Comparison of Two Gas Coolers in CO_2 Heat Pump Water Heater

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ABSTRACT

CO_2 transcritical cycle has been investigated as a potential alternative technology for the application of heat pump water heater. In this study, two tube-in-tube gas coolers in the CO_2 transcritical cycle heat pump water heater are studied. Two gas coolers are different on the internal tube. The one has only a single internal tube and the other has three screwed internal tubes. Two gas coolers were simulated and tested in the experimental system. The results show that although the heat exchanging surfaces of two gas coolers are same, the performance of the gas cooler with three screwed inner tubes is not better than the one with a single inner tube at least. But the gas cooler with three screwed inner tubes can help to decrease ratio of heating capacity and weight of gas cooler and pressure drop of water side and this type gas cooler can get a good performance by increasing the proper length of inner tube.

1. INTRODUCTION

The carbon dioxide transcritical cycle has been investigated as a potential alternative technology in the practical application. Lorentzen's pioneer researches revived carbon dioxide as a potential working fluid of certain applications such as the automobile air-conditioners, water heater heat pumps and residential air conditioners (Lorentzen G., 1995). But its disadvantage is significant that it has a low coefficient of performance compared with present conventional high performance refrigerant systems. Improving efficiency of a transcritical CO_2 cycle to an equivalent level of a conventional refrigerant system is the primary concern of current research.

CO_2 transcritical cycle system is thought to have an advantage on the application of heat pump water heater due to its special characteristics. Ssikawa M. et al (2000) and Mukaiyama H. and Kuwabara O. (2000) focused on the researches of CO_2 heat pump system and developed domestic heat pump water heater taking CO_2 as the working substance successfully. DENSO in Japan developed the counterflow heat exchanger for CO_2/water heater. The micro-channel concept is used in the CO_2 side and metal plate with the internal fin is utilized in 调 the water side. Yunho Hwang (1997) did lots of work on the simulation and experiment of CO_2 water source heat pump. They also set up the steady emulating models of counterflow tube-in-tube heat exchanger for CO_2

system including the evaporator and gas cooler using water source.

In his study, two gas coolers are studied to find the proper type gas cooler to improve the efficiency of CO_2 heat pump water heater.

2. DOUBLE PIPES CO_2 GAS COOLER

2.1 The Structure of Gas Cooler

Two double-pipe gas coolers are designed. CO_2 flows inside the internal tube and the water flows around the internal tubes. The structure of tube in tube type gas cooler is very simple and it is easy to make in the laboratory. Two designed gas coolers have a little difference with each other. The one, called gas cooler 1, has only one internal cooper tube, the other, gas cooler 2, has three internal screwed copper tubes with small inner diameter, which is shown in Fig.1. In order to keep the same heat transfer surface of both gas coolers, the gas cooler with three internal tubes is short. Then the size of gas cooler 2 is smaller than the gas cooler 1.But the external diameter of gas cooler 2 becomes bigger than that of gas cooler 1, because it is difficult to let three screwed inner tubes pass through the external tube with same diameter as gas cooler 1.

Fig.1 Gas cooler with three internal tubes

2.2 The Model of Gas Cooler

The following assumptions are necessary in the calculation.

1) The flow of fluid is stable.
2) The fluid in the tube is one dimension flow.
3) Outside surface of external tube is thought to be covered by insulating materials and no heat loss is transferred to the environment.
4) The influence of oil in tubes on heat transfer is ignored.
5) The heat transfer at axial direction is ignored.

The thermal parameters of CO_2 in the gas cooler are changed greatly at the critical region. So in the calculation, the tube is divided into many infinitesimal gas coolers. In each infinitesimal part, according to the energy conservation law, the rejecting heat of CO_2 side in equation (1) and the absorbing heat of water side in equation (2), were equal to the heat calculated by the heat transfer in equation (4).

$$Q_{fi} = Q_{ri} = Q \tag{1}$$

$$Q_{ri} = m_r \left[h(T,P)_{i,in} - h(T,P)_{i,out} \right] \tag{2}$$

$$Q_{fi} = m_f Cp_{fi} (t_{fi,out} - t_{fi,in}) \tag{3}$$

$$Q = KA \frac{(t_{ri,in} - t_{fi,out}) - (t_{riout} - t_{fi,in})}{\ln\left(\dfrac{t_{ri,in} - t_{fi,out}}{t_{riout} - t_{fi,in}} \right)} \tag{4}$$

2.3 Selected Correlations

In this paper, the correlation proposed by Pital et al (2002), formulas (5), is utilized to calculate the heat transfer of CO_2 in the gas cooler. According to the experimental results, the formula is modified by a correction factor C.

$$Nu = \left(\frac{Nu_w + Nu_b}{2} \right) \frac{\lambda_w}{\lambda_f} \tag{5}$$

$$Nu_b = \frac{\zeta / 8 \mathrm{Re}_f \mathrm{Pr}_f}{12.7\sqrt{\zeta / 8}(\mathrm{Pr}_f{}^{2/3} - 1) + 1.07} \tag{5-a}$$

$$Nu_w = \frac{\zeta / 8 \mathrm{Re}_w \mathrm{Pr}_w}{12.7\sqrt{\zeta / 8}(\mathrm{Pr}_w{}^{2/3} - 1) + 1.07} \tag{5-b}$$

The pressure drop is calculated by the following correlation (Zhao Z. 2000).

$$\Delta p = \frac{fu^2 L}{2\rho \ d} \tag{6}$$

$$f = 0.3164 / \mathrm{Re}^{0.25} \qquad \mathrm{Re} < 10^5 \tag{6-a}$$

$$f = (0.790 \ln \mathrm{Re} - 1.64)^{-2} \qquad 3000 < \mathrm{Re} < 5 \times 10^6 \tag{6-b}$$

The heat transfer coefficient of water side is calculated by the correlation of A.Zhukauskas (Zhao Z. 2000).

$$Nu = 1.04 \mathrm{Re}_f^{0.4} \mathrm{Pr}_f^{0.36} \left(\mathrm{Pr}_f / \mathrm{Pr}_w \right)^{0.255}, 1 < \mathrm{Re} < 5 \times 10^2 \tag{7-a}$$

$$Nu = 0.71 \mathrm{Re}_f^{0.5} \mathrm{Pr}_f^{0.36} \left(\mathrm{Pr}_f / \mathrm{Pr}_w \right)^{0.255}, 5 \times 10^2 < \mathrm{Re} < 10^3 \tag{7-b}$$

3. CALCULATION RESULTS

The calculated results are compared based on four groups of parameters which are shown in table 1. From the table 1, it can be seen that the area of section for CO_2 flow becomes small and the area of section for water flow becomes big when three screwed inner tubes with small diameter take the place of one inner tube with big diameter based on the same heat transfer surface. That will increase the velocity of CO_2 and benefit to the heat exchanging of CO_2, but it decreases the velocity of water outside the inner tube.

Table 1 Parameters of gas coolers

	Gas cooler 1	Gas cooler 2		
Case	1	2	3	4
Number of inner tube	1	3	3	3
Length (m)	12	8	8	10
Inner diameter of inner tube (mm)	6	3	3	3
Inner diameter of external tube (mm)	10	10	12	12
Area of section for CO_2 (mm^2)	28.26	21.2	21.2	21.2
Area of section for water (mm^2)	28.28	40.82	75.36	75.36
Heat transfer surface area (mm^2)	226.1	226.1	226.1	282.6

Weight (kg)	6.059	3.647	4.096	5.12

Fig.2 shows the outlet temperature of CO_2 and water in gas cooler 1 and gas cooler 2 at different parameters listed in Table 1. It can be seen from this figure that the outlet temperature of CO_2 of two gas coolers are almost same when the inner diameter of external tubes are same in gas cooler1 and gas cooler 2 of case 2.The velocity of CO_2 in gas cooler 2 is increased caused by the small inner diameter, but increasing effect of the overall heat transfer coefficient is not obvious. The reason is that the smaller inner section area for CO_2 causes the decrease of velocity of water and the heat transfer coefficient of water hereby. Meanwhile, an external tube with a big diameter is needed to make sure three screw inner tubes pass though. Then, the velocity of water in this gas cooler becomes slow further. So that, the outlet temperature of water in gas cooler 2 is a little lower than that in gas cooler 1 when the external diameter of gas cooler 2 of case 3 is bigger than gas cooler 1 at same heat exchanging surfaces, same mass flow rate and inlet temperature of working fluids. When the length of inner tube is enlarged, performance of the gas cooler 2 of case 4 is better and the weight of gas cooler 2 is still lighter than gas cooler 1.

Fig 3 shows the temperature distribution of CO_2 and water in gas cooler 1 and gas cooler 2 of case 4 in Table 1. It is found that the temperature of CO_2 and water along the tube in gas cooler 2 changes more quickly than that in gas cooler 1. The pressure drop of water side in gas cooler is shown in Fig.4. The pressure drop of water in gas cooler 1 is much lager than that in gas cooler 2 of case 4 in Table 1. So the latter can decrease the input work of water pump.

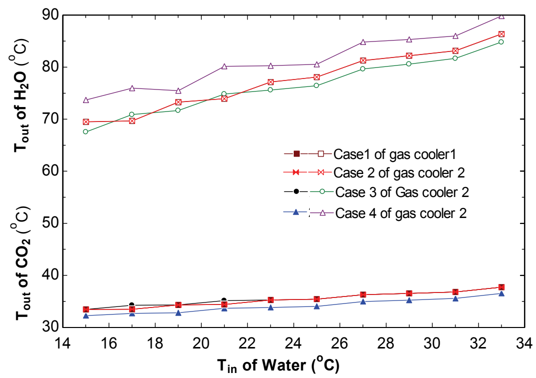

Fig.2 The outlet temperature of CO_2 and water of gas cooler

According the calculation, it also can be known that water flow in gas cooler is laminar current and the heat transfer coefficient of water is lower than that of CO_2. So reinforcing measurements for heat transfer can be applied in the external surface of inner tube.

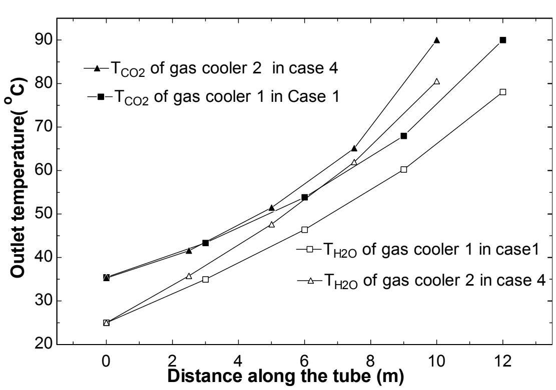

Fig.3 the temperature distribution along the tube

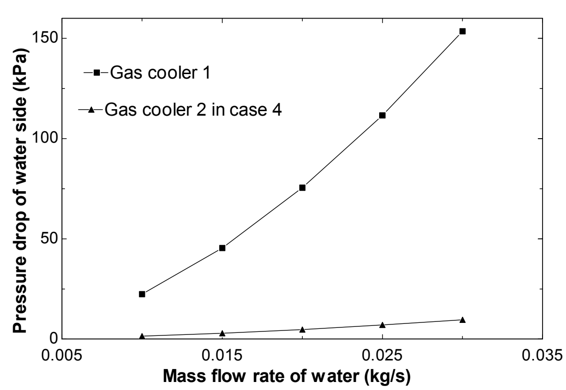

Fig.4 Pressure drop of water side

4. EXPERIMENTAL STUDY

4.1 Experimental System

Fig.5 shows the diagram of the experiment system (Liu Q, 2007). The whole system is composed of the following several parts: heat pump system, air system, humidifying system, heating system, measuring system and data acquisition system.

Heat pump system includes a compressor, an evaporator, a gas cooler, an internal heat exchanger and an electronic expansion valve. The compressor is a scroll type one with 1.8kW fixed power input. The evaporator is a tube-fine heat exchanger. Two gas coolers are both double-pipe heat exchangers with the main pipe length of 12m and 8m, and the refrigerant is mobile in the inner tube, the water flows outside the inner tube. Air system is composed of an air blower, rectifying boards, a nozzle and pipeline. The rectifying board is arranged to enable the wind to pass the evaporator evenly. The air blower is the type of frequency conversion, and its capacity can be adjusted. The experiment is carried on in the thermal equilibrium room. The environmental temperature and humidity of the evaporator is controlled by the heating system and humidifying system.

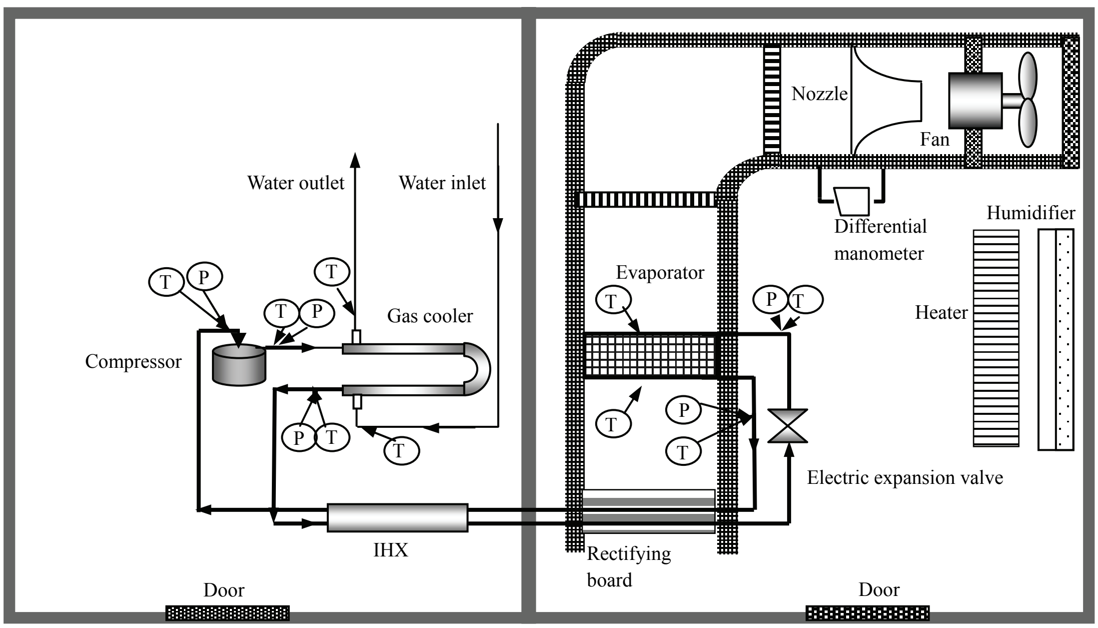

Fig.5 Experiment system of CO_2 transcritical cycle heat pump water heater

4.2 Experimental Results

In the experiments, two gas coolers are tested, gas cooler 1 and gas cooler 2 with parameters in case 3 of table 1. The tested data are listed in table 2. The analysis results are presented in Table 3.

Table 2 Experimental data

Unit	1		2	
Gas cooler	Gas cooler 1	Gas cooler 2	Gas cooler 1	Gas cooler 2
Air inlet temperature of evaporator (^oC)	23.3	24.9	31.0	30.2
Air outlet temperature of evaporator (^oC)	10.3	10.3	17.3	17.1
Inlet temperature of water in gas cooler (^oC)	20.6	21.0	32.9	32.5
Outlet temperature of water in gas cooler (^oC)	60.1	57.1	69.1	64.2
Discharge Pressure of compressor (MPa)	8.78	8.87	10.14	10.10
Absorbed pressure of compressor (MPa)	3.58	3.79	4.2	4.3
Outlet pressure of CO_2 in gas cooler (MPa)	8.55	8.53	9.96	9.80

Outlet temperature of compressor (°C)	101.4	96.7	105.9	104.5
Inlet temperature of compressor (°C)	26	24.5	34.4	34.6
Outlet temperature of CO_2 in gas cooler (°C)	31.8	30.3	38.6	36.3
Water mass flow rate (kg/s)	0.033	0.033	0.033	0.033

Table 3 Analysis results

Unit	1		2	
Gas cooler	Gas cooler 1	Gas cooler 2	Gas cooler 1	Gas cooler 2
Difference pressure of gas cooler (MPa)	0.23	0.34	0.18	0.30
Heating capacity Q_h (W)	5370	4908	4922	4310
Power of compressor (W)	1831	1784	1848	1795
Coefficient of performance of Q_h COPh	2.93	2.75	2.66	2.40
Cooling capacity Q_c (W)	3051	3426	3215	3074
Coefficient of performance of Q_c COP	1.67	1.92	1.74	1.72
Q_h/Weight (W/kg)	887.6	1198	812	1052

In Table 2, gas cooler 1 and gas cooler 2 are tested at similar conditions. Outlet temperature of water gas cooler 1 is higher than that in gas cooler 2 at the test conditions. COPh of the cycle with gas cooler 1 is also higher than that of gas cooler 2. So the proper increasing length of inner tube can help gas cooler 2 to get a higher efficiency. But the gas cooler 2 has a high ratio of heating capacity and weight of gas cooler.

It is also can be seen from the table 2, air outlet temperature from evaporator can reach 10.0°C at air inlet temperature 25°C. Then the cooling capacity from the evaporator could be utilized for air conditioning as well as heat water from the gas cooler. If the cooling capacity and the heating water both can be used, it is found that the COP of overall system is bigger than 4.0. But working time for cooling and hot water are different, the reasonable design of the system is important for good services. The COP of cycle with gas cooler 2 is higher than the gas cooler1 in Table 3. The main reasons are that the evaporating temperature of the cycle with the gas cooler 1 is lower than the gas cooler 2 and the CO_2 outlet temperature of gas cooler 1 is higher than in the gas cooler 2, which do not benefit to the cooling capacity.

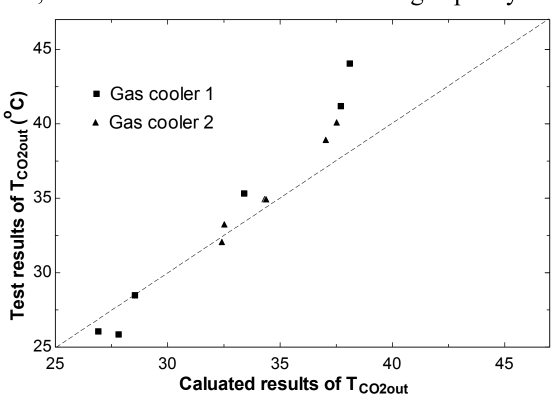

Fig.6 Comparison of theoretical and tested values of CO_2 outlet temperature in gas cooler

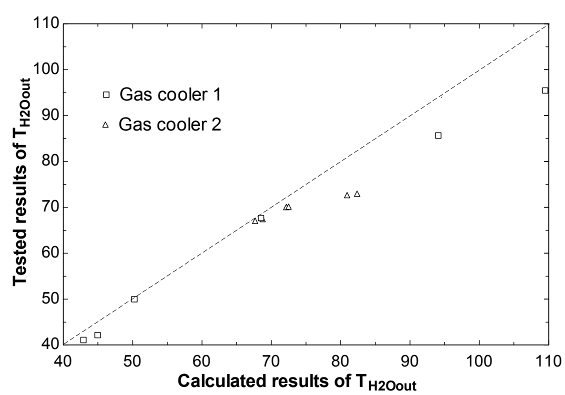

Fig.7 Comparison of theoretical and tested values of water outlet temperature in gas cooler

Fig.6 and Fig.7 show the comparison of calculated values and the experimental values. The calculated error of CO_2 outlet temperate for gas cooler 2 is within 6.5% and the error of CO_2 outlet temperate for gas cooler 1 is within 13.5%. The maximum error of water outlet temperate for gas cooler 2 is within 12.8% and the error of water outlet temperate for gas cooler 1 is less than 14.6%. So the theoretical results can be acceptable.

5. CONCLUSIONS

1) According to the analysis, the performance of the gas cooler with three screwed inner tubes is not better than the one with a single inner tube at least while the heat exchanging surfaces of two gas coolers are same.
2) The external tube with big diameter for the gas cooler is needed to make the inner three screwed inner tubes pass through the external tube successfully, which will cause the decrease of out temperature of water comparing to the gas cooler with single inner tube.
3) The gas cooler with three screwed inner tubes can help to decrease ratio of heating capacity and weight and pressure drop of water side and this type gas cooler can get a good performance by increasing the proper length of inner tube. The gas cooler with multi inner tubes is a good type heat exchanger by optimal design.
4）The use of the cooling capacity and heating water unify will increase the overall efficiency of system.

NOMENCLATURE

u	the velocity	(m/s)	**Subscripts**	
f	the friction factor		r	refrigerants
t	temperature of refrigerants	(^oC)	w	wall
Q	heat	(W)	in	inlet
L	length	(m)	out	outlet
K	overall heat transfer coefficient	(w/m^2 K)	f	fluid
A	heat exchanging area	(m^2)		

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