EXPERIMENTAL INVESTIGATION ON THE PERFORMANCE OF A MODERATE-TEMPERATURE AIR-SOURCE HEAT PUMP WITH LARGE TEMPERATURE-DIFFERENCE ACROSS CONDENSER

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Abstract: This work experimentally investigates the impact of several operating parameters on the heating performance of a moderate-temperature air-source heat pump water heater. The operating parameters considered in the study are the air inlet temperature, hot water inlet temperature, flow rate of hot water, while the heating performance studied herein include the heating capacity of the condenser, power consumption of the compressor, and COP of the heat pump. The effect of temperature lift of heat pump on COP is also discussed. The results show that the temperature lift of heat pump could be served as an indicator for the assessment of COP. The COP will decrease by 13.5% for each 10K increment of temperature lift for the moderate-temperature air-source heat pump. The COP is 2.2, when the temperature lift of the heat pump is 61.3°C and the outlet temperature of hot water is 81.5°C.

Key Words: moderate-temperature, heat pump, air-source, water heater, experiment

1 INTRODUCTION

For many countries, increasing energy efficiency and reducing greenhouse gas emissions are key countermeasures to cope with the energy crisis and climate change. Of the various heating equipment such as heat pumps, gas-fired boilers, oil-fired boilers, or electric boilers commonly used, heat pumps are widely adopted for space heating, water heating, and process heating by households, business, and industry due to high energy efficiency and effective reduction of greenhouse gases. Heat pumps can generate hot water at three different temperature levels including normal (<60°C), moderate (60-100°C), and high temperatures (>100°C). In terms of heat sources, heat pumps can be classified into air-source, water-source, and ground-source.

For hot water supplied to households and businesses, the water outlet temperature generated by the heat pump is generally below 60°C. For application of heat pumps in process heating, the outlet temperature is between 60 and 90°C. Additionally, the outlet temperature for boiler feed-water preheating is required to be maintained between 60 and 90°C. At the same time, the water inlet temperature for the condenser is generally fixed. Under the above operating conditions, several problems may occur with the condenser: (1) the temperature difference between hot water inlet and outlet temperatures is high; generally above 40K and even up to 60K; (2) the condensing temperature increases as the outlet temperature increases contributing to the increase in the sensible heat ratio of refrigerants during the condensing process, as shown in Figure 1. In the figure, the vapour compressor cycles of three heat pumps with the same evaporating, subcooling, and superheating temperatures were compared. When the condensing temperature was 40°C, the sensible heat ratio of refrigerants during the condensing process contributed to 9 % of total

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condensation heat transfer. When the condensing temperature was increased to 60°C, the sensible heat ratio was increased to 15 %. When the condensing temperature was continuously increased to 80°C, the sensible heat even rose to 24 %. Therefore, this study focused on how to effectively recover the energy with high sensible heat ratio as well as achieve favourable energy efficiency during industrial process heating using moderate-temperature heat pumps.

Several studies that dealt with improved vapour compression heat pumps have been reported so far. Liu et al. (2005) tested a moderately high temperature water source heat-pump system with a near-azeotropic refrigerant mixture of R124/R142b/R600a. The results show that the condenser output temperature could reach 60-85°C under the evaporator inlet temperature was 30-55°C. The COP of such heat pump was greater than three as the temperature lift was less than 30°C. Zhou et al. (2007) experimentally studied an R125 critical cycle heat pump. The COP ranges from 2.8 to 2.1 with outlet temperature of hot water ranging from 50 to 75°C. Zhang et al. (2009) experimental investigated the behaviour of zeotropic refrigerant mixtures applied in a moderately high temperature water source heat pump with condensing temperature ranging of 70-90°C and temperature lift of 45°C. The results show that the mixtures M1B (mass fraction of 37% R152a and 63% R245fa) have the best cycle performance and is recommended as working refrigerant for moderate or high temperature heat pump. Wang et al. (2010) improved a high-temperature heat pump using parallel cycles with serial heating on water side, and found it is competitive as comparing its performance with a heat pump in two-stage cycle with an intercooler under the same operating conditions.

Only limited studies have been conducted regarding the moderate-temperature air-source heat pumps that are the research target of this study. This work investigated the impact of different operating parameters on moderate-temperature heat pump performance. The parameters were air entering temperature, hot water entering temperature, and flow rate of hot water. The performance investigated in the work is the heating capacity, power consumption, and coefficient of performance (COP) of the heat pump.

2 EXPERIMENTAL SETUP

2.1 Experimental Apparatus

A moderate-temperature air-source heat pump system for heating water has been built and tested in this study. The aims of this study were focused mainly on the evaluation of performance of heat pump using an improved condenser designed for large temperature difference. Figure 2 shows the schematic diagram of the experimental setup and the location of the sensors. The heat pump system consists of a compressor, a condenser, a throttling device, and an evaporator. R134a was selected as the working refrigerant in the heat pump system. The compressor is a type of semi-hermetic scroll with a displacement volume of 46.5 m^3/hr. The condenser is a type of shell-and-tube heat exchanger with eight passes and 60 copper tubes. The evaporator is a cross flow air-to-refrigerant heat exchanger of finned-tube type. The throttling device is a thermostatic expansion valve with an external equalizer. Heat released from the condenser is transferred to water while the evaporator takes heat from air in a controlled environment room as heat source. The temperature and humidity of ambient air entering to the finned-tube evaporator was controlled by a testing facility used to conduct the heat pump experiment. The inlet water temperature is adjusted by circulating the generated hot water and mixing with colder water from both cooling tower and water main supply. The temperatures of water, refrigerant, and air at various points in the heat pump system were measured by T-type thermocouples with an accuracy of ±0.1K. The measurement of refrigerant pressures is made by calibrated pressure transducers with an accuracy of ±0.15%. The water flow rate of condenser is measured by an electromagnetic flowmeter with accuracy of ±0.5%, while the power consumed by compressor and fan are measured by power meter with an accuracy of ±0.5%.

2.2 Test Condition and Procedure

The experimental parameters of this work are inlet temperature of air, inlet and outlet temperatures of hot water, and flow rate of water passing through condenser. In order to investigate the effect of those parameters on the heating capacity and performance of moderate-temperature air-source heat pump, this work conducted 22 experiments. The detail of testing conditions of this work is listed in Table 1. The test data were acquired and recorded every five minutes intervals through the data logger system connected to a notebook computer after the test system operation had reached steady state. The reliability of experimental data recorded was confirmed by energy balance method with less than 5% between the measured and calculated values.

Table 1: Experimental Conditions

TEST	T_{db} [°C]	T_{wb} [°C]	Fc [LPM]	Twi [°C]
1	20	15	10	25
2	25	17	10	18
3	25	16	10	20
4	25	16	10	30
5	20	16	10	9
6	20	6	10	10
7	20	6	10	20
8	20	7	10	30
9	10	21	10	8
10	10	21	10	10
11	10	21	10	20
12	10	7	10	30
13	2	-1	10	20
14	2	-2	10	30
15	20	16	10	25
16	20	17	13	25
17	20	16	17	25
18	20	16	27	25
19	20	16	10	30
20	20	16	13	30
21	20	17	13	30
22	20	17	10	30

2.3 Data Reduction

- Temperature lift of heat pump, ΔT_{lift}

The temperature lift of heat pump is the temperature difference between hot water outlet temperature and air source inlet temperature as follows.

$$\Delta T_{lift} = T_{wo} - T_{ai} \quad [°C] \tag{1}$$

where T_{wo} is the inlet temperature of hot water, and T_{ai} is the outlet temperature of air.

- Heating Capacity, $\dot{Q}_H$

The heating capacity of heat pump can be determined as follows.

$$\dot{Q}_H = \dot{F}_c \cdot \rho_w c_{pw} (T_{wo} - T_{wi}) \quad [kW] \tag{2}$$

where $\dot{F}_c$ is water flow rate, ρ_w is density of water c_{pw} is specific heat of water, T_{wi} and T_{wo} represent the inlet and outlet temperatures of water, respectively.

- Total Power Consumption, $\dot{W}_{Total}$

The total power consumption of heat pump is the sum of the power consumption of compressor and fan, and can be calculated as follows.

$$\dot{W}_{Total} = \dot{W}_{comp} + \dot{W}_{fan} \quad [kW] \tag{3}$$

where W_c and W_{fan} represent the power consumed by compressor and fan, respectively.

- Coefficient of Performance, COP_H

The coefficient of performance for heating is defined as the ratio of heating capacity to total power consumption and can be determined as follows.

$$COP_H = \frac{\dot{Q}_H}{\dot{W}_{Total}} \tag{4}$$

3 RESULTS AND DISCUSSIONS

3.1 The Impact of Water Outlet Temperature

The hot water outlet temperature of moderate-temperature heat pumps is much higher than that of normal temperature heat pumps. Therefore, condensers of moderate-temperature heat pumps often encounter problems due to the higher temperature difference between inlet and outlet temperatures and higher sensible heat ratio. To overcome the above-mentioned issues, this study designed a 12-pass condenser. Figure 3 shows the variations of hot water outlet temperature to the condensing temperature under all experimental conditions. According to the curve, we discovered that when the condensing temperature was above 70°C, the water outlet temperature was generally 3 to 5°C higher than the condensing temperature. For normal temperature heat pumps, the water outlet temperature is 3 to 5°C lower than the condensing temperature. Results indicated that the condenser developed by this study could make the water outlet temperature higher than the condensing temperature as well as effectively recycle the sensible heat of refrigerants during the condensing process. The design of the condenser we developed was thus proved successful.

Table 2: Experimental Data

Case	P_1	T_1	P_2	T_2	T_e	T_c	F_c	T_{wi}	T_{wo}	Q_h	T_{ai}	T_{ao}	W_{in}	COP_h
	[MPa]	[°C]	[MPa]	[°C]	[°C]	[°C]	[LPM]	[°C]	[°C]	[kW]	[°C]	[°C]	[kW]	
1	0.405	17.6	2.141	90.7	9.3	70.5	10	25.0	75.8	37.6	20.1	14.6	14.3	2.6
2	0.532	21.9	2.337	88.4	17.7	74.5	10	17.7	75.6	41.2	25.0	20.7	15.5	2.7
3	0.552	20.4	2.405	89.5	18.9	75.8	10	20.1	76.7	40.2	25.0	21.0	15.7	2.6
4	0.552	21.5	2.523	93.0	18.9	78.0	10	29.7	78.9	39.1	25.0	20.7	16.3	2.4
5	0.454	17.0	1.895	79.7	12.8	65.1	10	8.6	64.8	38.4	20.1	16.3	13.2	2.9
6	0.454	17.0	1.905	81.1	12.8	65.4	10	9.9	65.4	37.5	20.1	16.3	13.2	2.8
7	0.473	17.5	2.317	90.8	14.1	74.1	10	20.0	79.7	41.6	20.1	16.3	15.3	2.7
8	0.464	17.6	2.317	91.3	13.4	74.1	10	30.1	78.6	33.9	20.0	16.8	15.3	2.2
9	0.317	6.3	1.287	68.0	2.2	49.1	10	7.9	49.6	29.0	10.1	6.4	9.9	2.9
10	0.326	6.7	1.366	68.6	3.1	51.4	10	10.1	51.5	30.1	10.0	7.1	10.2	3.0
11	0.326	8.6	1.739	80.6	3.1	61.4	10	20.0	60.7	29.9	10.0	6.5	11.8	2.5
12	0.356	8.3	2.062	89.0	5.5	68.8	10	30.1	69.0	27.2	10.0	7.2	13.4	2.0
13	0.199	-10.2	1.18	68.8	-10.5	45.7	10	20.0	45.7	18.5	2.0	-2.2	9.4	2.0
14	0.258	-0.6	1.699	84.4	-3.4	60.5	10	30.1	58.1	20.1	2.1	-0.9	11.5	1.8
15	0.454	15.7	2.327	89.9	12.8	74.3	10	25.0	76.0	37.0	19.9	16.5	15.1	2.5
16	0.454	14.6	1.944	79.8	12.8	66.3	13	25.1	65.9	36.8	20.1	16.6	13.3	2.8
17	0.434	14.4	1.582	70.5	11.4	57.4	17	25.1	55.8	36.9	19.9	16.2	11.7	3.2
18	0.434	13.2	1.229	60.3	11.1	47.2	27	25.0	45.6	39.0	19.9	15.7	10.2	3.8
19	0.464	16.3	2.553	95.2	13.4	78.6	10	30.0	81.5	36.0	20.2	16.8	16.4	2.2
20	0.464	15.5	2.16	84.6	13.1	70.9	13	30.3	70.2	34.8	20.1	16.6	14.4	2.4
21	0.444	14.6	1.739	73.8	12.1	61.4	18	30.2	60.0	37.9	20.0	16.1	12.5	3.0
22	0.434	13.9	1.376	63.9	11.1	51.7	29	30.3	50.1	40.4	20.0	15.9	10.8	3.8

Figure 4 shows the impact of water outlet temperature on the heating capacity under four different air inlet temperature conditions. When the air inlet temperature was 2°C and the hot water outlet temperature increased from 45°C to 58°, there were no major changes in the heating capacity. The same result was obtained in experiments on different air inlet temperatures. Figure 5 shows the impact of water outlet temperature on total power consumption under different air inlet temperature conditions. The total power consumption is the sum of the consumption of the compressor and the fan. When the air inlet temperature was 2°C, the condenser with higher water outlet temperature consumed more power. The same trend was discovered in experiments on different air inlet temperatures. The cause of the above-mentioned phenomenon was that the condensing temperature increased as the water outlet temperature increased; as a result, the compression ratio increased, which led to the increase in power consumption.

Figure 6 shows the impact of outlet temperature on the COP under four air inlet temperature conditions. The overall COP of the heat pump decreased as the condensing temperature increased. From Figures 4 and 5, we discovered that the COP decreased as the power consumption increased due to the small changes in heating capacity. When the water outlet temperature of the heat pump was higher than 70°C, the COP was still above 2.3.

3.2 The Impact of Temperature Difference of Water across the Condenser

Figure 7 presents the curve of the impact of inlet water temperature difference of the condenser on the COP of heat pump. The data of Table 2 and Figure 7 show that the impact of the inlet and outlet temperatures of the condenser on COP displayed two trends. In the constant flow-rate experiments (Case 1-15), noted as CF in the figure, the COP increased as the temperature difference between the inlet and outlet temperatures increased. However, in the variable flow-rate experiments (Case 16-22), noted as VF in the figure, the COP decreased as the temperature difference increased. If we compare the analytical data listed in Table 2, the main cause of the above-mentioned differences can be understood. In the constant flow-rate experiments, when the temperature difference between the water inlet and outlet temperatures increased from 20K to 60K, the heating capacity could increase from 18.5 kW to 41.6Kw and the power consumption from 9.4kW to 15.7kW. Obviously, the increase in heating capacity was greater than that of power consumption leading to the increase in COP as the temperature difference increased.

In the flow of hot water experiments, when the temperature difference between water inlet and outlet temperatures changed from 20K to 60K, the heating capacity decreased from 40kw to 35kW; the power consumption increased from 10.2 kW to 16.4kW, which led to the decrease in COP as the temperature difference increased.

From the above discussion, we found out that it was difficult to determine the trend of COP of heat pumps simply from the changes in temperature difference between hot water inlet and outlet temperatures of condensers.

3.3 The Impact of Temperature Lift in Heat Pump

The temperature lift in heat pumps was defined as the difference between hot water outlet temperature and air inlet temperature, as shown in Eq. (1). Figure 8 shows the impact of the temperature lift in heat pumps on the COP. When the temperature lift in the heat pump increased from 25K to 61K, the COP decreased from 3.8 to 1.8. Whether in the constant flow-rate or variable flow-rate experiment, the COP decreased as the temperature lift in the heat pump increased. The main cause for the above-mentioned phenomena can be discovered by examining the data of Figure 8 and Table 2. The data from the constant flow-rate experiments show that when the temperature lift was great and the change in the heating capacity was not obvious, the power consumption increased as the temperature lift increased, which led to the decrease in the COP.

The data from the variable flow-rate experiments showed that when the temperature rise in the heat pump increased and the heating capacity decreased from 40 kW to 35 kW, the power consumption increased from 10 kW to 16 kW leading to the decrease in the COP.

From the above discussion we can determine the COP trend from the temperature lift in the heat pump. The largest temperature lift of the heat pump developed by this study was 61.3°C, the hot water outlet temperature was 81.5°C, and the COP was 2.2. The experimental results of Liu et al. (2005) indicated that when the temperature lift in the heat pump was less than 30K, the COP was expected to be higher than 3. The experimental results from Case 22 of this study showed that the temperature lift was 30K, outlet temperature 50°C, and the COP 3.8, which is consistent with Liu's (2005) conclusions.

4 CONCLUSION

The research target of this study was a moderate-temperature air-source heat pump coupled with a condenser with great temperature difference. With experimental testing, we investigated the impact of the operating parameters such as the air inlet temperature, hot water inlet temperature, flow rate of hot water on the heating capacity of the condenser, power consumption of the compressor, and COP of the heat pump. After combining the results of experimental analysis, our conclusions were as follows:

(1) The temperature lift of heat pump could be served as an indicator for the assessment of

COP. The COP will decrease by 13.5% for each 10K increment of temperature lift.
(2) When the temperature lift of the heat pump is increased to 61.3°C and water outlet temperature 81.5 °C, the COP of the heat pump developed by this work was 2.2.
(3) When the temperature lift in the heat pump was 30K and the outlet temperature 50°C, the COP of the heat pump was 3.8. The performance results were consistent with Liu's (2005) results.

5 ACKNOWLEDGMENT

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6 REFERENCES

Liu, N., S. Lin, L. Han, and M. Zhu. 2005. "Moderately high temperature water source heat-pumps using a near-azeotropic refrigerant mixture". Applied Energy 80, 435-447.

Wang K., F. Cao, S. Wang, and Z. Xing. 2010."Investigation of the performance of a high-temperature heat pump using parallel cycles with serial heating on the water side." International Journal of Refrigeration 33, 1142-1151.

Zhou, X., Z. Lian, Z. Li, and Y. Yao. 2007. "Experimental study on HFC125 critical heat pump." Applied Thermal Engineering 27, 988–993.

Zhang, S., H. Wang, and T. Guo. 2009. "Experimental investigation of moderately high temperature water source heat pump with non-azeotropic refrigerant mixtures." Applied Thermal Engineering.

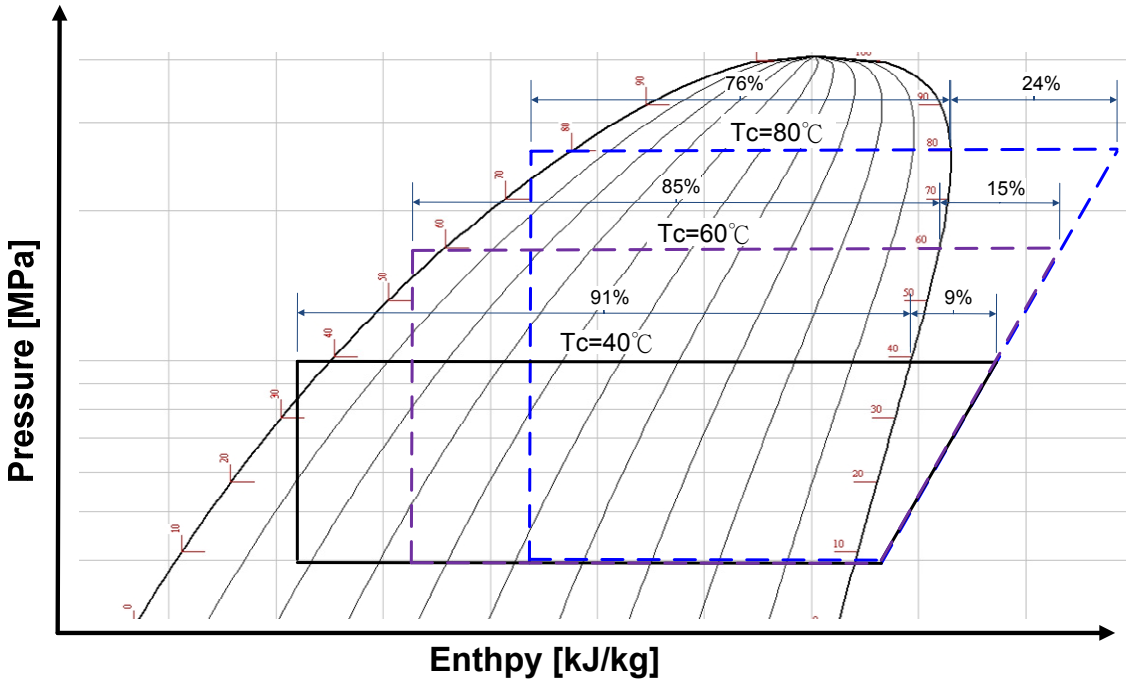


Figure 1: The impact of condensing temperature on the ratio of superheating

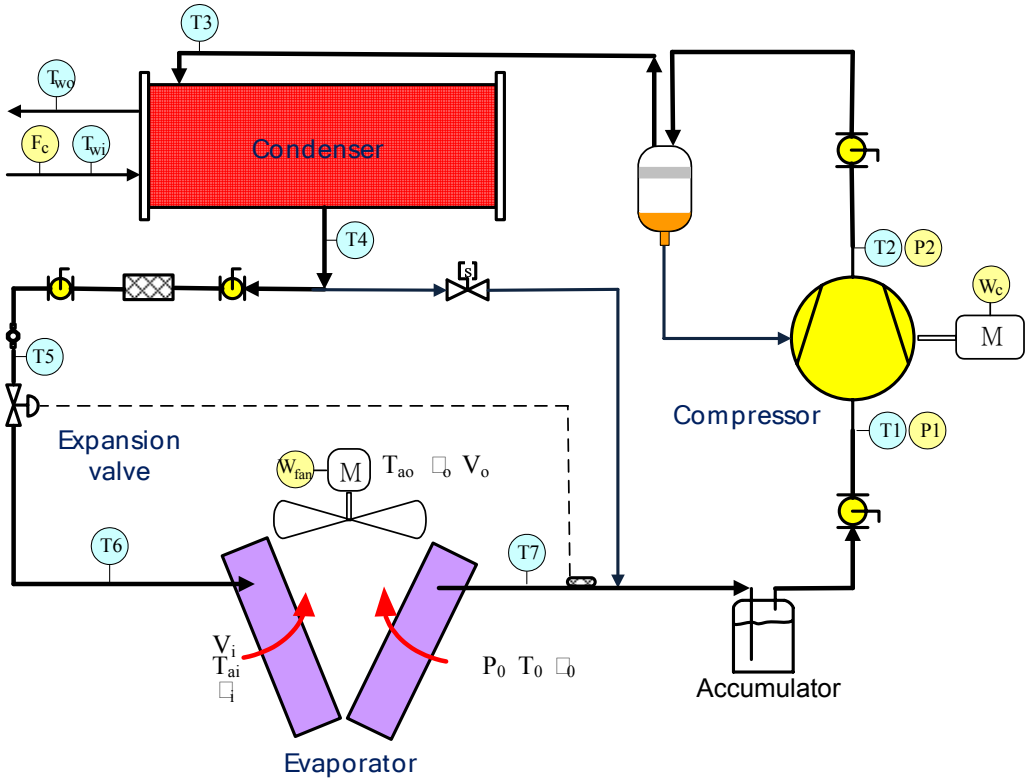


Figure 2: Schematic diagram of the experimental setup of an air-source heat pump

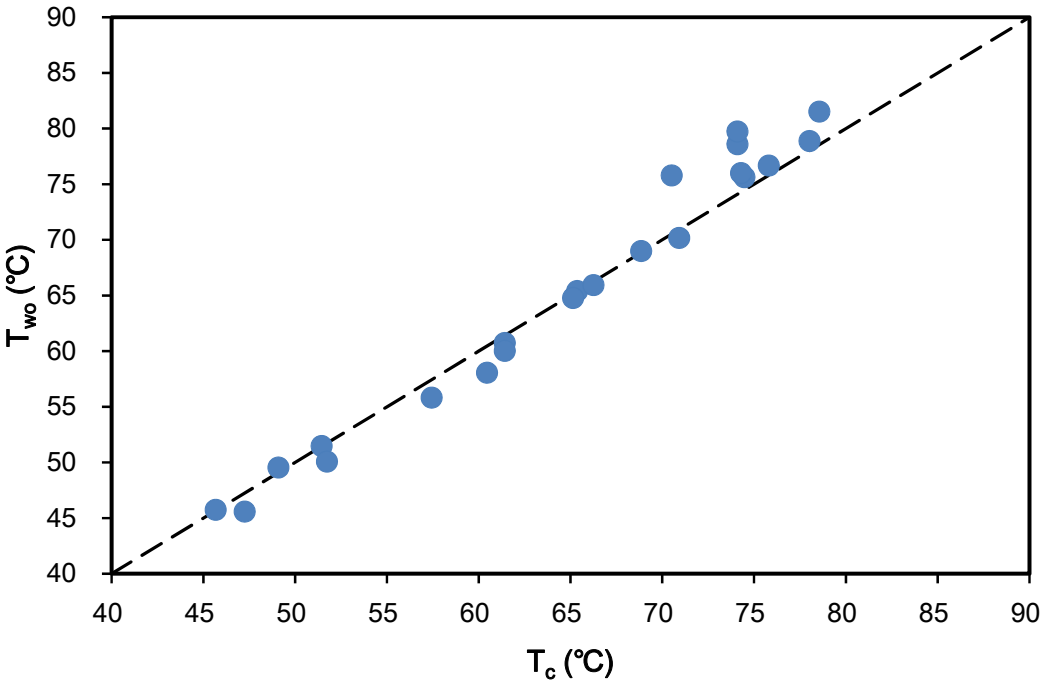


Figure 3: Variations of outlet temperature of hot water to condensing temperature

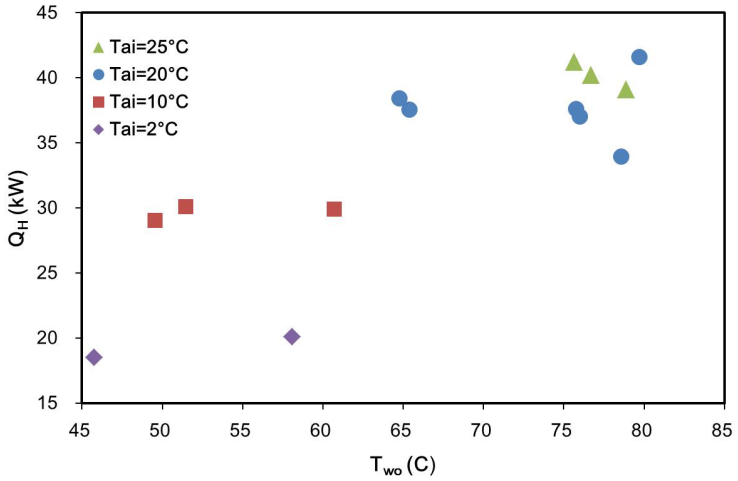


Figure 4: Variations of heating capacity to hot water outlet temperature

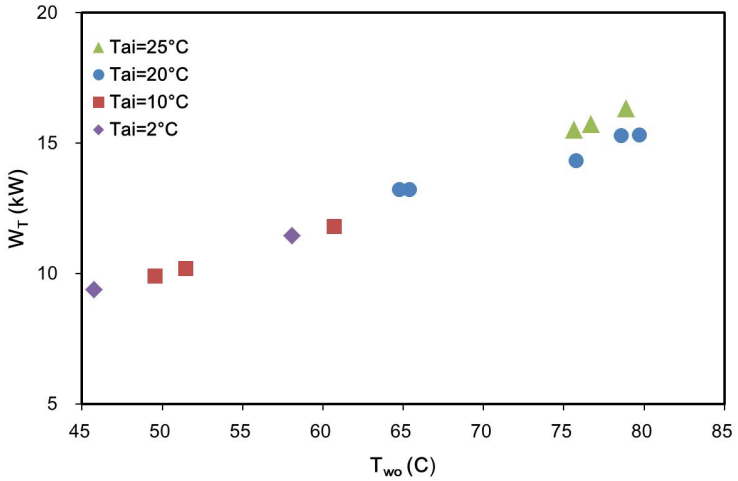


Figure 5: Variations of total power consumption to hot water outlet temperature

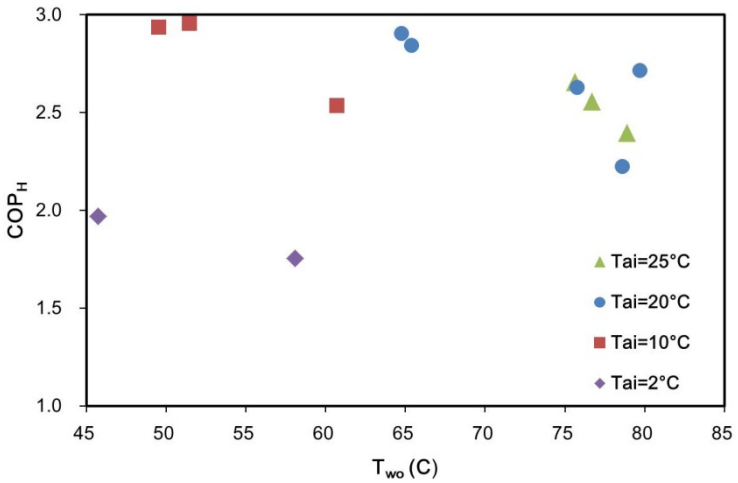


Figure 6: Variations of coefficient of performance to hot water outlet temperature

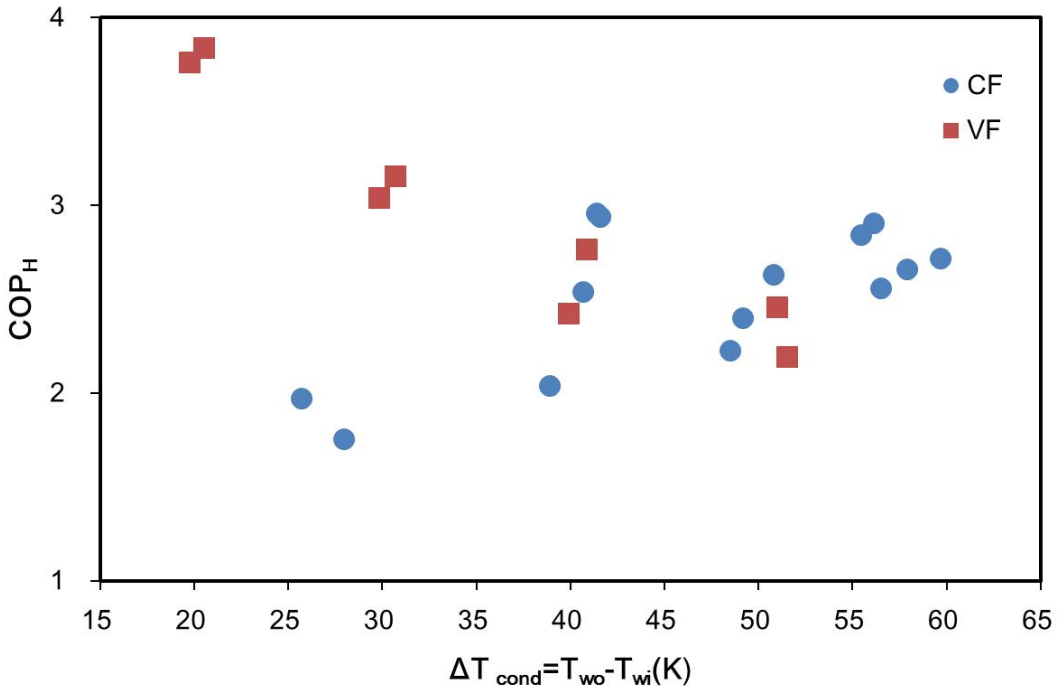


Figure 7: Variations of coefficient of performance to temperature difference of condenser

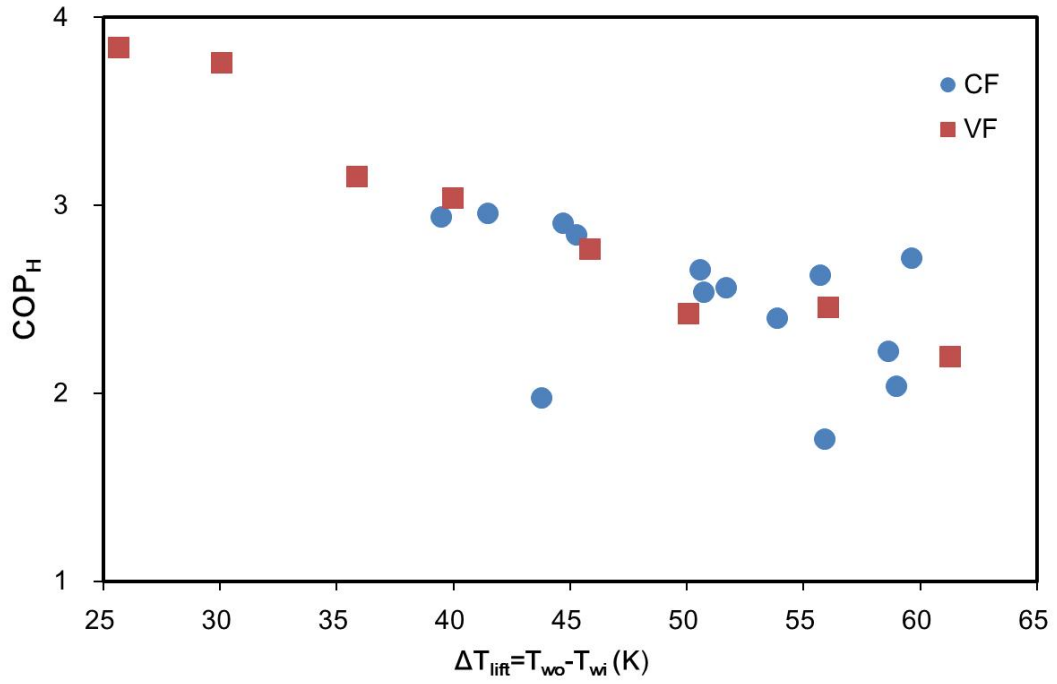


Figure 8: Variations of coefficient of performance to temperature lift of heat pump