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Study on Annual Performance of Room Air Conditioners under Partial Load Condition

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ABSTRACT

Because of the moderate climate of Japan, most of the air conditioners (A/Cs) used are split-type A/Cs and can provide both heating and cooling during the year. Therefore, the coefficient of performance (COP) and the annual performance factor (APF) are used as criteria to evaluate the annual average performance of A/Cs; these criteria are established on the basis of Japanese Industrial Standards (JIS). The JIS-based performance rating method is easy and useful but does not take into account the intermittently driven mode of the compressor. In practice, A/Cs are mainly operated under partial load conditions, which are often 30%–50% of the full load. In this study, partial load tests were conducted for three different room air conditioners, and the measured APFs were compared to those calculated using the JIS-based calculation method. Because the inverter-driven compressors, which are widely used in A/C systems, are driven intermittently when the load is small and show low COP, the measured APFs were found to be much lower than those calculated using the JIS-based method when taking into account the intermittently driven mode. It is suggested that the JIS be revised by considering the performance deterioration at low load conditions.

1. INTRODUCTION

Different types of air conditioners (A/Cs) are used in residences, stores, and office buildings, including split-type, window-type, and central-type A/Cs. These A/Cs have been developed according to the climatic conditions, volume of the conditioning space, and purpose of use. Though the climate of Japan is rather moderate, most of the A/Cs used in residences are split-type A/Cs and heat pumps, which can provide both cooling and heating. Because heat pumps can be operated in both heating and cooling modes, the energy efficiencies of both modes have to be considered. Japanese Industrial Standards (JIS) C-9612:2005 (Japanese Industrial Standards Committee, 2005) stipulates the method to calculate the performance throughout the year, using both the cooling and heating operations. According to JIS, the annual performance factor (APF) can be calculated using experimental results from five conditions, including the low temperature heating operation involving the defrost process. Using an inverter-driven compressor, A/C compressors are able to operate continuously, which leads to increased comfort and high energy efficiency even when the A/Cs are required to handle various loads. Because an inverter-driven compressor is installed in most A/Cs, the coefficient of performance (COP) and APF have been increasing year by year. Nowadays, the APF is about 4–6 for most of the residence A/Cs in Japan. Because A/Cs are mostly driven under partial load conditions, which are often 30%–50% of the full load, the performance of A/Cs under low load conditions has been of primary interest in terms of energy reduction. The COP under low load conditions is usually relatively low, due to the intermittently driven mode of the compressor. When the compressors are switched on and off repeatedly at a certain interval, energy consumption is high during compressor startup (Watanabe *et al*., 2004). Thus, the COP of the A/Cs is supposed to show a curve relative to the load condition that the A/Cs are required to handle. However, according to JIS, for an A/C installed with an inverter-driven compressor, the coefficient of degradation (C_D), which indicates the degradation in energy efficiency at low load, is set to 0 when the minimum capacity of the A/C is lower than half of its rated capacity, which is the case for almost all commercially available A/Cs in Japan. Because C_D equals 0, COP of the A/Cs will gradually increase as the load decreases. Baxter *et al*. (1982) conducted a long-term field experiment for a heat pump and compared the results with steady-state experimental results. Results of the comparison revealed that the cooling and heating seasonal performance decreased 10%–20% from steady-state performance. Katipamula and O'Neal (1992) measured the partial load factor by considering the cycling rate, unit ON time, etc., as variables to derive a correlation for obtaining the partial load function and then calculated the seasonal COP. Bettanini *et al*. (2003) considered a simulation model to calculate the performance of air conditioners and chillers under partial load conditions. Recently, the COP degradation under low load conditions has been studied for packaged A/Cs having a single outdoor unit with few indoor units (Hirota *et al.*, 2007). Cecchinato (2010) reported the partial load efficiency of packaged air-cooled water chillers with inverter-driven scroll compressors. While some researchers have reported on the relationship between the load and COP, still, there is a paucity of available data. In this study, partial load experiments using room air conditioners (RACs) were conducted to evaluate the COP degradation associated with a decrease in load. Additionally, the APF between the JIS-based method and experimental results was compared to reveal the difference in the APFs, taking into consideration the COP decrease at partial load conditions.

2. EXPERIMENT

In this study, two kinds of experiments, a standard test and partial load test, were conducted. The standard test is stipulated in JIS, with experiments conducted at five temperature conditions, including rated cooling, half-rated cooling, rated heating, half-rated heating, and low-temperature heating. Using the experimental results from these five conditions, APF can be calculated. The partial load test was conducted to evaluate the COP of the A/Cs in actual operation. The most notable difference between the standard test and partial load test is the compressor frequency. During the standard test, the compressor frequency is fixed; however, it is variable in the partial load test. Thus, the results of the partial load test reveal the actual performance of the A/Cs.

2.1 Experimental Apparatus

An air-enthalpy method test apparatus was used to evaluate the capacity and COP of the A/Cs, as shown in Figure 1. This experimental apparatus consists of two rooms—an outdoor-unit room and indoor-unit room—in which temperature and humidity can be controlled independently. Additionally, when the partial load test is conducted, the heater output and cooling water mass flow rate are adjusted to generate the designated thermal load. Photographs of the experimental apparatus are shown in Figure 2.

2.2 Experimental Conditions

Experimental conditions of the standard test were determined according to JIS. For partial load tests, the load and outdoor-unit room temperature were decided from the relationship stipulated in JIS. A load of 100% was set based on the rated capacity of the RACs, which was 4 kW for cooling and 5 kW for heating. The experimental conditions are shown in Table 1.

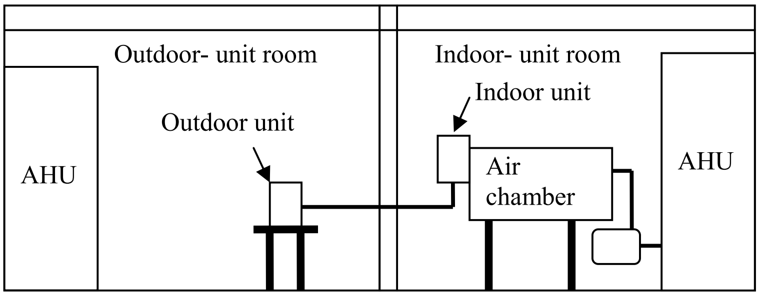

Figure 1: Experimental apparatus

2.3 Specifications of the Tested RACs

Three different RACs were tested, with each RAC having the same rated cooling and heating capacity. These RACs are all split-type heat pumps, which consist of one outdoor unit and one indoor unit. Machines A and B were purchased from the market, and machine C was provided by the manufacturer with necessary modification to measure refrigerant pressure and heat exchanger temperature.

Figure 2: Indoor-unit room (air chamber)

Figure 3: Outdoor-unit room

Table 1: Experimental conditions

	Indoor-unit room [DB/WB] [°C]	Outdoor-unit room [DB/WB] [°C]	Load [kW]
Rated cooling	27/19	35/24	4
Half-rated cooling			2
Rated heating	20/15	7/6	5
Half-rated heating			2.5
Low-temp. heating		2/1	-
Cooling 50% load	27/19	28/20.4	2
Cooling 30% load		26/17.1	1.2
Cooling 15% load		24.5/17.5	0.6
Heating 50% load	20/15	7/6	2.5
Heating 30% load		12/10.5	1.5
Heating 15% load		14/12.5	0.75

Table 2: Specifications of tested A/C

Machine	A	B	C
Rated cooling capacity [kW]	4.0	4.0	4.0
Rated heating capacity [kW]	5.0	5.0	5.0
Low-temp. heating capacity [kW]	5.7	8.2	-
APF	5.2	6.4	4.9

2.4 Experimental Method

During the standard test, the outdoor-unit room and indoor-unit room were controlled at a certain temperature and humidity as shown in Table 1. The test RACs were operated with fixed compressor frequency and air flow rate to obtain the necessary capacity shown in Table 1. The capacity of the A/C was measured using the inlet and outlet air temperatures and humidity of the indoor unit. Before the partial load test, outdoor-unit room and indoor-unit room temperatures and humidity were controlled without the tested RAC operated. After both room temperature and humidity were stabilized, the experiment was started with the operating test RAC. The designated load was generated when the experiment started. During the partial load experiment, the air handling unit (AHU), which consists of a heater and cooler using cooling water, was operated with fixed output. Because the AHU generated fixed heating and cooling capacity, the inside-room temperature and humidity would fluctuate depending on operation of the test RAC. The test RACs were controlled by the controller, to keep the indoor-unit room temperature at the same temperature shown in Table 1. For example, when the 50% load cooling experiment was conducted using machine A, the indoor-unit room was controlled to be 27/19 °C. After the temperatures and humidity of the indoor-unit room and outdoor-unit room were stabilized, the experiment was started and the test

RAC was operated according to its set temperature. The AHU in the indoor-unit room generated heating output of 2 kW (50% of 4 kW) when the experiment started, to obtain the designated load. (Machine A tended to make the room temperature lower than the temperature set by the controller. Thus, the controller was set to 29 °C in order to keep the indoor-unit room at 27 °C).

3. RESULTS

The results of the experiments are shown below. "Actual load" in the table is the measured average load during the experiment. The COP is calculated by dividing the capacity, which was measured by the air enthalpy method, by the electricity consumption. When the RAC was driven intermittently, the COP was calculated using the average capacity and electricity consumption of several cycles.

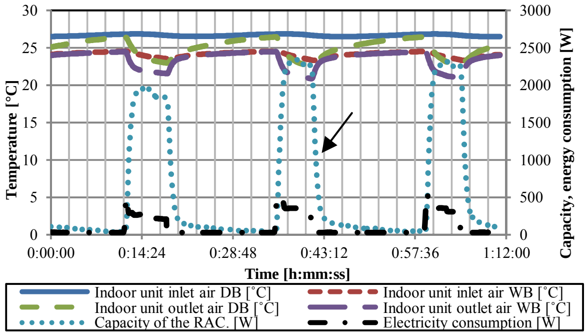

Figure 4: Experimental data for 15% load cooling (1)

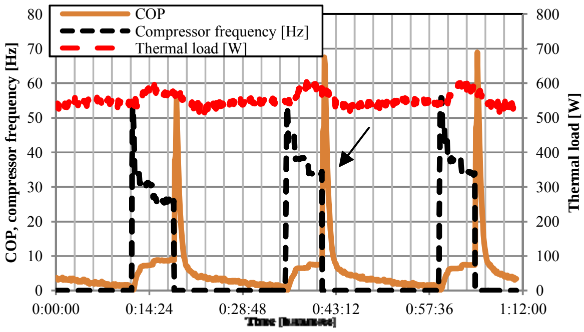

Figure 5: Experimental data for 15% load cooling (2)

Table 3: Experimental results of machine A

	Capacity [kW] (Catalog SPEC.)	Designated load/Actual load* [kW]	COP
Rated cooling	3.96 (4.0)	-/-	3.5
Half-rated cooling	1.82 (-)	-/-	5.9
Rated heating	4.89 (5.0)	-/-	4.2
Half-rated heating	2.34 (-)	-/-	5.9
Low-temp. heating	5.3 (5.6)	-/-	2.6
Cooling 50% load	0.85 (Sensible cooling capacity: 1.73)	2.0/1.69	3.8 (7.9)
Cooling 30% load	0.97	1.2/0.88	6.1
Cooling 15% load	0.60	0.6/0.52	4.8
Heating 50% load	2.59	2.5/2.65	5.1
Heating 30% load	1.69	1.5/1.69	5.4
Heating 15% load	0.88	0.75/0.97	4.6

*The actual load in this study is used as a reference because some errors were found on the temperature sensor of the cooling water. Thus, the capacity of the A/C is the actual load.

4. DISCUSSION

4.1 Comparing the APF Calculated by Experimental Results and JIS Method

The APF was calculated using the standard test and partial load test results. The JIS method estimates the COP change associated with the outdoor temperature, which determines the load that the RAC is required to handle during the cooling season and heating season. Thus, the energy consumption for cooling and heating can be derived by dividing the load by the COP. The annual energy consumption of the RAC can be calculated by summing the amount of energy consumption for both cooling and heating.

Table 4: Experimental results of machine B

	Capacity [kW] (Catalog SPEC.)	Designated load/Actual load* [kW]	COP
Rated cooling	3.82 (4.0)	-/-	4.2
Half-rated cooling	1.69 (-)	-/-	6.2
Rated heating	5.05 (5.0)	-/-	5.0
Half-rated heating	2.39 (-)	-/-	6.7
Low-temp. heating	8.07 (8.2)	-/-	2.2
Cooling 50% load	1.76	2.0/1.67	8.6
Cooling 30% load	1.12	1.2/0.88	7.8
Cooling 15% load	0.40	0.6/0.36	6.1
Heating 50% load	3.13	2.5/2.86	5.6
Heating 30% load	1.60	1.5/1.51	7.2
Heating 15% load	1.09	0.75/1.10	6.1

*The actual load in this study is used as reference because some errors were found on the temperature sensor of the cooling water. Thus, the capacity of the A/C is the actual load.

Table 5: Experimental results of machine C

	Capacity [kW] (Catalog SPEC.)	Designated load/Actual load* [kW]	COP
Rated cooling	3.94 (4.0)	-/-	3.1
Half-rated cooling	1.79 (-)	-/-	5.3
Rated heating	4.93 (5.0)	-/-	3.7
Half-rated heating	2.36 (-)	-/-	5.7
Low-temp. heating	5.25 (-)	-/-	2.5
Cooling 50% load	2.39	2.0/2.12	4.9
Cooling 30% load	1.73	1.2/1.07	7.5
Cooling 15% load	0.83	0.6/0.59	6.9
Heating 50% load	2.47	2.5/2.37	4.5
Heating 30% load	1.70	1.5/1.54	5.6
Heating 15% load	0.62	0.75/0.89	7.4

The APF of the RAC can be obtained using annual energy consumption and annual load. For instance, considering the cooling season, the load during the cooling season (*BLc* [kW]) can be calculated by Equation (1) which only depends on the rated cooling capacity (Φ_{rc} [kW]) of the RAC and outdoor temperature (*t* [°C]). The total load during the cooling season is calculated by Equation (2), accumulating the product of the load and the initiation time (*n* [hour]). Cooling season performance factor (CSPF) can be obtained from Equation (5) as well as the annual performance factor from Equation (6), where HSTL and HSEC are the heating season total load and heating season energy consumption, respectively. The equations to calculate HSEC and HSPF are not shown because they are not essential in this study. However, the idea is identical to the method to calculate cooling season load, etc.

$$BL_c(t) = \Phi_{rc} \times \frac{(t-23)}{(33-23)} \qquad (t<33) \tag{1}$$

$$CSTL = \sum_t BL_c(t) \times n(t) \tag{2}$$

$$P_c(t) = \frac{BL_c(t)}{COP(t)} \tag{3}$$

$$CSEC = \sum_t P_c(t) \times n(t) \tag{4}$$

$$CSPF = \frac{CSTL}{CSEC} \tag{5}$$

$$APF = \frac{CSTL + HSTL}{CSEC + HSEC} \tag{6}$$

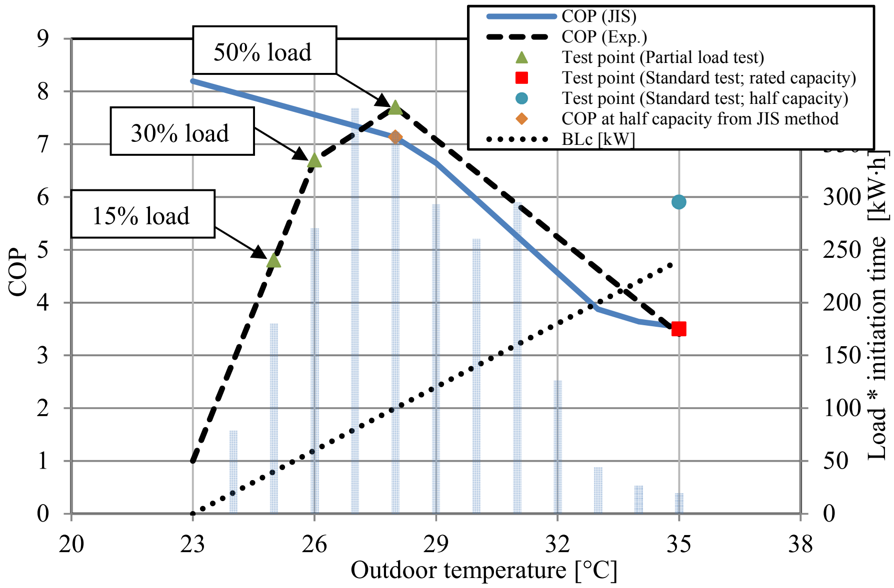

Figure 6: Cooling COP of machine A

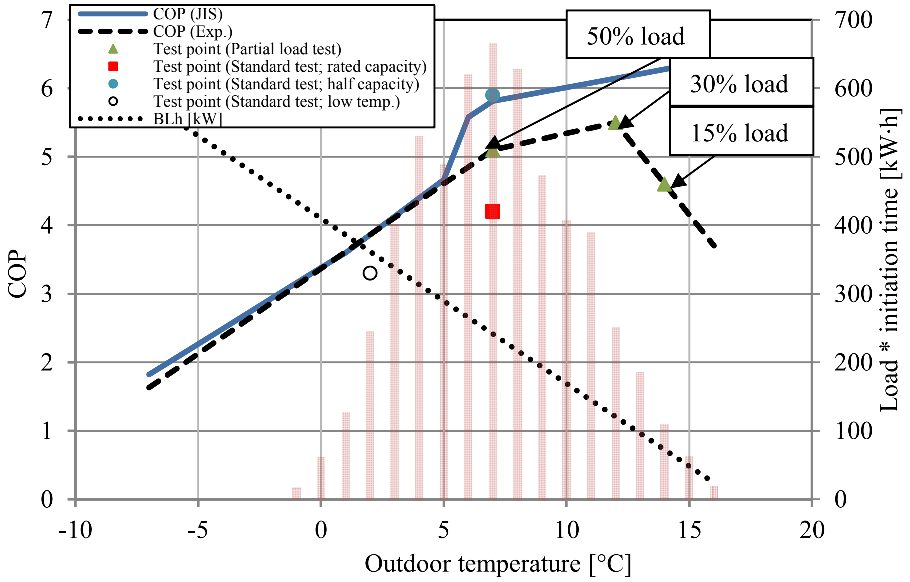

Figure 7: Heating COP of machine A

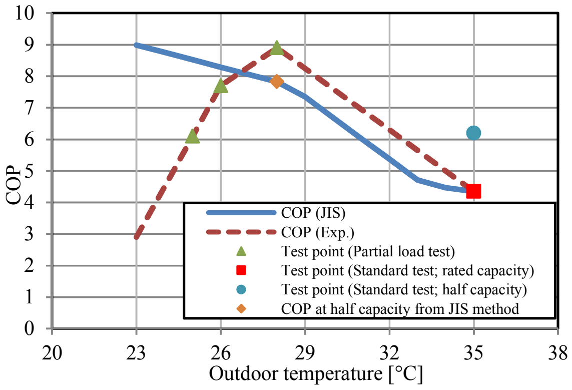

Figure 8: Cooling COP of machine B

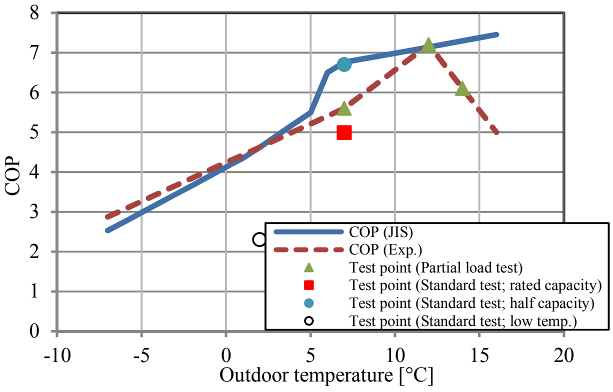

Figure 9: Heating COP of machine B

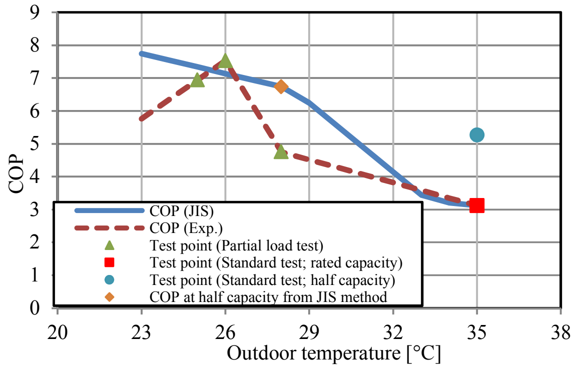

Figure 10: Cooling COP of machine C

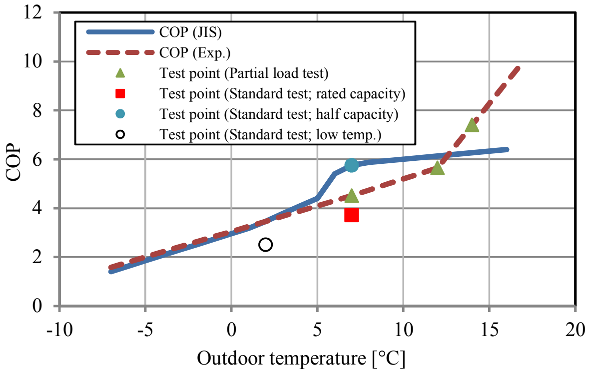

Figure 11: Heating COP of machine C

Figures 6–11 show the COP calculated by the experimental results COP (Exp.) and JIS method COP (JIS). During the experiment, the cooling COPs at three outdoor temperatures were directly measured and COPs at other outdoor temperatures were interpolated from the measured values. The three temperature conditions used in the experiment correspond to the load ratios of 50%, 30%, and 15%. The COP at a temperature below 25 °C, corresponding to a load ratio of 15%, was extrapolated using the measured COP at load ratios of 30% and 15%. The heating COP (Exp.) was calculated using results from three partial load tests and the slope stipulated by JIS. The COPs at other temperatures were interpolated from measured values. The heating COP (Exp.) at an outdoor temperature higher than 14 °C was extrapolated using the measured COPs at load ratios of 30% and 15%. The bars shown in Figures 6 and 7 indicate the product of the load and the initiation time. From the figure, 30%–50% load regions are big, so the COP at this outdoor temperature will strongly affect the CSPF, HSPF, and APF. From the experimental results shown in Figures 6–11, except for machine C, the highest COP appears at 50% load for cooling and 30% load for heating. However, machine C shows a different tendency, especially for the heating mode where the COP keeps increasing as the load decreases. The reason for this result is the minimum compressor frequency of the compressor. The minimum compressor frequency was about 20 Hz for machines A and B, while it was 12 Hz for machine C. The compressor of machine C was driven continuously even under the 15% load condition during heating. If the load is lower than the capacity when the compressors operate at minimum frequency, the compressor is driven intermittently. The COP when the compressor is driven intermittently is low due to large energy consumption during compressor startup. Thus, the A/Cs with smaller minimum compressor frequency usually have higher COP under low load conditions. Using COP (JIS) and COP (Exp.), CSPF, HSPF, and APF were calculated respectively. The value in parentheses in Table 6 shows the deviation of the value using the COP calculated by the JIS- method compared to that using partial load test results. As shown in Table 6, most of the values are higher using the COP based on the JIS-method than those using the partial load test results because the COP derived from the JIS- method is higher at loads of 30%–50% than that based on the partial load experiments.

Table 6: Comparison of CSPF, HSPF, and APF calculated between partial load test results and the JIS-based method

Machine	A	B	C
CSPF (JIS)/CSPF (Exp.)	6.4/6.1 (+4.7%)	7.2/7.3 (-2.3%)	6.0/5.0 (+19.9%)
HSPF (JIS)/HSPF (Exp.)	5.2/4.8 (+9.3%)	6.1/5.6 (+9.1%)	4.6/4.4 (+2.8%)
APF (JIS)/APF (Exp.)	5.5/5.1 (+8.2%)	6.4/6.0 (+5.9%)	4.9/4.6 (+6.8%)

4.2 Determining the C_D Value

As shown in Figures 6–11, the COP of the RACs does not always increase with a decrease in load. In order to evaluate the COP degradation at low load, a coefficient of degradation, C_D, is stipulated by JIS. According to JIS, this value is used when the minimum capacity of the RAC is not lower than half of its rated capacity. However, most RACs used in Japan exhibit a minimum capacity lower than half of the rated capacity. Thus, C_D is set to zero, which means no degradation occurs on the COP, as shown in COP (JIS) in Figures 6–11.

In this study, C_D was calculated to evaluate the degradation of the COP quantitatively. Figure 12 shows the definition of C_D on cooling COP. Point a is the COP measured from experimental results of rated cooling capacity and point b is that under the 50% load condition. Using the coefficient, which determines the slope of the line from point b to c, stipulated by JIS, the COP difference with a C_D of 0 was obtained. On the other hand, point d shows the COP when C_D is 1. When C_D is 1, the COP is 0 at the point where the load is 0 and the line interpolated between points b and d is the COP difference along the outdoor temperature (load). The C_D is between 0 and 1, which determines the ratio of the COP difference at points c and e and that at points c and d. Once C_D is calculated, the COP difference along the outdoor temperature below the load of 50%, which is below 28 °C for cooling and above 7 °C for heating, can be obtained. In order to calculate C_D, the electricity consumption below 50% load was considered. As mentioned above, the energy consumption can be calculated by dividing the load by the COP (Equations (3), (4)). In this study, C_D was calculated by minimizing the difference of the total energy consumption below 50% load, between that calculated from the COP (Exp.). It should be mentioned that only the total energy consumption below 50% load was considered because compensating the total energy consumption difference by adjusting C_D, which only affects the COP below 50% load, is illogical. The calculated results are shown in Figures 13–18. In Figures 13–18, the COP (JIS C_D = X) represents that when a C_D of X was applied, using COP (JIS) from 100%–50% load and below 50% load. On the other hand, the COP (Exp. C_D = X) shows the COP (Exp.) applying a C_D of X.

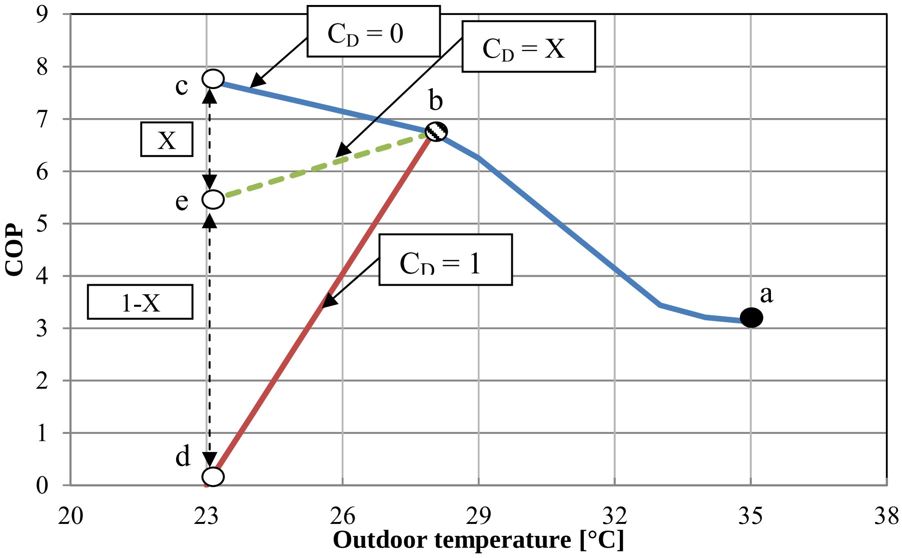

Figure 12: Definition of the C_D value

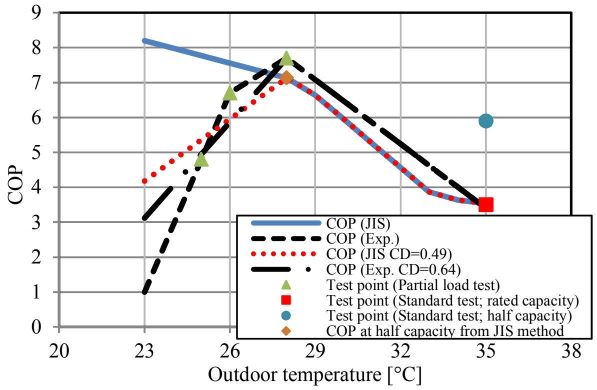

Figure 13: Calculated C_D value on cooling of machine A

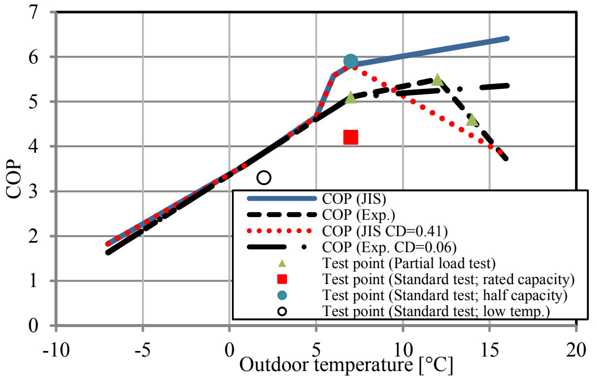

Figure 14: Calculated C_D value on heating of machine A

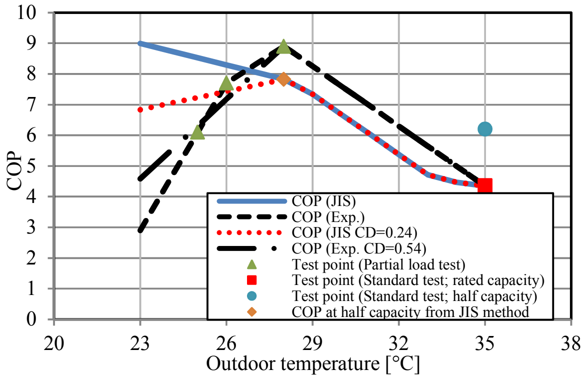

Figure 15: Calculated C_D value on cooling of machine B

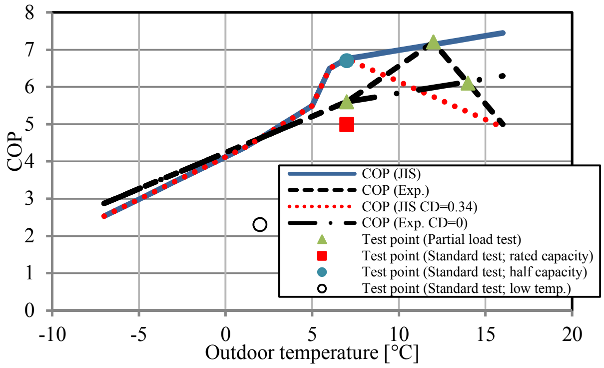

Figure 16: Calculated C_D value on heating of machine B

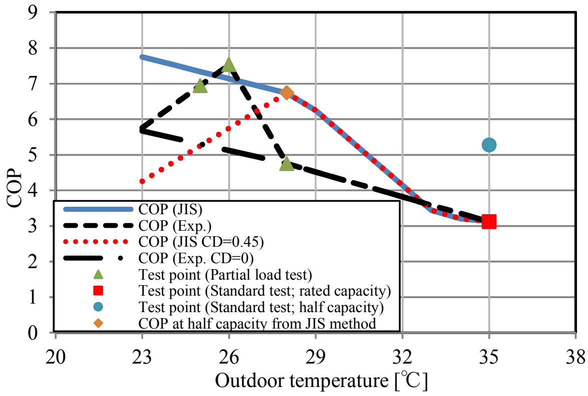

Figure 17: Calculated C_D value on cooling of machine C

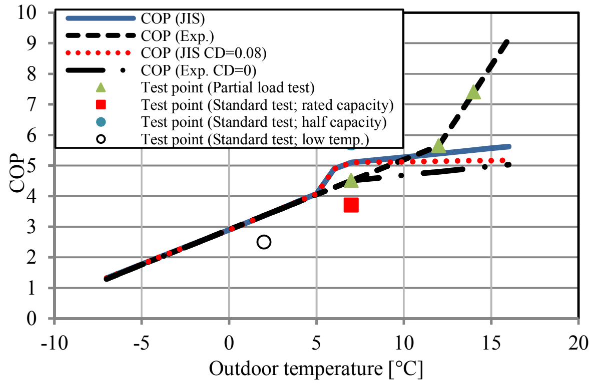

Figure 18: Calculated C_D value on heating of machine C

As shown in Table 7, values of C_D vary from 0 to 0.64 and are dependent on the machine characteristics. From Figures 13–18, when the COP at 30% load shows the highest COP, C_D will be rather small, opposite the case when the highest COP appears at 50% load. Comparing COP (JIS C_D = X) and COP (Exp. C_D = X), COP (Exp. C_D = X) has higher C_D on cooling mode due to the higher COP at the 50% load condition, which leads to a drastic degradation of the COP compared to the situation when 50% load COP is low. The C_D of COP (JIS C_D = X) is higher on heating mode, because the COP (JIS) at 50% load is bigger than COP (Exp.). The C_D for machine C, using 50% load experimental results, is 0 for cooling and heating, because COP (Exp.) is much higher than COP (JIS) even under low load condition. Each performance factor was calculated using four evaluation methods for the COP shown in Figures 13–18. Eventually, the APF using COP (JIS + C_D) was the closest, among the four evaluation methods. However, this does not mean that this method describes the actual COP degradation when the load is small.

Table 7: C_D value of each machine

Machine	A	B	C
COP (JIS C_D = X)	0.49/0.41	0.24/0.34	0.45/0.08
COP (Exp. C_D = X)	0.64/0.06	0.54/0.0	0.0/0.0

(Cooling/Heating)

Table 8: Performance factor using different evaluation method for machine A

	JIS	Exp.	JIS + C_D	Exp. + C_D
CSPF	6.4 (+4.7%)	6.1	5.8 (-4.4%)	6.1 (0.0%)
HSPF	5.2 (+9.3%)	4.8	4.9 (+2.1%)	4.8 (+0.2%)
APF	5.5 (+8.2%)	5.1	5.1 (+0.8%)	5.1 (+0.8%)

Table 9: Performance factor using different evaluation method for machine B

	JIS	Exp.	JIS + C_D	Exp. + C_D
CSPF	7.2 (-2.3%)	7.3	6.9 (-6.3%)	7.3 (0.0%)
HSPF	6.1 (+9.1%)	5.6	5.8 (+3.3%)	5.4 (-3.1%)
APF	6.4 (+6.1%)	6.0	6.1 (+0.8%)	5.9 (-2.4%)

Table 10: Performance factor using different evaluation method for machine C

	JIS	Exp.	JIS + C_D	Exp. + C_D
CSPF	6.0 (+19.9%)	5.0	5.5 (+10.6%)	4.6 (-8.2%)
HSPF	4.6 (+2.8%)	4.4	4.5 (+1.8%)	4.2 (-4.4%)
APF	4.9 (+6.8%)	4.6	4.8 (+4.1%)	4.3 (-5.5%)

5. CONCLUSIONS

In this study, experiments were conducted to evaluate the COP of RACs under partial load conditions. The following conclusions can be drawn from the obtained results.

- Partial load tests conducted for RAC showed that as the load decreased, the COP increased and the highest COP was obtained at around 30%–50% load; as the load decreased further, the COP decreased.
- The RAC having the lowest minimum compressor frequency exhibited the highest COP associated with the load decrease.
- C_D was calculated to evaluate the degradation of the COP, with results showing no single value. The calculated C_D varied from 0 to 0.64.

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