

COMPARISON OF CO₂ HEAT PUMP CYCLES FOR WATER HEATER

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ABSTRACT

Recently, CO₂ as a refrigerant has been attracting attention because of its little negative environmental impact, non-flammable and non-toxic. The properties of this refrigerant are very favorable for heat pump applications such as residential heat pump water heaters. Due to the low critical point of CO₂, the heat pump cycle becomes trans-critical. Hence, the high pressure doesn't depend on condensing temperature. The high pressure has large effects on the COP. By the way, CO₂ systems are the higher costs of production than HCFCs or HFCs systems, because CO₂ is required high-pressure resistance. So, it is also important to reduce manufacturing cost. In this paper, we investigated the possibility of three simple CO₂ heat pump cycles, paying attention to the relation between the initial refrigerant charge amount and the COP when the ambient conditions such as water inlet temperature and outdoor temperature change. As a result, we proposed the CO₂ cycles without an accumulator, or with an internal heat exchanger, which were achieved not only cost saving but also high COP.

Key Words: *carbon dioxide, heat pumps, water heaters, coefficient of performance (COP)*

1 INTRODUCTION

From the viewpoint of ozone-layer protection, production of hydrochlorofluorocarbons (HCFCs) containing chlorine will be stopped stepwise until 2020. Furthermore, Hydro fluorocarbons (HFCs) which are being replaced as alternative refrigerants were designated as control substances at COP3 at the end of 1997 because they have high global warming potential. On the other hand, a move has begun to review substances which have existed in nature from ancient days, and in recent years, a large number of development and research have been popularly undertaken on refrigeration and air-conditioning systems using natural refrigerants in place of HCFCs or HFCs. Among them, carbon dioxide (hereinafter called the "CO₂ refrigerant") attracts attention. Especially in the Japanese market, since 2001, heat pump water heaters using the CO₂ refrigerant have been commercialized. For further popularization of the CO₂ heat pump water heaters, low cost, space saving, and energy saving must be simultaneously achieved, as is the case with the conventional refrigeration equipment.

For the features of the CO₂ refrigerant, (1) a little negative environmental impact because of the ozone depletion potential of zero and the global warming potential of 1; (2) safety because the CO₂ refrigerant is non-flammable and non-toxic; (3) CO₂ refrigerant operates at higher pressure than HCFCs or HFCs; (4) the high-pressure side of refrigeration cycle in air-conditioners or water heaters operates in supercritical region because CO₂ refrigerant has low critical temperature; and other features can be mentioned.

Because no condensation temperature exists in the supercritical region, the high pressure can be adjusted irrespective of the condensation temperature. In the case of air-conditioners, once the gas cooler

outlet temperature is fixed, there is the high pressure where the coefficient of performance (hereinafter called the “COP”) becomes the maximum. In addition, in the case of water heaters, it is the important point in improving the COP to adjust the high pressure to the pressure where the temperature difference between water and refrigerant in the gas cooler can be made small.

The high pressure can be adjusted by increasing or decreasing the refrigerant hold amount in the high-pressure side by adjusting the expansion valve opening. For the refrigeration cycle effective for adjustment of the high pressure (refrigerant hold amount in high-pressure side) of the trans-critical cycle, the cycle for adjusting the liquid refrigerant hold amount in the receiver (accumulator) mounted on the downstream side of the evaporator has been proposed (Lorentzen 1989).

2 INVESTIGATION OF REFRIGERATION CYCLES

The most suitable refrigeration cycle was investigated in order to achieve cost reduction, space saving, and energy saving of CO₂ heat pump water heaters. From the viewpoint of energy saving, it is important to optimize the high pressure and maintain the high COP for both following two cases. One is the case that the water heaters are operated under the standard operating conditions, the other is the case that water inlet temperature of the gas cooler rises under the conditions such as the water storage tank is nearly filled with hot water. In the present investigation, the COP of the following three types of refrigeration cycles were experimentally compared and evaluated. The adopted compressor is a high-pressure shell type scroll compressor in which the shell inside is filled with high-pressure refrigerant. Figure 1 shows the refrigeration cycle configurations and their targets are explained as follows.

2.1 Cycle without an Accumulator

Figure 1 (a) shows a simple refrigeration cycle with no receiver, no accumulator, or no other liquid storage equipment. This cycle is effective for cost reduction and space saving because there are less component parts. At the same time, when the refrigerant becomes an overstock condition, for example, when water inlet temperature of the gas cooler rises, excessive pressure rise in the high-pressure side and decrease of COP is feared, because this cycle has no element to absorb the excess refrigerant. In addition, generally, the accumulator has a role to prevent the liquid return to the compressor in order to secure the reliability of the compressor. Consequently, by adopting a high-pressure shell type scroll compressor (Hiwata et al. 2004) which provides outstanding reliability in liquid return, the cycle without an accumulator could be achieved.

2.2 Cycle with an Accumulator

Figure 1 (b) shows a refrigeration cycle with a liquid storage (accumulator) equipped for adjusting the refrigerant hold amount in high-pressure side. It is expected to be effective for improving the COP,

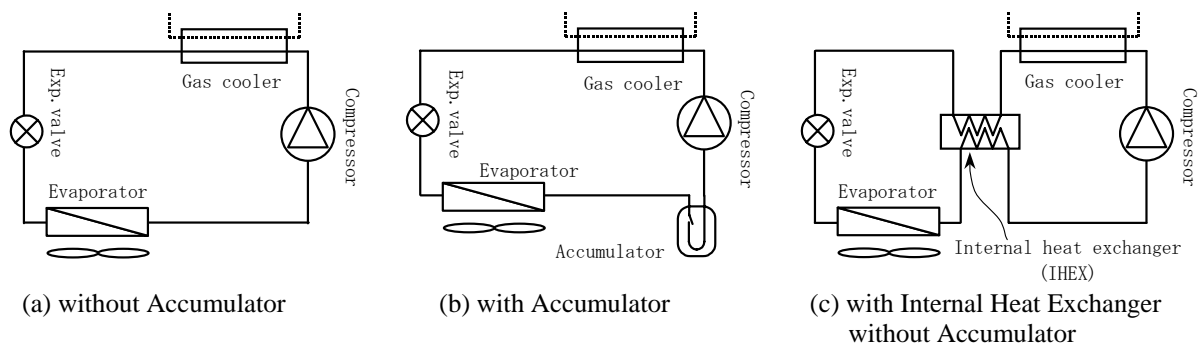


Fig. 1 Comparison of Refrigeration Cycles

because excessive pressure rise in the high-pressure side can be avoided even when the excess refrigerant is generated. On the other hand, adding an accumulator is disadvantageous from the viewpoint of cost reduction and space saving.

2.3 Cycle with an Internal Heat Exchanger without an Accumulator

In the cycle of Fig. 1 (c), no accumulator is equipped but an internal heat exchanger is equipped for adjusting the refrigerant hold amount in high-pressure side. It was assumed that the refrigerant density before and after the expansion valve could be increased, because the outlet refrigerant of gas cooler cooled by the suction refrigerant of compressor in the internal heat exchanger. Therefore, the optimization of the high pressure (or the refrigerant hold amount in high-pressure side) could be achieved. This cycle is advantageous over the cycle with an accumulator from the viewpoint of cost reduction and space saving, because the internal heat exchanger can be made into a comparatively simple construction by bringing the gas cooler outlet piping externally in contact with the suction piping.

3 EXPERIMENTAL APPARATUS AND TEST CONDITIONS

Table 1 outlines the component parts of the experimental apparatus. The accumulator is conventional type accumulator of which pressure resistance was only improved. The internal heat exchanger was adjusted to a size at which the maximum quantity of heat exchanged in the internal heat exchanger can be obtained within the range where the COP under the rated conditions does not decrease.

Table 2 shows the test conditions. These conditions were decided in reference to JRA 4050 standard (JRA 2004). Under the rated conditions, which are conditions of frequently occurrence, the water inlet temperature of gas cooler was fixed. However, under the winter conditions in which the excess refrigerant is generated and the high pressure is likely to increase, the water inlet temperature was varied.

Table 1. Specifications of Experimental Apparatus

Compressor	Inverter Scroll (High Pressure Type)
Evaporator	Fin and Tube (Ø7)
Gas-cooler	Concentric Triple Tube
Accumulator	Ø 90*290 mm
Internal Heat exchanger	Outer Contact Tube (Ø 6.4+ Ø 9.5)*800 mm

Table 2. Test Conditions

	Rated Conditions	Winter Conditions
Outdoor Temperature [°C] (DB / WB)	16 / 12	7 / 6
Water Inlet Temperature [°C]	17	9 35 55
Water Outlet Temperature [°C]	65	90

4 TEST RESULTS

4.1 Investigation at Optimum Initial Refrigerant Charge Amount under the Rated Conditions

First of all, investigation was made with the initial refrigerant charge amount that maximizes the COP under the rated conditions in each cycle. Figure 2 shows the ratio of the COP when the COP of the cycle with an accumulator is set to 100 under the rated conditions as well as the difference of suction pressure when the suction pressure of the cycle with an accumulator is set as a reference. In the cycle with an accumulator, the COP was decreased about 2-3% from other cycles due to increase of the suction pressure loss between the outlet of evaporator and the inlet of compressor. By the way, in the cycle with an internal heat exchanger, the quantity of heat exchanged in the internal heat exchanger was about 180W.

Figure 3 (a) shows the ratio of the heating capacity and the ratio of the COP when the heating capacity and the COP of the cycle with an accumulator are respectively set to 100 under the winter

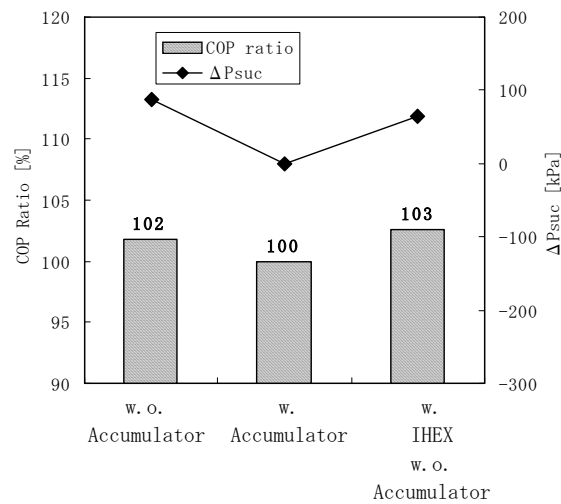


Fig. 2. Test Results under Rated Conditions at Rated Optimum Initial Refrigerant Charge Amount

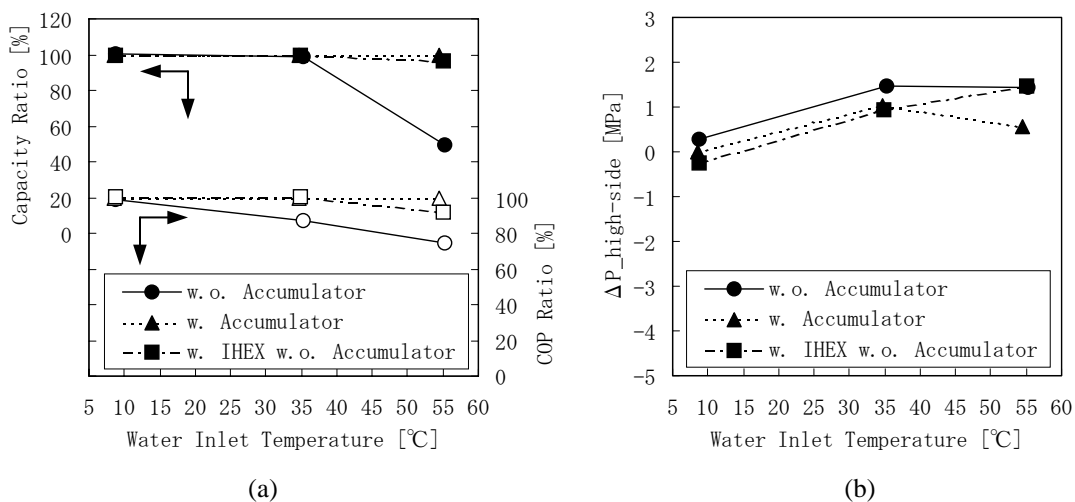


Fig. 3. Test Results under Winter Conditions at Rated Optimum Initial Refrigerant Charge Amount

conditions. Figure 3 (b) shows the difference of the high pressure when the high pressure of the cycle with an accumulator at 9°C water inlet temperature is set as a reference. At 9°C water inlet temperature, nearly equivalent COP is achieved in each cycle, but as the water inlet temperature increases, the COP of the cycle without an accumulator and the cycle with an internal heat exchanger have decreased as compared to the cycle with an accumulator. Especially, these decreases are large under the winter conditions at 55°C water inlet temperature (hereinafter called the “winter conditions at 55°C”).

This could be possibly attributed to the increase of the high pressure under the higher water inlet temperature conditions, because the initial refrigerant charge amount optimized under the rated conditions (hereinafter called the “rated optimum refrigerant charge amount”) is excessive.

4.2 Investigation at Optimum Initial Refrigerant Charge Amount under the Winter Conditions

The results of the preceding paragraph indicate that in the case of the rated optimum refrigerant charge amount, as the water inlet temperature rises under the winter conditions, the refrigerant is overcharged. Therefore, investigation was made at the initial refrigerant charge amount where maximizes the COP under the winter conditions at 55°C (hereinafter called the “winter optimum refrigerant charge amount”). Figure 4 (a) and (b) shows the ratio of the COP under the rated conditions and the winter conditions at 55°C, respectively, when the COP of the cycle with an accumulator at the rated optimum refrigerant charge amount are set to 100. In the case of under the rated conditions, the COP of each cycle at the winter optimum refrigerant charge amount is lower than the COP of each cycle at rated optimum refrigerant charge amount, as shown in Fig. 4 (a). However, in the case of under the winter conditions at 55°C, the COP of each cycle at winter optimum refrigerant charge amount becomes higher than the COP of each cycle at rated optimum refrigerant charge amount, because the initial refrigerant charge amount is adjusted. By comparison of the three cycles, the COP of the cycle without an accumulator is the lowest, as in the case of Fig. 2.

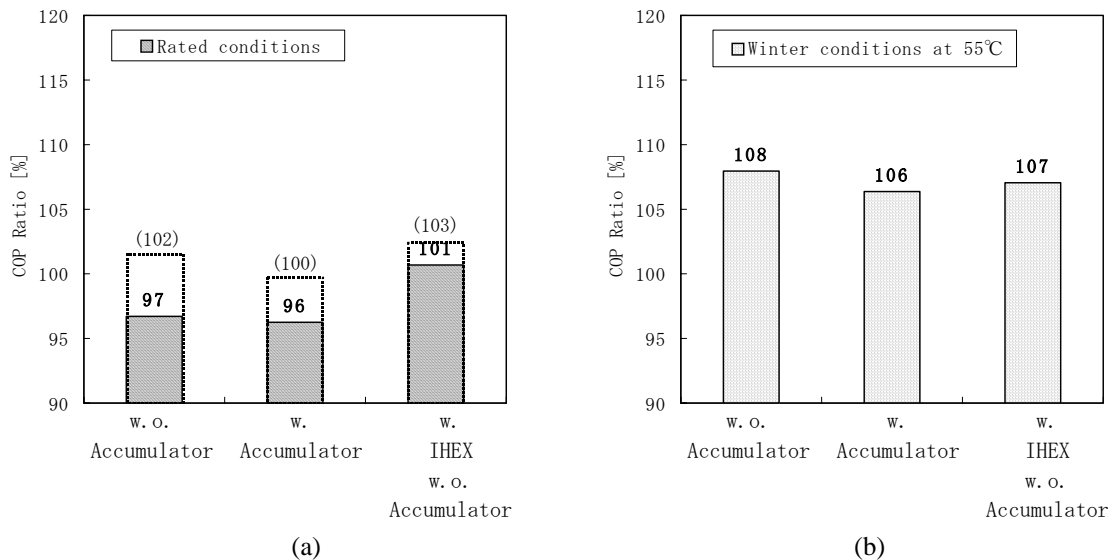


Fig. 4. Test Results at Winter Optimum Initial Refrigerant Charge Amount

4.3 Effect of Initial Refrigerant Charge Amount on the COP

The results of the preceding paragraph indicate that the initial refrigerant charge amount has large effect on the COP. Figure 5 (a) and (b) show changes of the COP as against the initial refrigerant charge amount under the rated conditions and under the winter conditions at 55 °C, respectively. In the cycle without an accumulator, the difference between the rated optimum refrigerant charge amount and the winter optimum refrigerant charge amount is about 150 g. This is comparatively greater than about 90-110 g of the difference in other cycles. So this difference causes the excess refrigerant under the winter conditions at 55 °C and results in decreased COP. On the other hand, the cycle with an accumulator and the cycle with an internal heat exchanger not only have the small difference of the refrigerant charge amount but also have gentle changes of the COP under the winter conditions at 55 °C. So these two cycles can absorb the excess refrigerant and can optimize the high pressure, it is assumed that even under winter conditions at 55 °C, these two cycles can maintain the high COP.

The reason of that the cycle with the internal heat exchanger can absorb the excess refrigerant is considered as follows, and also as shown in Fig. 6. (1) The quantity of heat exchanged in the internal heat

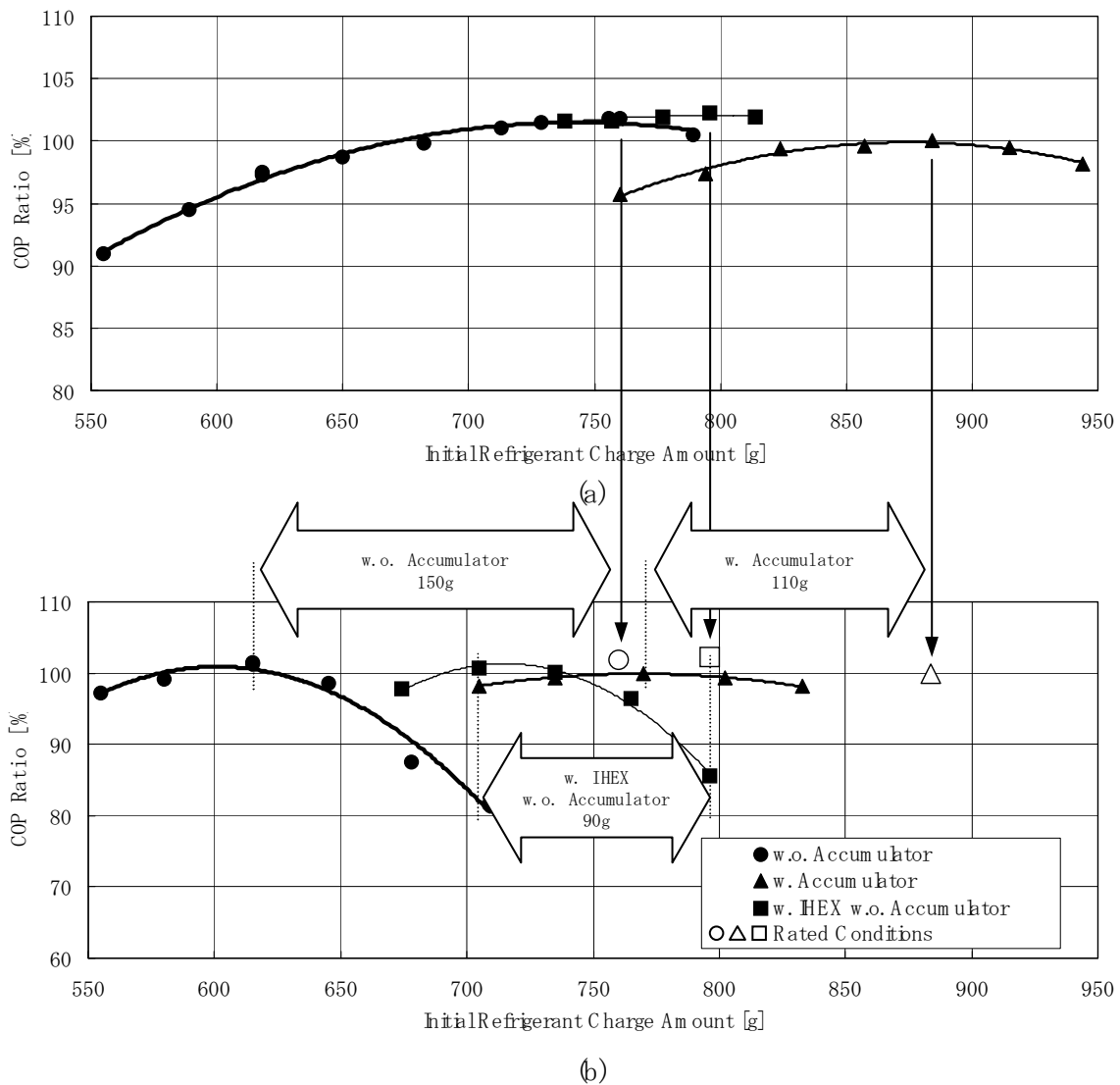


Fig. 5. Effect of Initial Refrigerant Charge Amount on the COP

exchanger was increased from about 180 W under the rated conditions to about 1.1 kW. (2) Then, the enthalpy of the expansion valve outlet decreased as compared to that of the cycle without an accumulator. (3) Consequently, because the quality of the evaporator inlet lowered from 0.6 to 0.4, the refrigerant hold amount in the evaporator increased about 30 g as compared to the cycle without an accumulator. Then the refrigerant hold amount in the high-pressure side could be possibly reduced. As a result, it is assumed that this change of the refrigerant hold amount in the evaporator adjusted the refrigerant hold amount in the high-pressure side and optimized the high pressure.

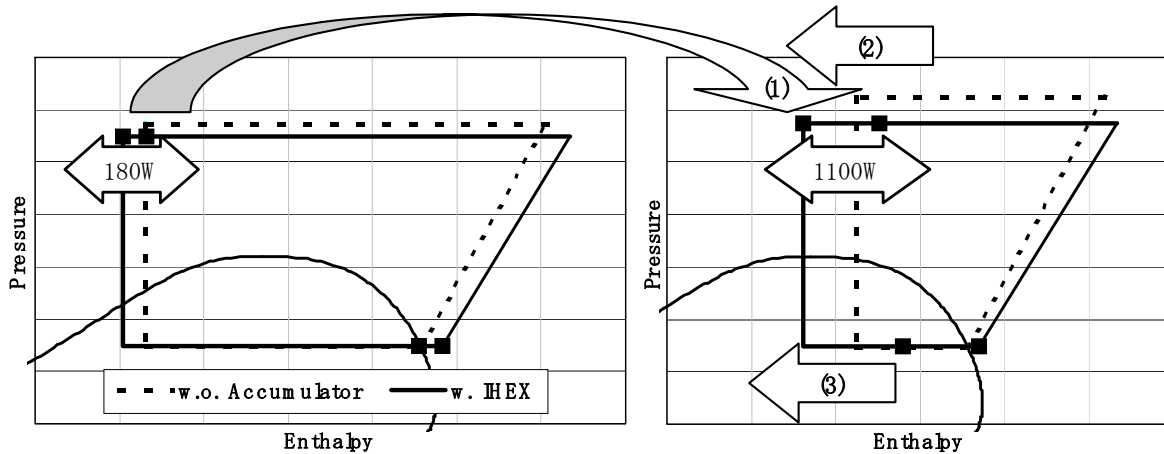


Fig. 6. Consideration of the effect of the internal heat exchanger

4.4 Investigation at Optimum Initial Refrigerant Charge Amount both under the Rated Conditions and under the Winter Conditions

Next investigation was made at the initial refrigerant charge amount that achieves satisfactory COP both under the rated conditions and under the winter conditions at 55 °C. The initial refrigerant charge amount of each cycle was adopted that the COP under the rated conditions could secure 99% or better COP of the cycle with an accumulator at the rated optimum refrigerant charge amount. Figure 7 (a) and (b) shows the ratio of the COP under the rated conditions and the winter conditions at 55 °C, respectively, when the COP of the cycle with an accumulator at the rated optimum refrigerant charge amount are set to 100. And Fig. 7 (b) also shows the difference of the high pressure when the high pressure of the cycle with an accumulator is set as a reference under the winter condition at 55 °C. In each cycle, under the rated conditions, the COP lowers about 0-2 % as compared to the COP at the rated optimum refrigerant charge amount. However, under the winter conditions at 55 °C, the COP improves about 4-7% as compared to the COP of the cycle with an accumulator at the rated optimum refrigerant charge amount because the high pressure can be optimized. The decrease of the COP under the rated conditions is smaller than that under the winter conditions at 55 °C. It can be attributed the changes of the COP under the rated conditions are more gently than that under the winter conditions at 55 °C, as shown in Fig. 5. It has been clarified that by adjusting the initial refrigerant charge amount, the COP of the cycle without an accumulator becomes equivalent to or higher than that of the cycle with an accumulator both under the rated conditions and under the winter conditions at 55 °C.

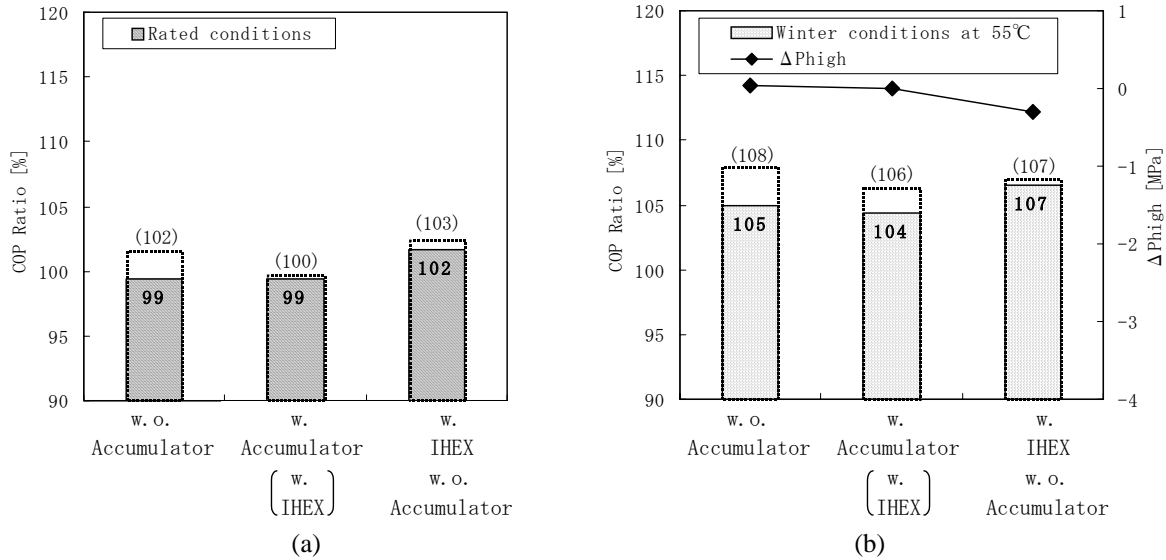


Fig. Test Results at Optimum Initial Refrigerant Charge Amount

In addition, the cycle with an internal heat exchanger provides the highest COP of the three cycles. It was because, as shown in Fig. 5, the difference between the rated optimum refrigerant charge amount and the winter optimum refrigerant charge amount is small. And also the higher discharge temperature than other cycles can achieve the equivalent capacity at the lower high pressure. By the way, in the case of the cycle with an internal heat exchanger installed with an accumulator, it is foreseen that its COP would be equivalent to that of the cycle without an accumulator or lower than that of the cycle with an internal heat exchanger. Because the more improvement of the COP by adjusting the refrigerant charge amount was not expected, and the decrease of the COP by increase of the pressure loss in the accumulator remains intact.

5 CONCLUSIONS

The investigation was made on the cycles that could simultaneously achieve energy saving, cost reduction, and space saving, and as a result, the following conclusions were obtained:

- (1) From the viewpoint of energy saving, the cycle with an internal heat exchanger (without an accumulator) can achieve the highest COP, then the cycle without an accumulator becomes second-highest COP, and the cycle with an accumulator becomes the lowest COP in these cycles.
- (2) From the viewpoint of cost reduction and space saving, it is effective in order of the cycle without an accumulator, the cycle with an internal heat exchanger (without an accumulator), and the cycle with an accumulator.
- (3) Therefore, the accumulator is not required for the trans-critical CO₂ cycle for heat pump water heaters in order to achieve cost reduction, space saving, and energy saving.

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