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Development of a New Type Heat Exchanger for Natural Refrigerant CO_2 Heat Pump Water Heaters

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Abstract

The hot-water supply heat exchanger installed in CO_2 heat pump water heater was developed. In order to use for the design of the heat exchanger, precise performance simulation was developed and the dimension was optimized. This heat exchanger can supply 90 degrees C hot-water, and the counter flow style is employed in order to use the characteristic of CO_2 refrigerant. Moreover, this heat exchanger doesn't need leakage detection structure which is used for conventional double tube heat exchanger, so it is excellent in manufacturability and compactness.
As a result of the development, the weight and volume of the new type heat exchanger were miniaturized to 1/3 as compared with the conventional double tube heat exchanger.

1. Introduction

Recently, the industry of freezing, air-conditioning, and water heating makes an effort to the product development that contributing from the viewpoint of the global environment protection to not only energy conservation but also the prevention of depletion of ozone layer and global warming. In Japan, about 1/3 of the household energy consumption is occupied by water heater. Generally, the combustion type water heater that uses the gas or oil, and the electric heating type with an electric heater are widespread. However, there are many opinions which have doubt in the energy saving effect of the combustion type water heater or the electric water heater, because their COP on the basis of fossil fuel cannot exceed 1.0. Therefore, for global warming prevention, it is very important to develop the water heater which has the high energy saving effect.
From such a situation, we developed the CO_2 heat pump water heater system of a new concept that is called "Eco-Cute" and started sale from February 2002 in Japan. This system uses CO_2 as the working refrigerant of the heat pump unit. And it can generate the hot water up to 90 degrees C, and COP of the annual average is over 3.0. CO_2 is capturing the spotlight as the eco-friendly refrigerant, because its ODP is zero and GWP is as small as 1/1730 compared with R410A.

This report reports development of the heat exchanger for CO_2 heat pump water heater which is one of the important components of this system.

2. CO_2 heat pump water heater

Before describing the developed heat exchanger, the outline of a CO_2 heat pump water heater in which it is installed is explained. CO_2 heat pump water heater has the following three features. (1)Since heat pump uses the heat in the atmosphere effectively, it is efficient and safety. (2)Using the physical properties of CO_2 of the super-critical state, 90-degree C high temperature water can be supplied quickly. (3)As shown in table 1, since the ODP equals 0 and GWP equals 1.0, CO_2 refrigerant can reduce the effects on the environment.

The appearance of this product is shown in Fig.1. The left-hand side in figure shows the heat pump unit to which appearance resembles the outdoor unit of an air-conditioning machine.

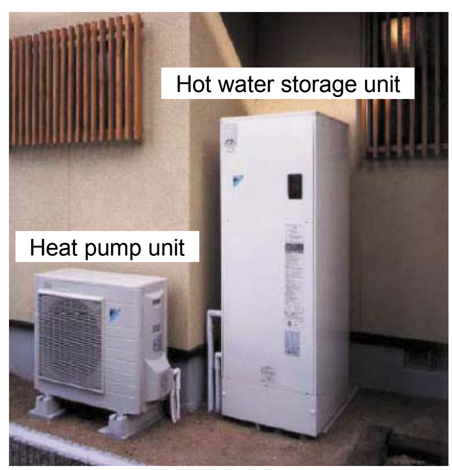


Fig.1 Photo of CO_2 heat pump water heater

Table 1. Characteristic comparison of R410A and CO_2

		R410A	CO_2 (R744)
Ozone depletion potential (ODP)		0	0
Global warming potential (GWP)		1730	1
High pressure	MPa	3.0	12
Low pressure	MPa	0.8	3.5
Differential pressure	MPa	2.2	8.5
Suction gas density	kg/m³	29	89
Refrigerating capacity	kJ/kg	144	219
	kJ/m³	4172	19503

The right-hand side in figure shows the hot water tank unit that consists of a tank where the boiled hot water is accumulated. This machine usually runs during nighttime when the electricity bill is cheap, and saves the boiled hot water into the tank.

Therefore, the running cost is cheap and economical. For deciding the capacity of the tank, large 460L tank is the main current because the general electric water heater should save the hot water for a day use by using the electric power during the nighttime. However, CO_2 water heater can perform the additional heating operation by high COP of the heat pump, so the capacity of the tank can reduce to 370L. Moreover, the performance of supplying hot water is equal to an electric water heater of 500L tank. This product is sold under the initiation of the electric power company in Japan by the pet name of "Eco-Cute". "Eco" of "Eco-Cute" shows Ecology, and "Cute" was named from the pronunciation of English Cute resembling Japanese hot-water supply.

3. Heat exchanger design

(1) Basic structure

Usually, double-tube heat exchanger is widely used for the water heat exchanger, and so on. However, when applying this heat exchanger to the heat pump water heater appliance, the leakage detection system is required in order to prevent refrigerant and lubricating oil penetrate into water through the wall. Therefore, the leakage detection channels shown in fig.2 must be employed. This leakage detectable tube is manufactured from the insertion of another tube in the inner grooved tube and then both are combined. However, it is very difficult for the leakage detectable tube heat exchanger to reduce its size and cost. The weight of the heat exchanger grows heavier because of the complex structure, so it is difficult for this HX to bend by small curvature and the manufacturing process becomes complicated. Then, in order to solve these problems, we developed the new structural heat exchanger for CO_2 heat pump water heater. The schematic view of the heat exchanger is shown in fig.3.

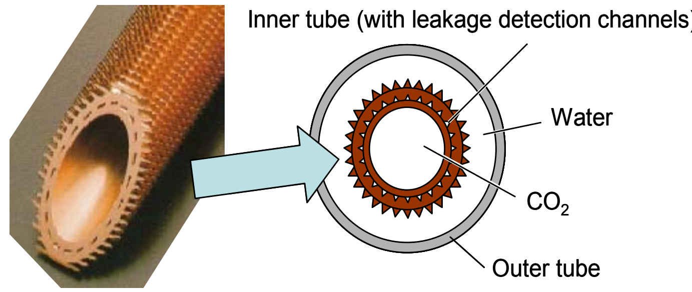


Fig.2 Double tube HX with leakage detection channels

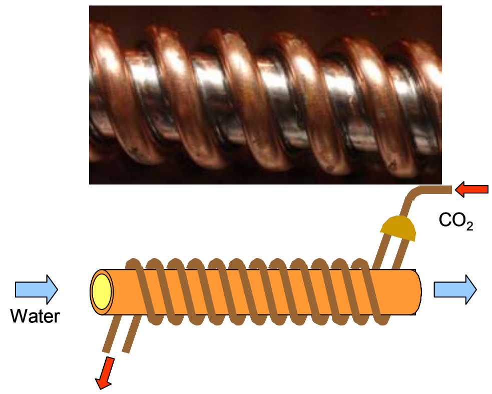


Fig.3 Photo and Schematic view of the developed HX

The developed heat exchanger has combined water tube (O.D.=9.5mm) and CO_2 tube (O.D.=4.0mm) by counter flow style, and it has the structure suitable for CO_2 which has large temperature gradient. Even if water tube corrodes, this heat exchanger has the structure where water begins to leak outside, before CO_2 tube corrodes as shown in fig.4. Therefore, there is no need for safety structure like leakage detection channel. Furthermore, since it is not necessary to keep the tubes straight before processing, the time and effort and transportation cost under manufacture are sharply reducible. The results mentioned above are summarized in Table 2. Table 2 shows that the newly developed heat exchanger has very many merits compared with the conventional heat exchanger.

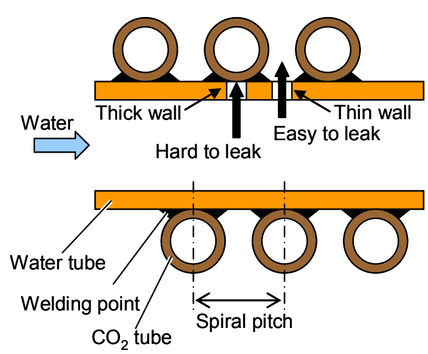


Fig.4 Leakage detection mechanism

Tabel.2 Characteristic comparisons between conventional HX and newly developed one

	Conventional double tube HX	Newly developed HX
Leakage detection	○	○
Manufacturability	△	○
Compactness	△	○
Design freedom	×	○
Cost	△	○

In other heat exchangers, for example, plate heat exchanger is very excellent especially in the compactness. However, since plate HX is manufactured by welding, it is unfit for high pressure use. And the leakage detection structure becomes complex according to the structure which accumulated the layer of water and CO_2 by turns. Therefore, it is difficult to apply plate HX to a heat pump water heater now.

(2) Performance prediction method

In order to design this heat exchanger, the performance predicting method was developed [1]. At first, the heat exchanger was divided into 1-dimensional cell arrays along the water tube. The number of cells was set to about 250 to the 10m heat exchanger, as a result of checking validity in advance. Next, the performance and the exit temperature for every cell were calculated, and the calculation was repeated until it converged. The temperature of each cell was calculated by the following equations.

$$T_{Ri-1} = T_{Ri} - \frac{\Delta Q_i}{Cp_{W_i} G_W} \tag{1}$$

$$T_{W i} = T_{W i-1} + \frac{\Delta Q_{i-1}}{Cp_{R_{i-1}} G_R} \tag{2}$$

The performance of each cell was calculated by the following equations.

$$\Delta Q_i = K_i \left(T_{Ri} - T_{Wi}\right) \Delta A_W \tag{3}$$

$$\frac{1}{K_i} = \frac{1}{h_W} + \frac{\Delta A_W}{\Delta A_R} \cdot \frac{1}{h_{Ri}} \tag{4}$$

$$h_R = \frac{\lambda_R}{D_R} Nu_R \tag{5}$$

Petukov-Gnielinski equation (P-G equation) for single phase fluid shown below was used for the heat transfer coefficient of CO_2 under the super-critical state.

$$Nu = \frac{(f/2)(Re - 1000) \cdot Pr}{1 + 12.7\sqrt{f/2}\left(Pr^{2/3} - 1\right)} \tag{6}$$

$$f = \left(3.64 \cdot \log_{10} Re - 3.28\right)^{-2} \tag{7}$$

However, since the actual heat transfer coefficient is little higher than the value of P-G equation [2], the compensation coefficient C identified from the result of a preliminary experiment was used. In this development, it is always fixed at C=1.3. The influences of the internal flow by CO_2 tubes being spiral (flow field, effect of centrifugal force, etc.) were not considered. The heat transfer coefficient of the w ater side was treated as developed laminar flow in the case of laminar flow.

As a heat transfer coefficient by the side of water, it treated as developed laminar flow of a round tube in the case of a laminar flow, and in the case of turbulence, the P-G equation was used. For the water side heat transfer coefficient, it is treated as developed lami nar flow in a round tube in the case of laminar flow, and the equation 6 was used in the case of turbulence. The correction factor is not used for the water side heat transfer coefficient. For the thermophysical properties of CO_2, the value which carried out Lagrange interpolation from the data table created by NIST REFPROP Ver.6.01 was used. Microsoft Excel® was used for the calculation software.

It is necessary to use fin efficiency for a water and CO_2 side in calculation of heat transfer area, respectively. So, the model of fin efficiency was assumed as shown in fig.5, and Eq.(10) which is usually applied to a straight line fin was used.

$$A = A_{weld} + \eta \cdot A_{fin} \tag{8}$$

$$u_b = W_{fin} \sqrt{\frac{h}{\lambda \cdot t_{fin}}} \tag{9}$$

$$\eta = \frac{\tanh(u_b)}{u_b} \tag{10}$$

$$W_{fin} = \frac{1}{2}\left(W_{pitch} - W_{weld}\right) \tag{11}$$

In calculation of fin height W, as for water tube, the tube wall except the welded width exposed to outside shown in fig.5 was assumed to be a fin, and the length of the half was made equivalent to the fin height W. Similarly, also in CO_2 tubes, it was considered that the tube wall except the welded width was a fin, and the length of the half was assumed to be the fin height. Water side and CO_2 side also assumed symmetrical conditions for one side heat insulation, so the wall thickness of each tube was used for the thickness of the fin. Using this performance predicting method, the calculation results were compared to the experimental results shown in fig.6. We can see from fig.6 that the calculation results suit the experimental results very well. Therefore, the validity of this calculation technique was checked.

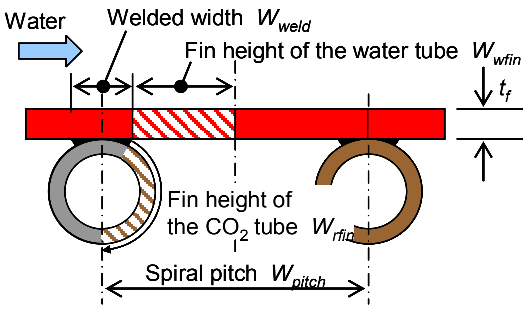


Fig.5 Analysis model of fin efficiency

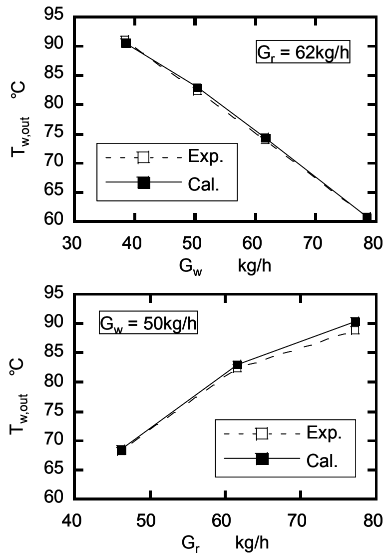


Fig.6 Comparison between prediction and calculation

4. Results and discussion

By using the performance predicting method mentioned above, the influence of the dimension of a heat exchanger (inner diameter of water tube, inner diameter of CO_2 tube, spiral pitch) which affects performance was investigated. The conditions used for calculation are shown in Table 3. First, inner diameter of water tube was examined. Fig.7 shows the calculation result of the outlet water temperature Two when changing the Dw,i of water tube, and pressure drop.

Tabel.3 Calculation condition

		CO_2	Water
Inlet pressure	MPa	12	-
Inlet temperature	℃	110	8
Mass flow rate	kg/h	62	50

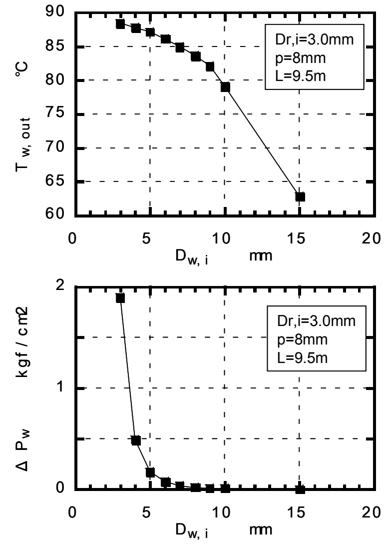


Fig.7 Influence of water tube diameter

The number of the passage of the water side is always one. From fig.7, if the inner diameter of water tube is less than 5mm, the pressure drop of water will increase rapidly. And, if the inner diameter of water tube exceeds 9mm, outlet water temperature will fall rapidly. When the pressure drop of water tube is large, much pumping power will be consumed. Moreover, when a scale adheres, there is a problem which water tube may blockage. Then, we selected the inner diameter as 7mm in consideration of the durability to scale adhesion, and highly efficient both sides.

Next, the dimension of CO_2 tubes was examined. Fig.8(a) shows the calculation result of the performance when changing the inner diameter of CO_2 tubes.

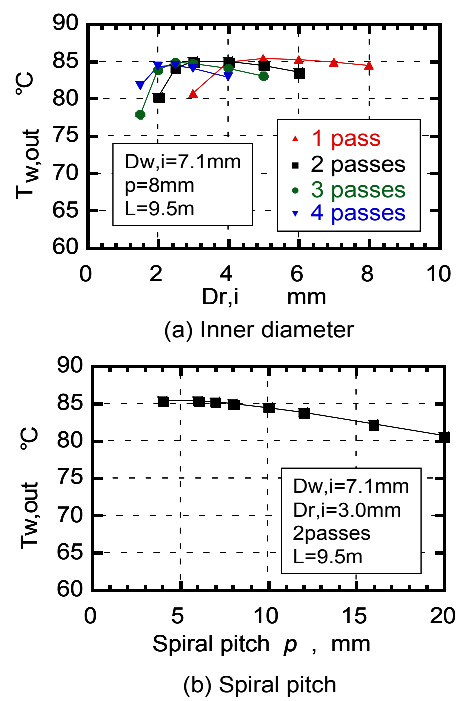


Fig.8 Influence of specification of CO2 tube

The number of CO_2 passages was changed from 1 to 4. From fig.8(a), it is found that the performance has a peak point corresponding to a certain inner diameter, and the inner diameter tends to become so small that the number of passes increases.

Since a heat exchanger will become lightweight if the inner diameter of a CO_2 tube is made small, cost falls and it is convenient. Then, we selected the CO_2 tube with inner diameter of 3mm in consideration of the availability of a tube, or the ease of carrying out of processing. The number of passes was set to 2. Fig.8(b) shows the calculation result of the performance when changing the spiral pitch of CO_2 tubes. The performance of a heat exchanger improves as the spiral pitch of CO_2 tubes increases.

However, when the spiral pitch is increased, it is found that the effect of the improvement in performance is saturated. Since the copper heat conductivity is high enough, even if the spiral pitch is small, tube wall temperature can be made constant (that is, fin efficiency is almost 1.0). If a CO_2 tube is joined with high density, material cost will go up. So, it is convenient that the CO_2 tube should be wound around low density. After all, we selected the spiral pitch of CO_2 tube as 8mm.

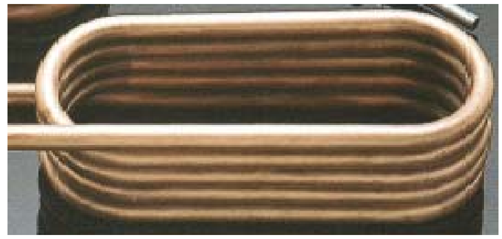
The specification of the heat exchanger was determined through the process mentioned above, and the product shown in fig.9(a) was completed. As for the newly developed heat exchanger, compared with the conventional heat exchanger shown in fig.9(b), weight and volume were miniaturized to 1/3 or less.

5. Conclusion

The compact and highly efficient heat exchanger installed in CO_2 heat pump water heater (Eco-Cute) was developed, and the following results were obtained.

(1)The performance prediction method was developed by assuming the heat transfer characteristic of CO_2 of super critical state to the single phase heat transfer characteristic.
(2)Using the heat exchanger structure of perfect counter style, hot water temperature of 90 degrees C or more was obtained.
(3)The newly developed heat exchanger succeeded in one third of miniaturizations by weight and volume compared with the conventional heat exchanger.

(a) Newly developed HX



(b) Conventional double tube HX

Fig.9 Photos of the HX installed into water heater

NOMENCLATURE

A	:	heat transfer area (m^2)
D	:	tube diameter (m)
f	:	friction factor
h	:	heat transfer coefficient (W/m^2K)
K	:	over all heat transfer coefficient (W/m^2K)
Nu	:	Nusselt number
Pr	:	Prandtl number
Re	:	Reynolds number
t	:	fin thickness (m)

(Greek symbols)

η	:	fin efficiency
λ	:	thermal conductivity (W/m K)

(Subscripts)

i	:	inner side
fin	:	fin area
out	:	outer side
R	:	refrigerant side
W	:	water side

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