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Experimental investigation of condenser with small diameter copper tube in air source heat pump water heater

Tiantian Wang[a], Zhanpeng Liu[a], Naiping Gao[a,*], Tingwei Fan[b], Hengyi Zhao[c], Yifeng Gao[c]

[a]School of Mechanical Engineering, Tongji University, Shanghai, 201804, China
[b]Gomon New Energy Ltd. of Jiangsu Province, Taizhou, 214500, China
[c]International Copper Association, Shanghai Representative Office, Shanghai, 200020, China

Abstract

In this paper, a series of experimental tests on system coefficient of performance (COP) of air source heat pump water heater (ASHPWH) working with R22 were carried out. ASHPWH equipped the condenser which was wrapped around copper tubes with different inner diameters of 4.5 and 6.4mm and variable types of smooth tube and internal threaded tube. Besides, the economic cost of aforementioned systems were compared and analyzed. The results show that the system performance of ASHPWH with small diameter copper tubes of 4.5mm is improved compared with the large diameter copper tube of 6.4mm, meanwhile the total costs are greatly reduced. Given that the inner diameter is constant, the internal threaded tube has a significant improvement in system COP compared with the smooth tube. Moreover, COP of ASHPWH with internal threaded tubes whose inner diameter is 4.5mm can reach 4.17, therefore the small diameter copper tube has a good application prospect in ASHPWH.

Keywords: heat pump water heater; coefficient of performance (COP); condenser; small diameter copper tubes.

1. Introduction

With the rapid rise of Chinese economy and advancement of urbanization, the "energy bottleneck" problem is becoming increasingly serious. The energy cost of Chinese construction operation was 864 Mtce (million tons of standard coal equivalent) in 2015 excluding biomass energy [1], accounting for about 20% of the total energy consumption in China. As for urban dwelling, the urban residential energy consumption was 192 Mtce in 2015 excluding northern heating, and the energy consumption of domestic hot water was equal to 27 Mtce, accounting for about 14% of total residential energy consumption.

The concentrated supply of urban residential hot water in China mainly depends on electricity, fuel (coal, oil, gas) and solar energy. With increasing awareness of energy saving and emission reduction, the advantages of heat pump water heater, including air source [2-4], ground source [5-6] and solar source [7-8], are significantly obvious in medium-sized centralized hot water supply and small domestic hot water supply. ASHPWH is one of the most widely used style in the market due to its energy-savings, environmental friendliness, flexibility and convenience over the recent decades.

In general, the analysis of the dynamic system characteristics under different working conditions of ASHPWH can be carried out by means of modelling and experiments. Ibrahim et al. [9] proposed a dynamic simulation model to predict the performance of an ASHPWH. The developed model was utilized to assess its performance from the perspective of energy savings and greenhouse gas emissions. Peng et al. [10] developed an ASHPWH model to work under wide operating conditions using different expansion devices, such as electronic expansion valve (EEV), capillary tube and short tube orifice, it was found that the EEV throttling system performed best. Zhang et al. [11] investigated the system performance of an ASHPWH via calculating

* Corresponding author. Tel.: +86-021-65983867, +86 13817847420.
E-mail address: gaonaiping@tongji.edu.cn.

and testing, it pointed out that the refrigerant filling quantity played an important role in heat pump system running.

Some investigations were conducted to compare the different types of refrigerant used in the air source heat pump (ASHP) system. Wang et al. [12] presented a novel frost-free ASHP system working with R134a and R407C as an R22 alternative, the results showed that R134a was more promised alternative than R407C to R22 for the novel ASHP system. Li et al. [13-14] compared the effects of R22, R134a and R744 on the solar-air hybrid heat source heat pump water heater, it was found that the COP of R744 was highest within the ambient temperature of 5~13°C while the COP of R134a was best when the ambient temperature was higher than 13°C.

Moreover, the condenser characteristics were also paid special attention. Yang et al. [15] analyzed the flow condensation heat transfer and pressure drops of R1234yf and R134a in a small circular tube. The results showed that both pressure drop and condensation heat transfer performance depended on the fluid properties, flow conditions and flow patterns. Yan et al. [16] investigated the characteristics of condensation heat transfer and pressure drop of R134a flowing in a horizontal small circular pipe with an inside diameter of 2.0mm, it was found that the condensation heat transfer coefficient of small pipe was about 10% higher than that of large pipe with the inside diameter of 8.0mm. Son et al. [17] experimentally studied the condensation heat transfer of R22, R134a and R410a flowing in the horizontal copper tube of 1.77, 3.36 and 5.35mm inner diameter, respectively. In case of two-phase flow, the condensation heat transfer coefficient for R22, R134a and R410a increased with increasing mass flux and decreasing tube diameter.

The literatures listed above mainly attached importance to the system COP related with expansion devices, refrigerant and its filling quantity. And special attention was paid to the condenser characteristics. But the effects of structural parameters of copper tubes in the condenser on system COP have rarely been investigated. Accordingly, the purpose of this study is to carry out new experimental research on copper tube with different inner diameters, lengths and types used in the condenser of ASHPWH. The effects of aforementioned parameters on system COP are analyzed and these parameters are optimized in order to improve the COP of system. Meanwhile the economic analyses between copper tubes and aluminum microchannel are also taken into consideration.

2. Experimental apparatus and procedures

2.1. ASHPWH experimental system description

The experimental apparatus established in the present study is schematically shown in Fig.1. And the theoretical *P-h* diagram is depicted in Fig.2. The picture of experimental bench is illustrated in Fig.3. The ASHPWH consists of three main loops: the air loop, the refrigerant R22 loop and the water loop. More special attention are paid to the refrigerant R22 circle. As can be shown in Fig.2, its basic components include compressor, condenser, expansion valve and evaporator. The superheated refrigerant vapor is produced in the evaporator, then it flows into the compressor and turns into high temperature and pressure refrigerant vapor via the isentropic compression process 1-2. Next it is sent to the condenser to release heat to the water tank and itself is cooled down to the liquid state, thereby the domestic water at a certain temperature can be obtained through the isobaric cooling process 2-3. Subsequently the liquid refrigerant turns into a gas-liquid mixed state after passing through the expansion valve and then it flows into the evaporator. The refrigerant absorbs heat from the outside air through the isobaric evaporation process 4-1, and enters the compressor again to start a new cycle.

The thermodynamics of ASHPWH can be calculated according to Fig.2. In the actual operation process, the electric energy consumed by the compressor can be expressed by the following equation (1).

$$W = \frac{m_f(h_2 - h_1)}{\eta_o} \tag{1}$$

And the mass flow rate of refrigerant R22 can be calculated according to equation (2).

$$m_f = \frac{N V_{cp} \rho_1 \eta_v}{60} \tag{2}$$

Then the released heat from the refrigerant R22 to water in the condenser can be calculated according to equation (3). Equally, this part of heat is absorbed by the water in the condenser.

$$Q_c = m_f(h_2 - h_3) = \frac{\rho_w V_w C_p (T_{out} - T_{in})}{t} \quad (3)$$

Meanwhile the absorbed heat from the ambient air is defined as the equation (4).

$$Q_e = m_f(h_1 - h_4) \quad (4)$$

Finally the system COP can be expressed as the following equation (5).

$$COP = \frac{Q_C}{W} \quad (5)$$

In the above equation (1) ~ (5), m_f represents the mass flow rate of refrigerant R22. The values of rotating speed N, displacement volume rate V_{cp} and volumetric efficiency η_v are 2880rpm, 17cm^3/rev and 91%. h_1, h_2, h_3 and h_4 stand for the enthalpy of point 1, point 2, point 3 and point 4 in Fig.2 respectively. η_o represents the overall efficiency of compressor and the value of it is 0.7 [18] in this study. ρ_w stands for the average density of domestic hot water in the heating process. V_w represents the volume of domestic hot water. C_p represents the average specific heat capacity of water. T_{in} and T_{out} mean the initial temperature and final temperature of water during the heating process. t represents the time of heating process. It is worth mentioning that the enthalpy of refrigerant R22 can be obtained according to the measured temperature and pressure in the corresponding position.

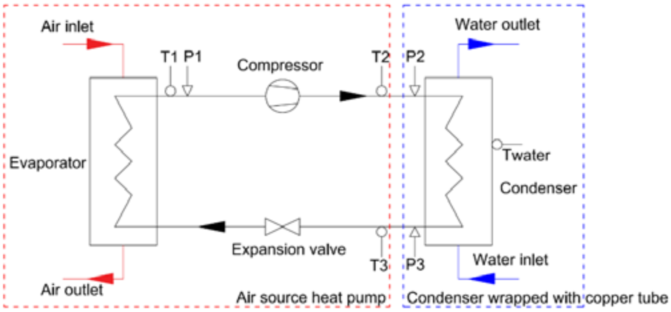


Fig. 1. Schematic diagram of the experimental system.

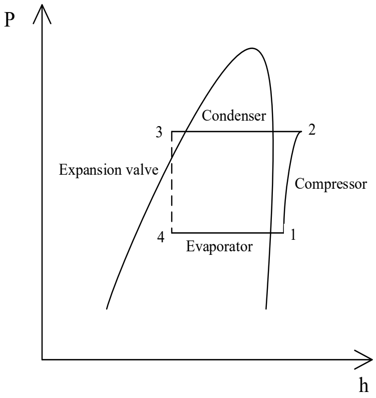


Fig. 2. Theoretical *P-h* diagram of ASHPWH.

2.2. Testing procedure and measuring sensors

The main goal of these experiments is to investigate the effects of different structural parameters of copper tubes on COP of ASHPWH. In this process, 200L water is heated from 15°C to 55°C, and the electric energy consumed by the compressor can be obtained due to the detected voltage and current. Besides, the heat exchange capacity in the condenser can be calculated according to Equation (3). Therefore the system COP can be obtained based on Equation (5). Meanwhile the economic analysis is also taken into consideration for practical application. In this study, the experimental tests are carried out via combining the water tank wrapped around copper tubes in different cases with the host of ASHP system. It should be noted that the dry bulb temperature and the wet bulb temperature of the ambient environment are 20°C and 15°C respectively. The performance parameters of the host are listed in Table 1.

Fig.4 (a) and (b) depict the geometrical and physical diagram of the water tank wrapped around copper tubes respectively. Table 2 illustrates five variable winding schemes of copper tubes outside the water tank in experimental tests. According to Table 2, group A and B study the effects of variable diameters and lengths of copper tubes on system performance. Group B and C pay special attention to copper tube arrangements. Group C and D investigate the effects of length of copper tube and refrigerant charge. Moreover, group D and E compare the effects of type of copper tube on system performance.

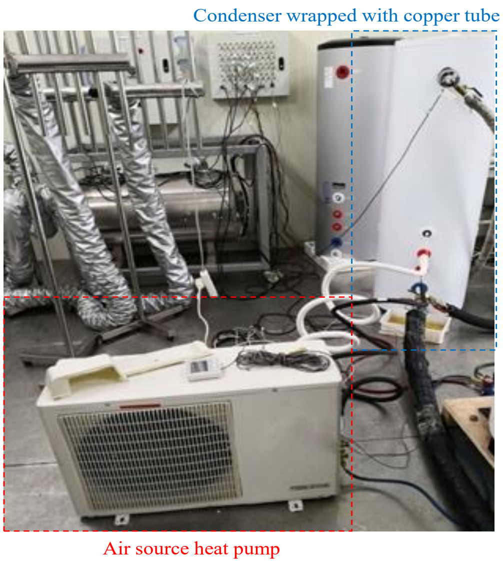


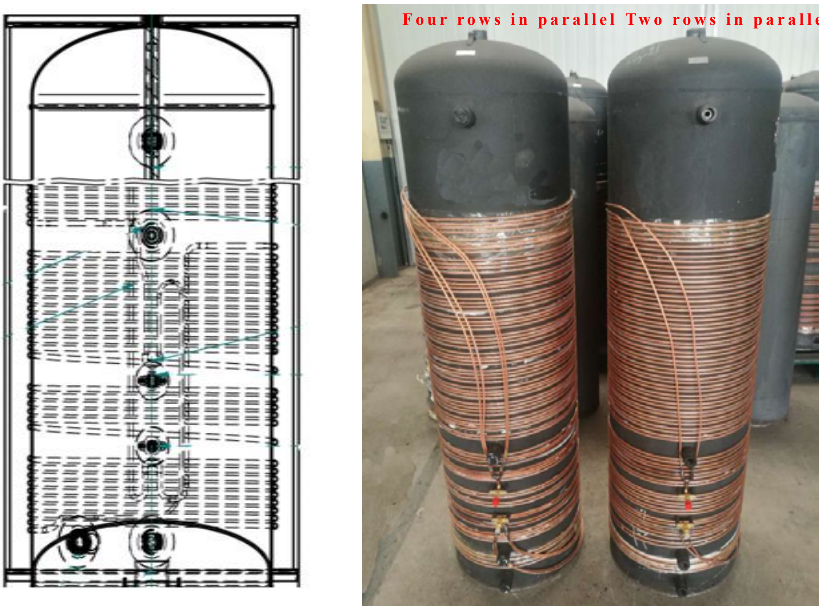
Fig. 3. Picture of the ASHPWH experimental bench.

Table 1. Performance parameters of host of ASHP system

Parameters	Value
Type	KF35E
Rated heating capacity (kW)	3.5
Domestic hot water output (L/h)	80
Rated input power/current (kW/A)	0.83/4.0
Maximum input power/current (kW/A)	1.3/6.0
Refrigerant/rated charge volume (-/g)	R22/1050
Maximum allowable pressure on high/low pressure side (MPa)	3.0
Allowable working overpressure on exhaust side (MPa)	3.0
Allowable working overpressure on suction side (MPa)	0.7

Table 2. Five winding schemes of copper tubes outside the water tank

Group	Inner diameter (mm)	Type	Length (m)	Arrangement	Refrigerant charge (g)
A	6.4	Smooth tube	60	Two rows in parallel	1050
B	4.5	Smooth tube	80	Two rows in parallel	1050
C	4.5	Smooth tube	80	Four rows in parallel	1050
D	4.5	Smooth tube	100	Four rows in parallel	1130
E	4.5	Internal threaded tube	100	Four rows in parallel	1130



(a) geometrical diagram (b) physical diagram

Fig. 4. Picture of water tank wrapped around copper tubes.

As can be seen in Fig.1, the experimental bench equips 4 thermocouples (T1-T3 and Twater), 3 pressure sensors (P1-P3). They are used to analyze the system characteristics under variable conditions. The specific information about these measuring sensors, such as the instrument type, measuring range and accuracy are given in Table 3.

Table 3. Major measuring sensors used in the experimental system

Parameter	Instrument type	Measuring range	Accuracy
P	diffused silicon pressure sensor	0-2MPa	±0.2% of MV
T	K-type thermocouple	0-1000°C	±1.5°C

3. Results and discussion

3.1. System performance of ASHPWH

The performances of five winding schemes of copper tubes outside the water tank are experimentally investigated using the host of ASHP system. The results of these tests are shown in Table 4. It is found that the COP of group A is 3.95 and it is higher than that of group B (3.66) and group C (3.82). Given that the refrigerant charge and the copper tube type are fixed in these three groups, the heat exchange area of group A is larger than group B and C because of the variable diameters and lengths of copper tube. Besides, comparing group B and C, the arrangement of copper tubes can also affect the system performance. Obviously the arrangement of four rows in parallel runs better than that of two rows in parallel under the same condition. It can be clearly seen in Table 4 that the values of power consumed by compressor of group B and C are 0.83kW and 0.84kW respectively, which are nearly the same. However, the heating capacity of group C is 3.21kW and it is obviously higher than that of group B (3.04kW). Meanwhile the heating time of group C is a little shorter compared with group B. Furthermore, the type of copper tube is also a significant factor affecting system performance. It can be easily found that the internal threaded tube in group E can make the COP of ASHPWH increase by 5% compared with smooth tube in group E considering other things being equal. This is because the internal threaded tube increases the heat exchange area while also enhancing the heat transfer effect on the refrigerant side, thus increasing the heat transfer coefficient of the refrigerant side. Therefore the heating time required for group E is greatly shortened to 9310s compared with 10160s in group D when heating the same volume of water.

Table 4. Experimental results of five variable winding schemes of copper tube

Group	Volume of water tank (L)	Heating time (s)	Heating capacity (kW)	Power consumption (kW)	COP
A	200	9640	3.47	0.88	3.95
B	200	11000	3.04	0.83	3.66
C	200	10420	3.21	0.84	3.82
D	200	10160	3.29	0.83	3.96
E	200	9310	3.59	0.86	4.17

Further to say, the variation of supercooling degree of refrigerant at the outlet of condenser is also taken into consideration. The variation ranges of five different cases are shown in Fig.5. Moreover, special attention is paid to the flow resistance of refrigerant in the copper tubes. The flow resistance of these five groups are depicted in Fig.6. What worth mentioning is that flow resistance in this paper represents the temperature difference corresponding to inlet and outlet pressure of condenser.

As can be seen from Fig.5, the supercooling degree of refrigerant in group A, B, C and D is basically between 5~10°C while the supercooling degree in group E is much higher. It means that the internal threaded tube makes heat transfer coefficient of refrigerant higher compared with the smooth tube, the heat exchange is so sufficient that energy efficiency of ASHPWH is greatly improved.

As shown in Fig.6, flow resistances of group B and E are larger than 3°C. It indicates that longer length, arrangement of two rows in parallel and internal threaded tube have adverse effects on flow characteristics in the copper tubes. Honestly speaking, although the COP of group E is highest, more attention should be paid to reduce the flow resistance in the future study in order to have a better system performance.

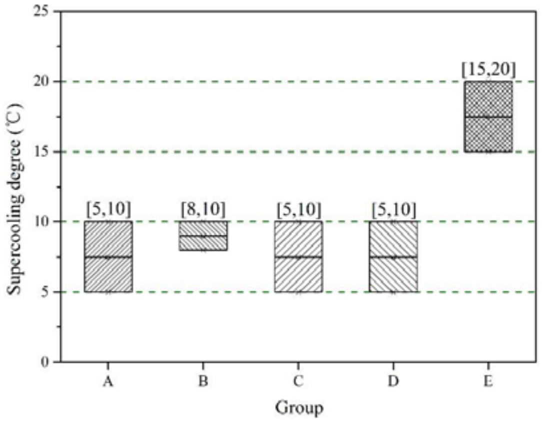


Fig. 5. Variation ranges of supercooling degree of five different groups.

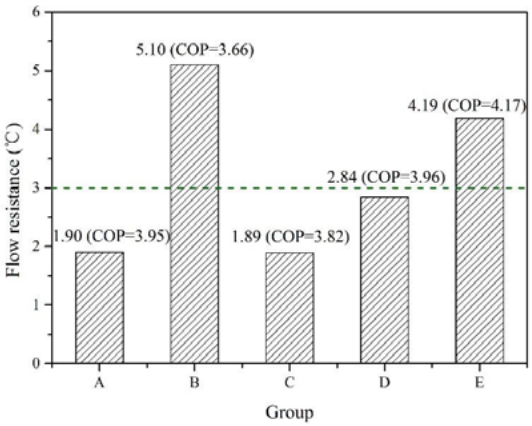


Fig. 6. Flow resistance of these five different groups.

3.2. Economic analysis of tubes

Generally speaking, the total costs of copper tubes consist of material cost and processing cost. And material cost takes a large proportion of total costs, while processing cost only accounts for 10%-20% of material cost. According to the survey, the material cost of copper is ¥45,000 per ton. The processing cost of smooth copper tube is ¥4,500 per ton, and that of internal thread copper tube is ¥6,500 per ton. The total costs of group A, D and E are listed in Table 5. Meanwhile the total cost of aluminum microchannel (group F) is also considered and compared with that of copper tubes.

As for the smooth copper tubes (group A and D), it indicates that copper tubes with smaller diameter can make ASHPWH run better while reducing the total costs. Besides, it is obvious that the total costs of internal threaded copper tubes with the inner diameter of 4.5mm in group E reduce by 17% compared to the smooth copper tubes with 6.4mm in group A. Meanwhile the COP of system increases by 5%. The main reason is that the internal thread copper tubes with smaller diameter can increase the heat exchange area while enhancing the convective heat transfer on the refrigerant side, thereby improving the system energy efficiency. However, what worth mentioning is that the smaller the diameter, the thinner the wall. Considering that the refrigerant pressure is relatively high within high temperature range, if the tube wall is too thin, it is easy to make the D-type copper tube change into O-type, thus reducing the heat exchange area. With regard to the water tank using aluminum microchannel, it is well-known that the unit cost of aluminum is lower than that of copper, but the processing cost of the former is too high. The values of COP in group D and F are 3.96 and 3.95 respectively, the total costs of smooth copper tubes with smaller diameter of 4.5mm reduce by 29% compared to that of aluminum microchannel. Moreover, the internal threaded copper tubes in group E can both increase the system COP and reduce the total costs. In summary, the copper tubes with smaller diameter are relatively more cost-effective, and can also improve the system COP. Thus it has a good application prospect in the area of ASHPWH in the future.

Table 5. Economic analysis of tubes in variable groups

Group	Type	Inner diameter (mm)	Weight per unit length (kg/m)	Length (m)	Total weight (kg)	Total costs (¥)	COP
A	Smooth copper tube	6.4	0.0537	60	3.22	159	3.95
D	Smooth copper tube	4.5	0.0317	100	3.17	157	3.96
E	Internal threaded copper tube	4.5	0.0256	100	2.56	132	4.17
F	Aluminum microchannel	--	--	--	--	220	3.95

4. Conclusions

In this study, the system performance of ASHPWH with variable water tanks using five winding schemes of copper tubes are experimentally investigated. Besides, special attention has been paid to the economic analysis of tubes utilized outside the water tank. The effects of inner diameter and type of copper tubes on system COP have been studied. Moreover, the total costs of copper tubes and aluminum microchannel have been analyzed. The following conclusions can be drawn:

1. As for the smooth copper tubes with different inner diameters (6.4 and 4.5mm), the smaller diameter copper tubes dominate in terms of system performance and economic cost of ASHPWH. Besides, the arrangement of four rows in parallel runs better than that of two rows in parallel considering all other things being equal.
2. With regard to the internal threaded tubes and smooth tubes with same inner diameter, the former can increase the heat exchange area while enhancing the heat transfer effect on the refrigerant side. Therefore the highest COP of ASHPWH can reach 4.17 using the internal threaded copper tubes with the inner diameter of 4.5mm. However, the internal threaded tubes have an adverse effect on system operation, meanwhile the flow resistance increases accordingly.
3. Small diameter copper tube outweighs aluminum microchannel in terms of economic cost of ASHPWH. The total costs of smooth copper tubes with inner diameter of 4.5mm reduce by 29% compared to aluminum microchannel when the system COP of these two cases are almost the same.

Nomenclature

C_p	average specific heat capacity (kJ/(kg·K))	*Subscripts*	
h	specific enthalpy (kJ/kg)	1-4	state point
m	mass flow rate (kg/s)	c	condenser
N	rotating speed (rpm)	cp	compressor
Q	heat transfer amount (kW)	e	evaporator
t	time (s)	f	working fluid
T	temperature (°C)	in	initial
V	volume (L)	o	overall
W	power (kW)	out	final
Greek symbols		out	v
ρ	density (kg/m^3)	w	water
η	efficiency		

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Responses to Reviewers' Comments

Dear Editor and Reviewers,

We quite appreciate the comments concerning our manuscript entitled "Experimental investigation of condenser with small diameter copper tube in air source heat pump water heater". Those comments are all valuable and very helpful for revising and improving our paper, as well as the important guiding significance to our researches. We have studied comments carefully and have made correction which we hope meet with approval. Revised portion are marked in red in the paper. The main corrections in the paper and the responses to the reviewer's comments are written in blue as following:

Reviewer #1

1. The description of symbols should add their units.

Discussion: Thanks very much for reviewer's careful suggestion. The "Nomenclature" section has been supplemented in order to describe the symbols in details and marked in red in the manuscript.

2. From the introduction, I can not understand the need of your research. The knowledge gap should be properly issued.

Discussion: Thanks for reviewer's valuable advice. The purpose of this study is to investigate the effects of structure parameters of copper tubes in the condenser on the COP of system throught experiments, which has rarely been studied before. Besides, it can provide the guidance for copper tubes applied in the area of ASHPWH. According to the reviewer's suggestion, we have supplemented the "Introduction" section and the modified texts are marked in red in the manuscript.

3. The overall efficiency of compressor η, how did you calculate it?

Discussion: Thanks for reviewer's question. According to some published literatures[1-3], the recommended range of overall efficicncy of compressor η_o is 0.7~0.75. In our experimental bench, the power consumed by the compressor can be detected directly by the dynamometer, the enthalpy of working fluid R22 at the inlet and outlet of compressor can be determined by the measured pressures and temperatures in the corresponding position. And the mass flow rate of working fluid can be calculated according to the following equation.

$$m_f = \frac{N V_{cp} \rho_1 \eta_v}{60}$$

The value of rotating speed N, displacement volume rate V_{cp} and volumetric efficiency η_v are 2880rpm, 17cm^3/rev and 91%. The density of R22 at the inlet of compressor ρ_1 can be obtained through Refprop 9.0 according to T_1 and P_1. Then the average overall efficiency of compressor in our experiments can be calculated accroding to equation (1) in the manuscript and the value of it in this study is 0.7, which is within the recommended range.

According to the reviewer's question, we have modified the section 2.1 and made explanations in the manuscript.

[1] Li YW, Wang RZ, Wu JY, Xu YX. Experimental performance analysis and optimization of a direct expansion solar-assisted heat pump water heater. *Energy* 2007;**32**:1361-74.

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4. There are still some English grammar mistakes in your paper. Maybe a native speaker is needed.
Discussion: Thanks a lot for reviewer's suggestion. We have examined the grammar in details and modified the full paper carefully. There are some minor modifications but they are **not** marked specifically in the manuscript.

5. Some quantitative analysis data should be given in the text of results section, especially when comparing performance.
Discussion: Thanks very much for reviewer's valuable suggestion. We have modified section 3.1 and 3.2 in the manuscript accordingly and the modified texts are marked in red.

Reviewer #2
This paper presented experimental tests on system coefficient of performance (COP) of air source heat pump water heater (ASHPWH) working with R22 in new experimental research of copper tube with different inner diameters, lengths and types used in the condenser. The author clearly shows the experimental apparatus, procedures, system performance and economic analysis. The paper is well-organized and the quality of English is satisfactory. The paper can be accepted.
Discussion: We appreciate for the reviewers' warm work earnestly.

We tried our best to improve the manuscript and made some changes in the manuscript. We appreciate for Editors/Reviewers' warm work earnestly, and hope that the correction will meet with approval.
Once again, thank you very much for your comments and suggestions!
Naiping Gao