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Performance Evaluation of a Hot-Water Supply System Utilizing Wasted Heat of an Air-Conditioning Machine*

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Abstract

A hot-water supply system was constructed to utilize wasted heat of an air-conditioning system with HFC134a refrigerant. A desuperheater was equipped ahead of the condenser of an air-conditioning machine to extract thermal energy of compressed high-temperature refrigerant. HFC134a was selected as refrigerant because its pressure was relatively lower at higher temperature. The required refrigerant charge was investigated and performance of the air conditioning system with/without a desuperheater was compared to assess the effect of installing a desuperheater. It was concluded that the required refrigerant charge increased by installing a desuperheater, and that the ability of cooling heat exchange was similar for both with/without a desuperheater with required refrigerant charges. It was also shown that cooling COP decreased 15% by installing a desuperheater, because the work done by the compressor increased, but the overall energy efficiency including cooling and hot-water supply increased 34%.

Key words: Desuperheater, Hot-Water Supply System, Air-Conditioning Machine, HFC134a

1. Introduction

The impact on global warming by energy consumption of air-conditioning systems is so large that various research and development projects are performed aiming at high efficiency and energy saving of air-conditioning systems. Irrespective of these efforts, it is usual that the released heat from air-conditioning systems is merely discharged into the atmosphere and never recovered. As a result, this is not only a waste of energy but also a causes of a “heat island phenomenon” in the central area of cities where buildings are overcrowded. The heat island phenomenon means that the temperature of the atomosphere becomes several dgrees higher than that of surrounding suburbs like an island (1). Once the heat island phenomenon occurs, ambient temperature does not fall even at night and thus we would be forced to live unpleasant life.

In this research, a desuperheater was installed on the air-conditioning system to supply hot water by regenerating heat released from air-conditioning systems instead of being discharged in the atmosphere, and performance of supplying hot water was evaluated. A desuperheater is a heat exchanger that collects heat released from air-conditioning systems during condensation of the refrigerant and makes water hot. It is usually set between compressor and condenser with a separate cooling water system. Due to this, the water flow rate of the desuperheater can be independently adjusted to supply high temperature water. Major contribution on the research and development of a desuperheater was achieved mainly in the house equipment field. There exist some research papers on desuperheaters (2), (3). However, regarding the refrigerant, HCFC22 was only applied to all research projects.

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Authors have been studying the energy saving methodologies of air-conditioning systems using HFC134a and additional condenser [(4), (5)]. Comparing with HCFC22, HFC134a has advantages that it has zero ozone depleting potential and lower global warming potential [(6)]. Also HFC134a is more appropriate to supply high temperature water because it has lower pressure characteristics in higher temperature region. Therefore in this study, HFC134a was adopted as refrigerant and a water-cooled additional condenser was utilized as a desuperheater [(7)]. The effect of the quantity of charged refrigerant on characteristics of the system (cooling heat exchange, COP, and overall energy efficiency including both supplying hot water and air-conditioning) was measured with/without installing a desuperheater.

2. Experimental Setup

The air-conditioning system (Refrigerant: HCFC22; Compressor power output: 3.75 kW; Air-conditioning output: 14.5 kW) was used as a basic experimental equipment. The major dimensions of the condenser are: fin pitch: 1.8 mm (slit fin); heat transfer tube: inner diameter 7.94 mm × thickness 0.3 mm (bare tube), 2 arrays - 48 stages, frontal width: 832.4 mm, frontal area: 1.014 m^2, array pitch: 19.04 mm. Regarding the evaporator: fin pitch: 1.6 mm (louver fin); heat transfer tube; inner diameter 9.4 mm × thickness 0.41 mm (grooved tube), 3 arrays - 11 stages, frontal width; 1270 mm, frontal area: 0.355 m^2; array pitch; 19.04 mm. Regarding the capillary tube for cooling: inner diameter: 1.4 mm; length: about 400 mm.

A water-cooled additional condenser was inserted between the compressor and the condenser of the air-conditioning system as a desuperheater. Figure 1 shows the circuit chart of the experimental equipment. Valves were equipped between the condenser and the desuperheater to switch the operational mode without the desuperheater to that with the desuperheater. The mineral oil (Barrel Freeze 32s) was used for the lubricating oil of the compressor and HFC134a was used for the refrigerant. As we stated in the previous studies [(4), (5)], it was confirmed that the air-conditioning system worked normally even if HCFC22 was replaced by HFC134a without changing the lubricant oil.

The detailed structure of the desuperheater is shown in Figure 2 and the set up configuration of the outdoor unit is shown in Figure 3. The desuperheater was installed vertically between the compressor and the condenser. The length of the copper helical tube in the desuperheater is about 19 m and the inner diameter of the tube is 7.93 mm. Inside the desuperheater, counter flows of cold water and hot refrigerant exchange heat, *i.e.*, the high temperature refrigerant becomes cooler flowing from the upper side of the helical tube to the lower side and the low temperature water becomes warmer flowing from the lower side of the container to the upper side.

The outdoor unit and the indoor unit were set up in separate laboratory rooms where the wall, the ceiling, and the floor were insulated. Temperature of the refrigerant was measured by T-type thermocouples attached on the tube at inlets and outlets of the compressor, the condenser, the desuperheater, the capillary tube, and the evaporator. Temperature and humidity of the air was measured at both sides of the condenser and the evaporator using conventional wet and dry bulb thermometers. The error in temperature measurement was less than one degree. Pressure of the refrigerant was measured at the inlet and the outlet of the compressor by pressure gauges.

During the experiments, the room temperature of the indoor unit side was kept 27 ^{o}C and that of the outdoor unit side was kept 35 ^{o}C using extra air-conditioning machines for room temperature adjustment. This condition is based on the performance test method of the air-conditioning equipment specified in the Japanese Industrial Standards (Japanese Industrial Standards 1999, JIS B 8615-1) [(8)].

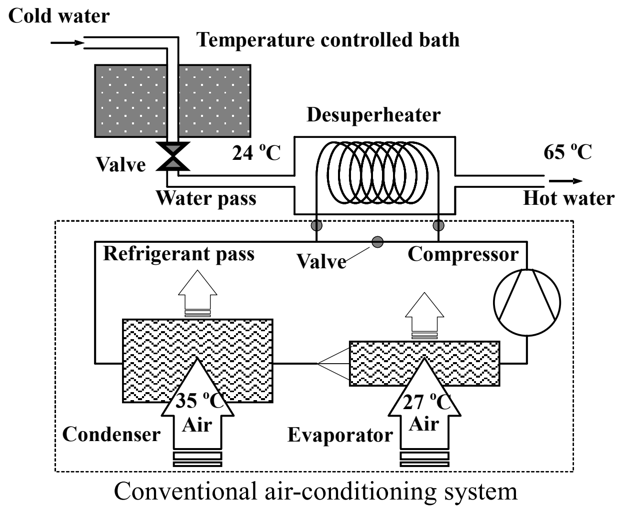

Fig. 1 Circuit chart of experimental equipment

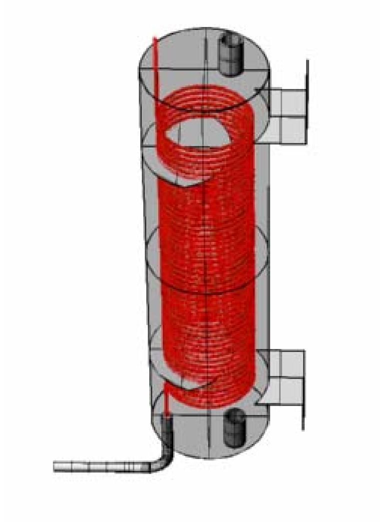

Fig. 2 Schematic diagram of desuperheater

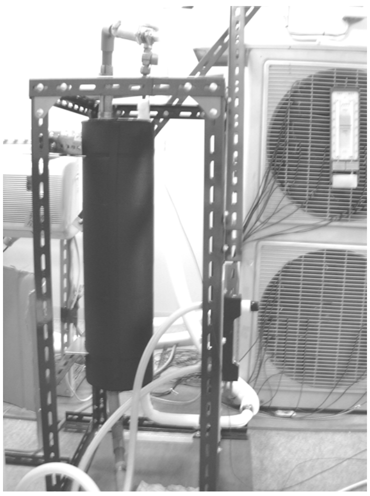

Fig. 3 Setup configuration of desuperheater

The ability of cooling heat exchange was measured as follows: Conservation of energy for air passing through the evaporator is described as

$$\rho_{\mathrm{out}} V_{\mathrm{out}} h_{\mathrm{out}} = \rho_{\mathrm{in}} V_{\mathrm{in}} h_{\mathrm{in}} - q \tag{1}$$

where q is the ability of cooling heat exchange, ρ is the density of air, V is the volumetric flow rate, h is the specific enthalpy, and suffix “in” and “out” correspond to the conditions at the inlet and the outlet of the evaporator respectively. Since no drain was observed throughout the experiments due to low humidity, conservation of mass is described as

$$\rho_{\mathrm{out}} V_{\mathrm{out}} = \rho_{\mathrm{in}} V_{\mathrm{in}} \tag{2}$$

From the equations (1) and (2), q is derived as

$$q = \rho_{\mathrm{out}} V_{\mathrm{out}} \left(h_{\mathrm{in}} - h_{\mathrm{out}} \right) \tag{3}$$

Values of the specific enthalpy and the density of air were derived from measured temperature. V_{out} was evaluated by multiplying the average flow velocity of the outlet of evaporator by the area and assumed to be constant throughout the experiments. The average flow velocity was measured by a handy anemometer at several locations of the outlet of evaporator. The current value and the integral of the electric power of the compressor were also measured during the experiments.

The hot water temperature in the desuperheater was measured by T-type sheathed thermocouples inserted into the flow field in the tube. The water temperature at the inlet of the desuperheater was kept 24 ^{o}C through the temperature controlled bath and that at the exit was kept 65 ^{o}C by adjusting the water flow rate. This method was based on the test method for the residential heat pump water heater according as Japan Refrigeration and Air-conditioning Industry Association standard (JRA 4050) [(9)].

The ability of heat exchange of the desuperheater was measured as follows:

$$q = \rho V c \left(T_{\mathrm{out}} - T_{\mathrm{in}} \right) \tag{4}$$

where ρ is the density of water, V is the volumetric flow rate, c is the specific heat, T is the temperature and the suffix “in” and “out” correspond to the conditions at the inlet and the outlet of the desuperheater respectively.

3. Results and Discussion

Firstly, the ability of supplying hot water was evaluated by changing the quantity of the charged refrigerant from 2.5 to 4.5 kg. Figure 4 shows the relation between the quantity of the charged refrigerant and the ability of hot water supply. As the quantity of the refrigerant increases, the ability of hot water supply improves until reaching 7.53 kW in average for 4.1 kg of the refrigerant. At this point, the flow rate of supplying hot water of 65 ^{o}C is 2.6 l/min in average. Beyond this point, the ability of hot water supply decreases even if the refrigerant quantity was increased.

The relation between the quantity of the charged refrigerant and the ability of air-conditioning heat exchange is shown in Figure 5 with comparison of with/without the desuperheater. The refrigerant quantity was changed from 2.5 to 4.5 kg in the case with the desuperheater and from 1.3 to 3.7 kg in the case without the desuperheater. For both cases, as the refrigerant quantity increases, the ability of air-conditioning heat exchange increases until reaching the maximum value and then the ability decreases. The ability increases until reaching 14.2 kW for 3.7 kg of the refrigerant quantity in the case without the desuperheater. On the other hand, the ability increases until reaching 13.6 kW for 4.1 kg in the case with the desuperheater. Thus the maximum amount of exchanged heat is decreased by installing the desuperheater.

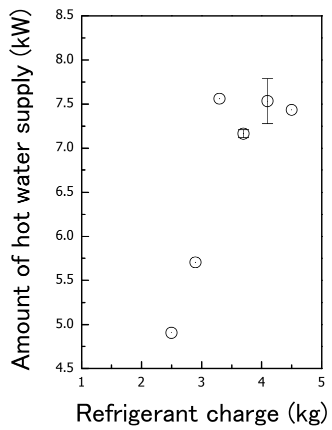

Fig. 4 Variation of the ability of hot water supply for different refrigerant charges

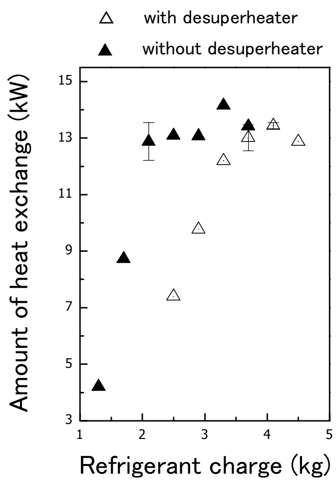

Fig. 5 Variation of the ability of cooling heat exchange for different refrigerant charges

The decrease of the ability of air-conditioning heat exchange by installing a desuperheater is probably caused by reduction of the refrigerant mass flow rate due to the reduction of refrigerant density at the inlet of the compressor. Observation through the sight glass at the outlet of the desuperheater showed that the refrigerant was in gas-liquid two phase condition. Thus the increase of required refrigerant quantities was caused by, for one thing, the increase of the total tube volume with installing a desuperheater and the other, the increase of the refrigerant density induced by the reduction of refrigerant quality inside the condenser.

The relation between the quantity of the charged refrigerant and the cooling COP is shown in Figure 6 with comparison of with/without the desuperheater. The cooling COP is defined as the ratio between the amount of cooling heat exchange and the input electric power. In this figure, as the refrigerant quantity increases, the cooling COP increases until reaching 3.31 for 3.7 kg of the refrigerant quantity in the case without the desuperheater. On the other hand, the cooling COP increases until 2.91 for 4.1 kg of the refrigerant quantity in the case with the desuperheater. Beyond the maximum value, COP becomes constant or decreases for both cases. It will be discussed later in this section why the cooling COP is lower in the case with the desuperheater.

Figure 7 shows the relation between the quantity of the charged refrigerant and the energy efficiency. The energy efficiency is defined as the ratio between the sum of exchanged heat due to both hot water supply and air-conditioning and the input electric power. It is seen from the figure that the energy efficiency improves as the refrigerant quantity increases until reaching 4.54 for 4.1 kg of the refrigerant quantity. The average value of the energy efficiency is 4.35 for the refrigerant quantity of 3.3 - 4.5 kg.

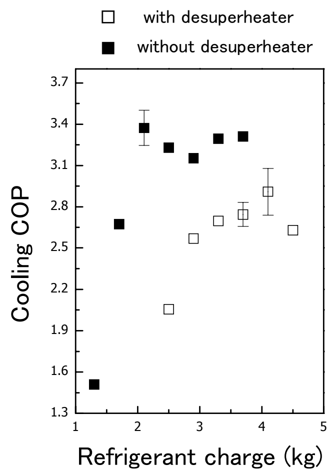

Fig. 6 Variation of cooling COP for different refrigerant charges

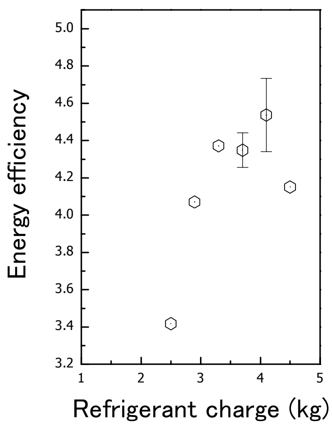

Fig. 7 Variation of energy efficiency for different refrigerant charges

Table 1 lists the average characteristics for the refrigerant quantity 3.3 - 4.5 kg in the case with the desuperheater and for 2.5 - 3.7 kg in the case without the desuperheater. The table shows that the cooling COP of the case with the desuperheater is lower by about 15 % than that of the case without the desuperheater and the ability of the air-conditioning heat exchange is a little lower for the case with the desuperheater.

Figure 8 shows the Mollier diagram obtained from the averaged temperatures and pressures of the refrigerant listed in Table 1. It is seen from this figure that the amount of exchanged heat per unit refrigerant mass in the evaporator is a little larger for the case with the desuperheater. However, due to the decrease of the refrigerant density at the evaporator, the ability of heat exchange in the evaporator gets lower for the case with the desuperheater. Furthermore larger work needs to be done by the compressor for the case with the desuperheater due to higher temperature and pressure after compression. Thus the COP decreases because of the reduction in the ability of heat exchange in the evaporator and the increase in the work done by the compressor.

On the other hand, it is seen from Table 1 that the overall energy efficiency of the case with the desuperheater is higher by about 34% than that of the case without the desuperheater. Since the heat rejected during air-conditioning was regenerated for supplying hot water, the energy efficiency is dramatically improved by installing the desuperheater. This indicates the advantage of installing the desuperheater for supplying hot-water by regenerating heat from the air-conditioning system under cooling operation.

Table 1 Characteristics of hot-water supply system for required refrigerant charges

Case	Amount of hot water supply [kW] (max)	Amount of heat exchange [kW] (max)	Cooling COP (max)	Overall energy efficiency (max)	Refrigerant temperature [℃]			Refrigerant pressure [MPa]	
					Compressor		Condenser outlet	Compressor	
					Inlet	Outlet		Inlet	Outlet
Without desuperheater	—	13.4 (14.2)	3.25 (3.31)	3.25 (3.31)	9.5	71.5	41.6	0.351	1.57
With desuperheater	7.40 (7.56)	13.0 (13.6)	2.77 (3.08)	4.35 (4.73)	10.4	94.3	38.7	0.335	2.05

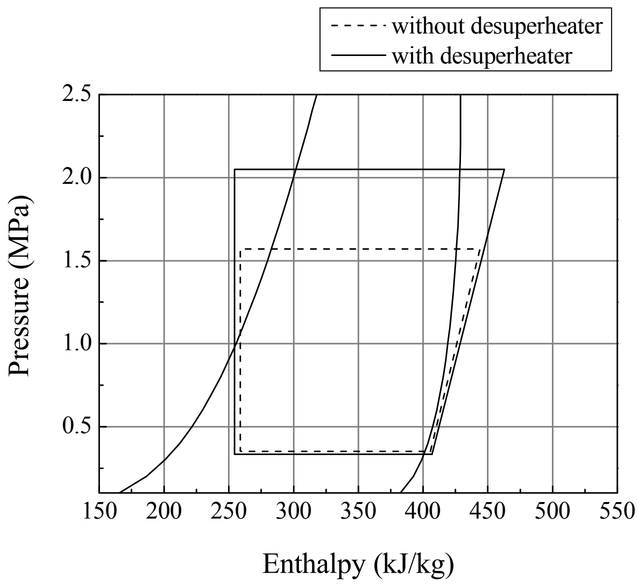

Fig. 8 Mollier diagram for the required refrigerant charges

4. Conclusion

In this study, hot water was supplied by regenerating the heat rejected from the air-conditioning system, which was equipped with a desuperheater and HFC134a refrigerant, and the performance was evaluated. The obtained results are listed as follows:

(1) Installing a desuperheater requires an additional quantity of refrigerant for the optimal condition.

(2) The COP becomes lower by about 15 % when a desuperheater is installed because the desuperheater requires larger work of the compressor due to higher temperature and pressure after compression.

(3) However, the energy efficiency of heat exchange including both air-conditioning and supplying hot water becomes higher by about 34 % than that of the case without a desuperheater. Thus we conclude that the energy efficiency of the air-conditioning system is dramatically improved by supplying hot water using a desuperheater.

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