.1510	0.1259
Fan Power	(kW)	1.50	1.33	1.09	0.93	0.78
Fan Flow	(m^3/h)	12496	11107	9717	8331	6943

In TRNSYS, type 941 was selected as air source heat pump and Xiangtan City as weather file. The water output temperature was set to 323K. In the design of heating capacity, with large hotels as the standard, hot water supply was divided by guest rooms and 43 rooms, each of which could accommodate 2 people, with an occupancy rate of 75%. The number of people was set to 64, whose per capita water consumption was 160 L/D. The hourly variation coefficient of water consumption was 2.6, the correction coefficient of heating capacity was 0.8, and the correction coefficient of power was 0.99. And in the Load section of the model, the daily water use percentage was entered, with a scale range of 0 to 0.2, and the peak water use period was from 20:00 to 22:00 each night.

4 Experimental verification

As part of the validation, experimental tests were conducted on ASHP in November 2022.

The experimental measurement parameters included air temperature, humidity and air speed at the inlet of evaporator as well as air temperature and humidity at the outlet of evaporator, which were measured by multi-parameter ventilation meter TSI-9555A and thermal recorder Tr7WF, respectively, and the temperature of refrigerant at the inlet and outlet pipe sections of evaporator, compressor, condenser and expansion valve by Ni-Cr and Ni-Si thermocouples. The accuracy level of thermocouple was 0.2, with the measurement error less than 0.2%. The measurement data was recorded using a paperless recorder PLR. The water temperature of the condenser inlet and outlet was measured by a high precision digital display thermometer SGD-155LED with a measurement accuracy of 0.1. The water flow was measured by a high precision electronic flow meter TS-13 with a measurement accuracy of 0.01. In addition, a wired power recorder WGLZY-1 was employed to measure the heat pump power with a measurement accuracy of 0.01 during the experiment.

The water temperature was relatively stable on November 28, the wind speed changed little, and the temperature showed a curvilinear change of rising and then falling, so the data was relatively reliable for research.

The water temperature obtained from the experiment on November 28 compared with the water temperature obtained from the simulation in the same time period is compared in fig.3**.** As can be seen from the figure, the maximum and average errors error between the experimental and simulated values were 9% and 4%, respectively, showing that the average error between the simulated and experimental results was small. Therefore, it can be inferred that the experimental and simulated values were in good agreement.

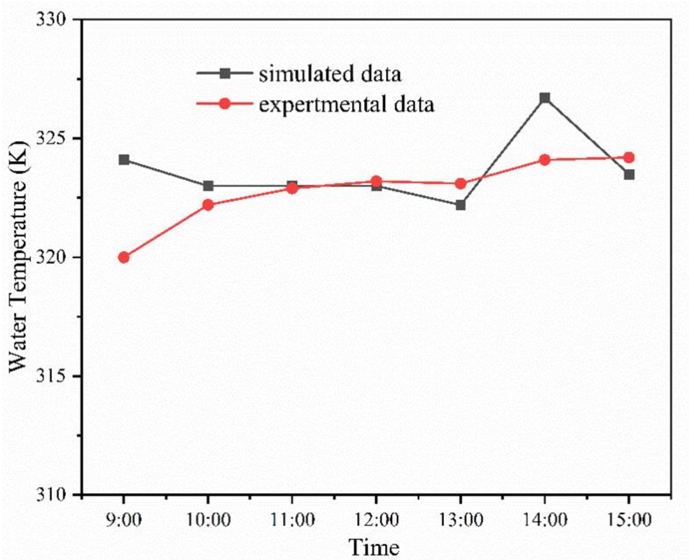

Figure 3. Comparison of water temperature between simulation and experiment

In addition, to further analyze the differences between the simulated and experimental values, relative error (RE) and mean relative error (MRE) were used in this study. The relative error (RE) and mean relative error (MRE) are given by:

$$RE = \frac{\left| t_{si} - t_{ei} \right|}{t_{ei}} \tag{8}$$

$$MRE = \frac{\sum_{i=1}^{n} RE_i}{n}$$

where t_{si} and t_{ei} are the simulation and experimental results of the measuring point temperature, respectively.

The relative errors between the simulated and experimental values for each measuring point are shown in tab.2.

Table 2. Error Comparison

Simulated versus experimental values	Percent of condenser outlet water temperature
MRE (%)	4
RE_{max} (%)	9

5 Results and Discussion

The ASHP hot water production system was simulated to study the relationship between unit heat production, unit power, COP and system entransy dissipation of air source heat pump system. The inlet water temperature was set to 277K, 283K, 288K, 293K and 298K respectively, and the condenser outlet water temperature to 323K.

5.1 The effect of heat pump heating capacity on entransy dissipation

The heat transfer analysis (eq.(2)) is entered in the TRNSYS module Equ-3, and Equ-2 directly converts the output heating capacity.

The entansy dissipation of the system is directly related to the heat production of the heat pump, and fitted with (eq.(5)), the variation of the system's entansy dissipation with the heat production of the heat pump was simulated as follows:

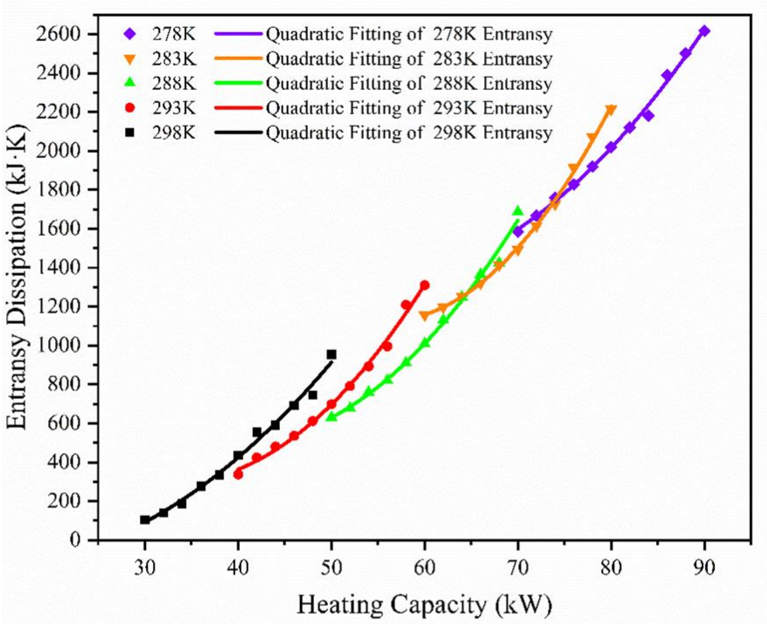

Figure 4. The relationship between heat pump heating capacity and entransy dissipation at different inlet water temperatures

As can be seen from fig. 4 , at different inlet water temperatures, both the heating capacity and entransy dissipation of the system varied only within a certain range, and both increased with the decrease of inlet water temperature. In addition, under the same conditions, the system's entransy dissipation reached its minimum at the inlet water temperature of 298K. At this temperature, the system's heat transfer capacity was stronger than that at other temperatures, but with the same highest heat transfer efficiency. However, the water temperature of 278K was the most unfavorable conditions, where the system's heat transfer capacity was reduced the most, and its heat transfer efficiency was relatively from the perspective of heat transfer.

The fitted curves of the system's entransy dissipation as a function of heat pump heating are given in fig. The curve base equation was obtained according to (eq.(5)). The quadratic term coefficients of the resulting curves were in the range of 0.78 to 2.0, and the squared covariance of the resulting curves were all greater than 0.98, indicating that the curves were highly consistent with the data. The curves could be used as a function of the variation of entransy dissipation with heat pump heating. According to the influence of ambient temperature on the heat pump parameters, the system operated best at the inlet water temperatures of 293K and 298K, so the corresponding curve function at both temperatures was respectively presented as:

$$G_{tem,20} = 1861.1832 - 94.0827Q_{tem,20} + 1.4149Q_{tem,20}^2 \quad (9)$$
$$G_{tem,25} = 42.8723 - 21.9723Q_{tem,25} + 0.7880Q_{tem,25}^2$$

In actual life and engineering applications, the heating capacity of air source heat pump can be controlled according to inlet water temperature to minimize heat loss and improve heat transfer efficiency.

5.2 The effect of heat pump power on entransy dissipation

The heat transfer analysis (eq.(2)) is entered in the TRNSYS module Equ-3, and Equ-2 directly converts the output heat pump power.

To study the relationship between the power of the ASHP and the entransy dissipation of the system, inlet water temperature was selected as the variable to obtain the power of the heat pump at different water temperatures and the corresponding instantaneous entransy dissipation of the system.

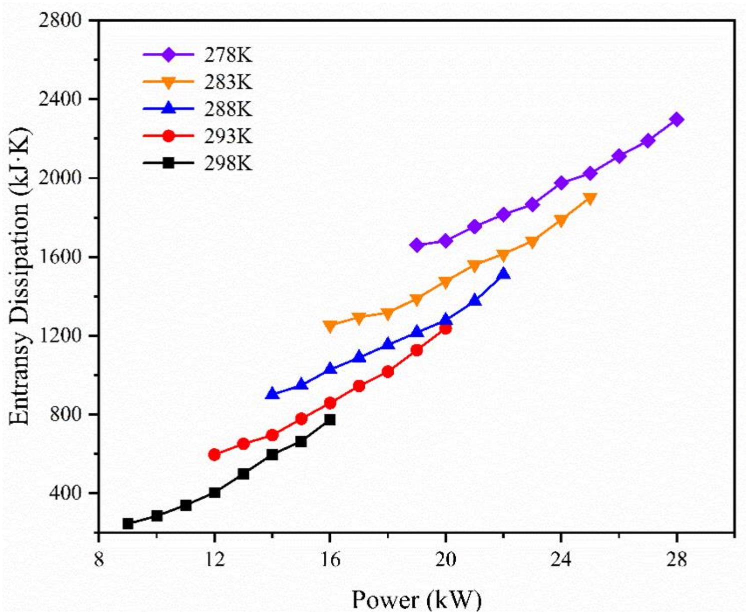

Figure 5. The relationship between heat pump power and entransy dissipation at different inlet water temperatures

As can be seen from fig.5, the entransy dissipation of the system increased with the power of the heat pump, and the power of the heat pump corresponding to each inlet water temperature varied within a certain range. When inlet water temperature was 298K, the overall power of the heat pump was the smallest at 9 kW and so was the corresponding entransy dissipation at 245.4 kJ·K. As the power increased, the overall power of the heat pump reached its maximum at 16 kW, while the corresponding entransy dissipation was only 773.9 kJ·K. When inlet water temperature was 278K, the power of the heat pump as a whole was topped at 30 kW, so was entransy dissipation at 2541.3 kJ·K. Under such condition, the power of the heat pump was bottomed at 19 kW, so was entransy dissipation of the system at 1659.4 kJ·K, which means that the greater the inlet water temperature, the smaller the power required by the air source heat pump to prepare hot water of the same temperature, the smaller the entransy dissipation of the system. To put it in another way, the system exhibited the best heat transfer capacity and the highest heat transfer efficiency.

In addition, the increased power of the ASHP also resulted in increased operation cost. Heating water from 298K to 323K was the relatively most economical option for operation, without considering the demand for equipment investment. The actual life of tap water temperature was difficult to reach 298K. The energy efficiency of air source heat pump could be established according to the inlet water temperature of heat pump power to achieve the purpose of energy saving.

5.3 The relationship between system COP and entransy dissipation

The heat transfer analysis (eq.(2)) is entered in the TRNSYS module Equ-3 and the system COP is output directly.

In order to study the effect of system COP on system entransy, the trend of system entransy dissipation with COP when the ASHP heated cold water of different temperatures to 323K was obtained, as shown in fig.6.

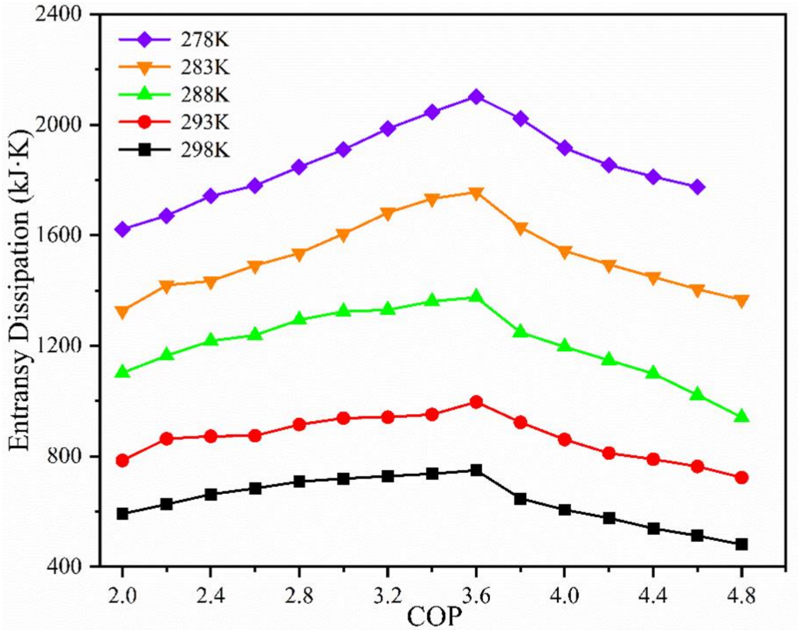

Figure 6. COP versus entransy dissipation of the system at different inlet water temperatures

As shown in fig.6, the COP of the system for heating cold water of different temperatures up to 323K was between 2.0 and 4.8. The lowest entransy dissipation of the whole system was observed at the inlet water temperature of 298K, while the highest entransy dissipation of the system at the water temperature of 283K. Under the same conditions of COP, the higher the water temperature, the greater the entransy dissipation of the system, and the greater the difference in the entransy dissipation between the water temperatures. It can be seen from fig.6. that the system's entransy dissipation increased by 300 kJ·K on average as water temperature decreased every 5K which was mainly caused by the increased difference between inlet and outlet water temperatures, which further indicates that when using air source heat pumps to prepare hot water, inlet water temperature should be controlled above 293K in order to reduce the system's entransy dissipation.

5.4 Entransy dissipation rate and Entropy generation rate

The entransy dissipation rate and entropy generation rate on the condenser side of the air source heat pump are calculated by (eq.(5)) , (eq.(6)) and (eq.(7)), and the results are shown as follows:

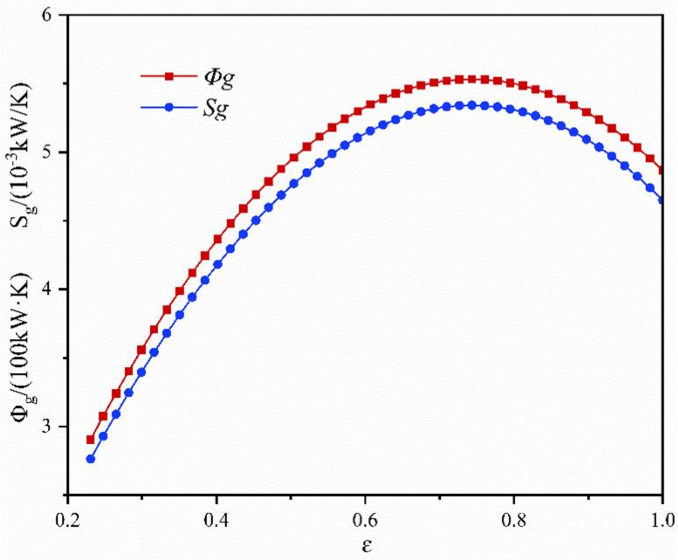

Figure 7. Variations of entransy dissipation rate and entropy generation rate with efficiency

It can be seen from fig.7, entransy dissipation rate and entropy generation rate in the efficiency range is not monotonous change, and the trend of change is roughly the same, in the efficiency of 0.7 when both reached the maximum value, and for the case, the trend of change of the efficiency and heat flow is the same, then the two can not be fully described the heat exchanger efficiency and the change of heat transfer. Therefore, for the analysis of the heat transfer process on the condenser side of the system, it is relatively objective to directly use the entransy dissipation to show its changes.

6 Conclusion

This paper analyzes the operation of ASHP based on entransy and entransy dissipation theory, through the establishment of TRNSYS model and experimental testing, it proves that the entransy theory can be used in the analysis and optimization of specific working conditions of the ASHP, and gives the relevant functional relationship to provide a little bit of ideas for future research, the main conclusions are as follows:

(1) The heat production of air source heat pump is proportional to the system's entransy dissipation. The system's entransy dissipation increases wit heat production. Within a certain range, inlet water temperature can be controlled at 298K to minimize the system's entransy dissipation, at which the system's heat transfer capacity is stronger than that at other water temperatures, accompanied by the highest heat transfer efficiency. At this time, the heat production of air source heat pump is maintained between 30 kW and 40 kW, when the system exhibits the smallest entransy dissipation but the strongest heat transfer capacity.

(2) The power of the air source heat pump is also proportional to the entransy dissipation of the system. The entransy dissipation of the system increases with power, and the overall

power of the heat pump is the smallest when inlet water temperature is 298K. It is the most economical operation option to heat the water from 298K to 323K.

(3) In the case of different water temperatures, the entransy dissipation of the system reaches its maximum when the COP is 3.6. The system's entransy dissipation at the water temperatures of 288K, 293K and 298K is already lower than the initial value when the COP is close to 4.4, and decreases to the minimum when the COP is 4.8.

Although entropy generation has been widely used in the evaluation of the irreversibility of thermodynamic processes, there are still certain problems in the analysis and optimization of heat transfer processes without heat work conversion. This study uses entransy dissipation as an index to optimize the heat transfer process of an ASHP, which provides a reference for the development of entransy theory, although there are still some gaps in comparison with the studies of other researchers from the details, for example, there are limitations in the applicability of the theory, and this paper mainly focuses on the heat transfer process at the condenser side, whereas the whole heat pump's Heat transfer analysis is not enough.

Acknowledgements:

This work was supported by Hunan Provincial Natural Science Foundation of China (2022JJ50135).

7 References

[1] M. Usman, *et al.*, A methodology for multi-criteria assessment of renewable integrated energy supply options and alternative HVAC systems in a household, *Energ. Buildings, 273* (2022), pp. 112397. https://doi.org/10.1016/j.enbuild.2022.112397

[2] Y. Wang, *et al.*, Heating performance of a novel solar-air complementary building energy system with an energy storage feature, *Sol. Energy, 236* (2022),pp. 75-87. https://doi.org/10.1016/j.solener.2022.02.054

[3] C. Lee, C. Wang, Does natural resources matter for sustainable energy development in China: The role of technological progress, *Resour. Policy, 79* (2022),pp. 103077. https://doi.org/10.1016/j.resourpol.2022.103077

[4] G. Zhang, *et al.* Review on recent developments of variable refrigerant flow systems since 2015. *Energ Buildings, 198*(2019),pp. 444-466. https://doi.org/10.1016/j.enbuild.2019.06.032

[5] Z. Xu, *et al.*, Atmospheric air quality in Beijing improved by application of air source heat pump (ASHP) systems, *J. Clean. Prod, 257* (2020),pp. 120582. https://doi.org/10.1016/j.jclepro.2020.120582.

[6] Ibrahim, *et al.*, Air source heat pump water heater: Dynamic modeling, optimal energy management and mini-tubes condensers, *Energy, 64* (2014),pp. 1102-1116. https://doi.org/10.1016/j.energy.2013.11.017

[7] K. Gram-Hanssen, *et al.*, Air-to-air heat pumps in real-life use: are potential savings achieved or are they transformed into increased comfort. *Energ Buildings, 53* (2012),pp. 64-73. https://doi.org/10.1016/j.enbuild.2012.06.023

[8] G. Leonzio, P. S. Fennell, N. Shah, Air-source heat pumps for water heating at a high temperature: State of the art, *Sustain. Energy. Techn and Assessments.* **2022,** *54*, 102866. https://doi.org/10.1016/j.seta.2022.102866
[9] Y. Sun, *et al.*, Performance analysis of air source heat pump space heating system with an adaptive control for supply water temperature, *Appl. Therm. Eng, 211* (2022), pp. 118401. https://doi.org/10.1016/j.applthermaleng.2022.118401
[10] Z. Zhang, *et al.*, Whole building energy model for HVAC optimal control: A practical framework based on deep reinforcement learning, *Energy. Build, 199* (2019),pp. 472-490. https://doi.org/10.1016/j.enbuild.2019.07.029
[11] J. Long, *et al.*, Study on energy-saving operation of a combined heating system of solar hot water and air source heat pump, *Energ. Convers. Manage, 229* (2021),pp. 113624. https://doi.org/10.1016/j.enconman.2020.113624
[12] Y. Wang, *et al.*, Operation mode performance and optimization of a novel coupled air and ground source heat pump system with energy storage: Case study of a hotel building, *Renew. Energ, 201* (2022), pp. 889-903. https://doi.org/10.1016/j.renene.2022.11.016
[13] T. Zhao, *et al.*,Irreversibility evaluation for transport processes revisited, *Int. J. Heat Mass Transf*, *189* (2022), pp. 122699. https://doi.org/10.1016/j.ijheatmasstransfer.2022.122699
[14] Z. Guo, *et al.*, Entransy—A physical quantity describing heat transfer ability, *Int. J. Heat. Mass. Tran, 50* (2007), pp. 2545—2556. https://doi.org/10.1016/j.ijheatmasstransfer.2006.11.034
[15] J. Guo, M. Xu, The application of entransy dissipation theory in optimization design of heat exchanger, *Appl. Therm. Eng. 36* (2012),pp. 227–235. https://doi.org/10.1016/j.applthermaleng.2011.12.043
[16] X. Cheng, X. Liang, Discussion on the application of entransy theory to heat-work conversion processes, *Acta. Phys. Sin*, *19* (2014),pp. 190501. 10.7498/aps.63.190501
[17] Y. Xu, *et al.*, Entransy dissipation-based constraint for optimization of heat exchanger networks in thermal systems, *Energy, 86* (2015),pp. 696–708. https://doi.org/10.1016/j.energy.2015.04.024
[18] X. Chen, *et al.*, Entropy and entransy in convective heat transfer optimization:A review and perspective, *Int. J. Heat. Mass. Tran, 137* (2019),pp. 1191—1220. https://doi.org/10.1016/j.ijheatmasstransfer.2019.04.017
[19] Z. Guo, Entransy · Thermomass energy · Relativistic kinetomass energy, *Scientia. Sinica. Technologica*, *10* (2021),pp. 1137-1154. 10.1360/SST-2021-0139
[20] X. Cheng, X. Liang, Discussion on the applicability of entropy generation minimization and entransy theory to the evaluation of thermodynamic performance for heat pump systems, *Energ. Convers. Manage*, *80* (2014), pp. 238-242. https://doi.org/10.1016/j.enconman.2014.01.008
[21] J. You, *et al.*, Entransy based heat exchange irreversibility analysis for a hybrid absorption-compression heat pump cycle, *Energy*, *289* (2024), pp. 129990. https://doi.org/10.1016/j.energy.2023.129990

Submitted: 16.10.2023
Revised: 11.11.2023
Accepted: 02.02.2024.