

ENERGY EFFICIENCY OF ROOM AIR CONDITIONER UNDER VARIOUS OUTDOOR CONDITIONS AND OPERATING MODES

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Abstract: Energy efficiency of room air conditioner for residential house depends much on compressor frequency, the ambient temperature and humidity of the external unit, operation mode and so on. Heating and cooling loads of a house are widely distributed in Japan because occupants normally stop heating or cooling during their absence, and thereby the room air conditioner often operates with low compressor frequency. Efficiency for varying partial load of an air conditioner is hence essential to calculate seasonal energy consumption for heating and cooling. In this paper, we tested a room air conditioner in the experimental house built in an artificial climate chamber and measured the steady-state efficiency in various conditions such as heating/cooling load, outdoor and indoor temperature and humidity and the operating mode. The results clarified that the efficiency and sensible and latent heating/cooling capacity of the tested room air conditioner depended on the conditions and the operating mode, and also clarified that the efficiency especially dropped in intermittent on-off operation and defrosting operation.

Key Words: *room air conditioner, efficiency, operating mode, partial load*

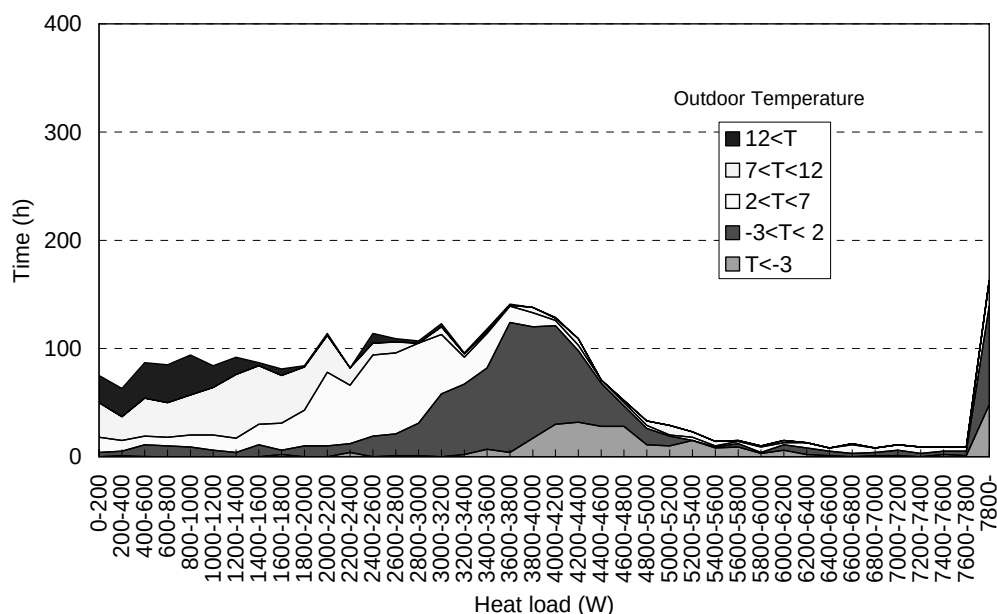
1 INTRODUCTION

For the evaluation of the energy performance of a house for heating and cooling, we need to consider the performance of the installed heating/cooling appliances such as air conditioner in addition to evaluate the envelope performance of the house. The performance of heating/cooling appliances is often measured according to the test defined by standards such as ISO and JIS (Japanese Industrial Standard). Room air conditioners are tested under ISO 5151, JIS 8605-1, JIS 9612 and so on, and the tested performance is represented as COP (Coefficient of Performance) or EER (Energy Efficiency Ratio), which performance is tested under rated condition. Meanwhile, as is well known, energy efficiency depends much on compressor frequency, the ambient temperature and humidity of the external unit, operation mode and so on.

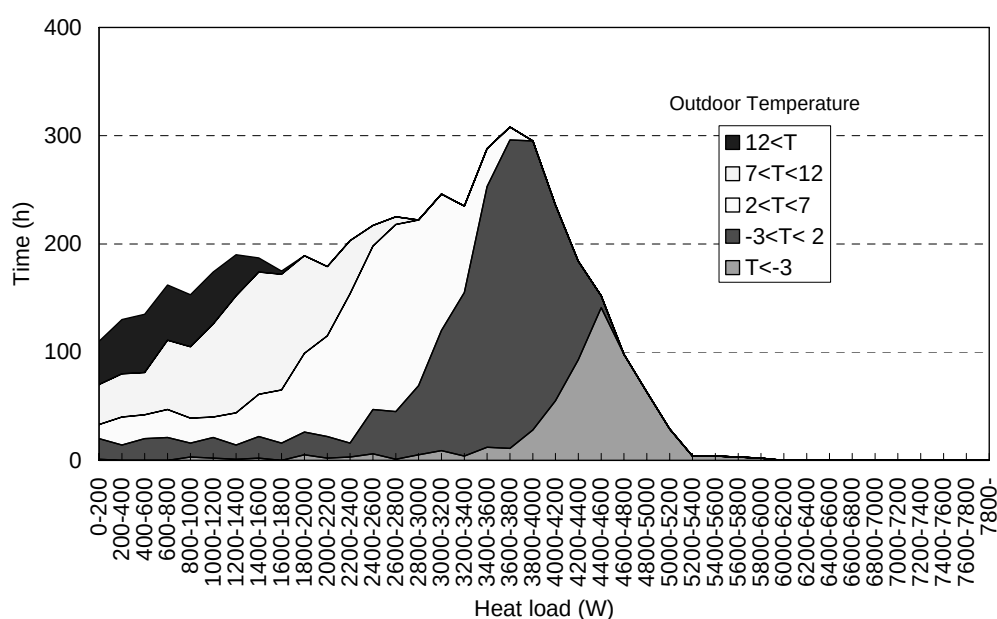
The heating and cooling loads of a house are widely distributed in Japan because occupants normally stop heating or cooling during their absence. Figure 1 shows the distribution of the heating load in the living room of a typical residential house built in a northern area of Japan, which was calculated on a heat load calculation program "SIM Heat". Figure 1 (a) shows the case that the occupants stop heating during their absence, which case is typical in Japan. Figure 1 (b) shows the case that the occupants continue heating regardless of their absence in 24 hours a day. In the case (a), the maximum heating load is over 7900 W, the room air conditioner which has a large maximum capacity is accordingly necessary. And thereby it will often operates with low compressor frequency and will often work with intermittent operation. On the other hand, in the case (b), the heating load is distributed in the range of 0 to 6200 W.

And thereby, the room air conditioner which has less maximum capacity could be installed and accordingly the room air conditioner may work with the range of high compressor frequency.

Efficiency for varying partial load of air conditioners is hence essential to calculate seasonal energy consumption for heating and cooling. In this paper, we tested a room air conditioner in the experimental house built in an artificial climate chamber and measured the steady-state efficiency in various conditions such as heating/cooling load, outdoor and indoor temperature and humidity and the operating mode.



(a) Occupants stop heating during their absence, which case is typical in Japan.



(b) Occupants do not stop heating during their absence and consequently heat the room in 24 hours a day.

Figure 1: Case Study of Heating Load at the living room in a House

2 MEASUREMENT

We installed a room air conditioner (Figure 2) into the experimental wooden house built in an artificial climate chamber and measured the performance with varying the ambient temperature and humidity of the internal and external units, which condition was controlled by changing the chamber temperature and humidity and the ventilation rate of the experimental house and the amount of heat generation by electric heaters in the house.



Figure 2: Tested Room Air Conditioner

Table 1 shows the specification of the tested room air conditioner. We measured the ambient temperature and humidity of the internal and external units, the electric power consumption and the temperature and humidity of the indoor intake airflow and discharge airflow of the internal unit. In order to measure heating/cooling capacity, we measured the enthalpy of the indoor intake airflow, the enthalpy of the indoor discharge airflow and the volumetric airflow, and then we multiplied the flow by the enthalpy difference. In order to measure the airflow, we set a rotation frequency meter at the fan shaft of the internal unit and then calculated the airflow from the measured rotation frequency based on the relationships between them as shown in Figure 3, which relationships were measured in additional tests carried out at a testing body. The intervals of all measurement items were 1 minute.

Table 1: Specification of the Tested Room Air Conditioner

	COP	Capacity (kW)			Electric Power Consumption (W)		
		Minimum	Rated	Maximum	Minimum	Rated	Maximum
Cooling	6.38	0.6	2.2	3.3	75	345	690
Heating	6.67	0.6	2.8	5.9	75	420	1300

Table 2 shows the experimental conditions. Table 2 (a) is the outdoor temperature and humidity, the operation mode and the setting temperature. The indoor temperature and humidity were not controlled, and instead, the heating or cooling load of the house was controlled by varying the volume of the exhaust air of the house and by varying the heater generated by the electric heaters in the room. Table 2 (b) shows given volume of the exhaust air and given heat by the electric heaters. In each condition shown in Table 2 (a), we carried out the tests changing the settings from 1 to 7 for cooling and the settings from 1 to 4 for heating in turn. For the test in all settings, we kept the condition constant in at least three hours, in order to measure steady state performance.

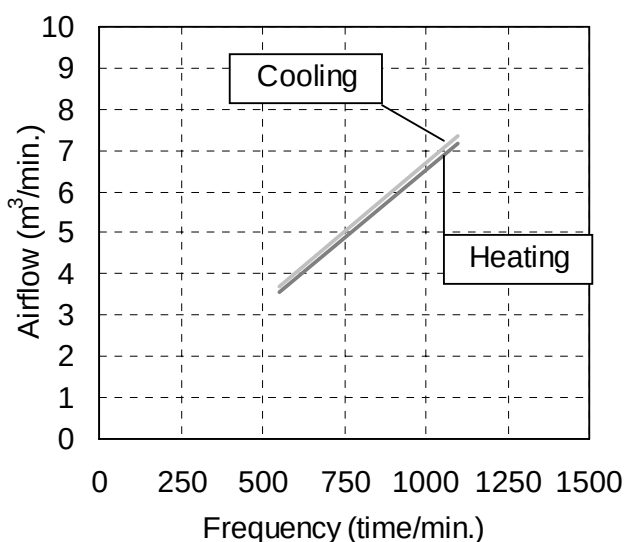


Figure 3: Relationships between Indoor Airflow and Rotation Frequency of Internal Unit Fan

Table 2: Experimental Conditions

(a) Outdoor Temperature and Humidity, Operation Mode and Setting Temperature				
Operation	Considered Parameter	Outdoor Condition		Setting Temperature (°C)
		Temperature (°C)	Humidity (%)	
Cooling	Rated (*2)	35	40	27
	Outdoor Temperature	30	40	27
	Outdoor Humidity	25	40	27
	Indoor Temperature	35	80	27
	Dehumidification (*1)	35	60	27
	Indoor Temperature	35	40	30
	Dehumidification (*1)	35	40	24
	Dehumidification (*1)	35	40	27
Heating	Rated (*3)	7	87	20
	Outdoor Temperature	-3	87	20
	Outdoor Humidity	2	87	20
	Indoor Temperature	12	87	20
	Indoor Humidity	7	70	20
	Indoor Temperature	7	50	20
	Indoor Humidity	7	87	22
	Indoor Temperature	7	87	24

*1: Cooling with dehumidification is one of the operation modes, which is selectable by the remote controller.

*2 & *3: These conditions are equal to the rated conditions in outdoor temperature and humidity.

(b) Settings of Ventilation and Heater								
	Settings	1	2	3	4	5	6	7
Cooling	Ventilation (m³/h)	150	150	150	150	100	50	0
	Heater (W)	1500	1000	500	0	0	0	0
Heating	Ventilation (m³/h)	150	100	50	0	-	-	-

3 RESULTS

3.1 Time Series Data

Two examples among the test results are shown in Figure 4.

Figure 4 (a) is the result of setting 1, where the cooling load was large. For 30 minutes after start-up, both energy consumption and cooling capacity were large. After 1 hour and 30 minutes, steady-state operation could be observed. Difference of absolute humidity between the intake airflow and the discharge airflow was small and the latent heat capacity was little. On the other hand, the latent heat capacity could be observed for 30 minutes after the start-up. The reason for this is supposed to be that after start-up, the evaporation temperature was lower than that in steady state and the surface temperature at the heat exchanger in the internal unit was below the dew point temperature of the intake airflow.

Figure 4 (b) is the result of setting 7, where the cooling load was small. The room air conditioner operated intermittently, the temperature of the discharge airflow was 16 to 18 °C and it was decreasing gradually after the re-start. Energy consumption during the operation was approximately 220 W, the cooling capacity was approximately 700 to 900 W and consequently the efficiency was approximately 3 to 4. However, just after the operation restarted, the energy consumption was a little large to 250 W although the total cooling capacity was small and the efficiency was accordingly low. And the average efficiency was consequently low and resulted 3.0.

3.2 Effects of Operation and Condition on Heating/cooling capacity

3.2.1 Cooling

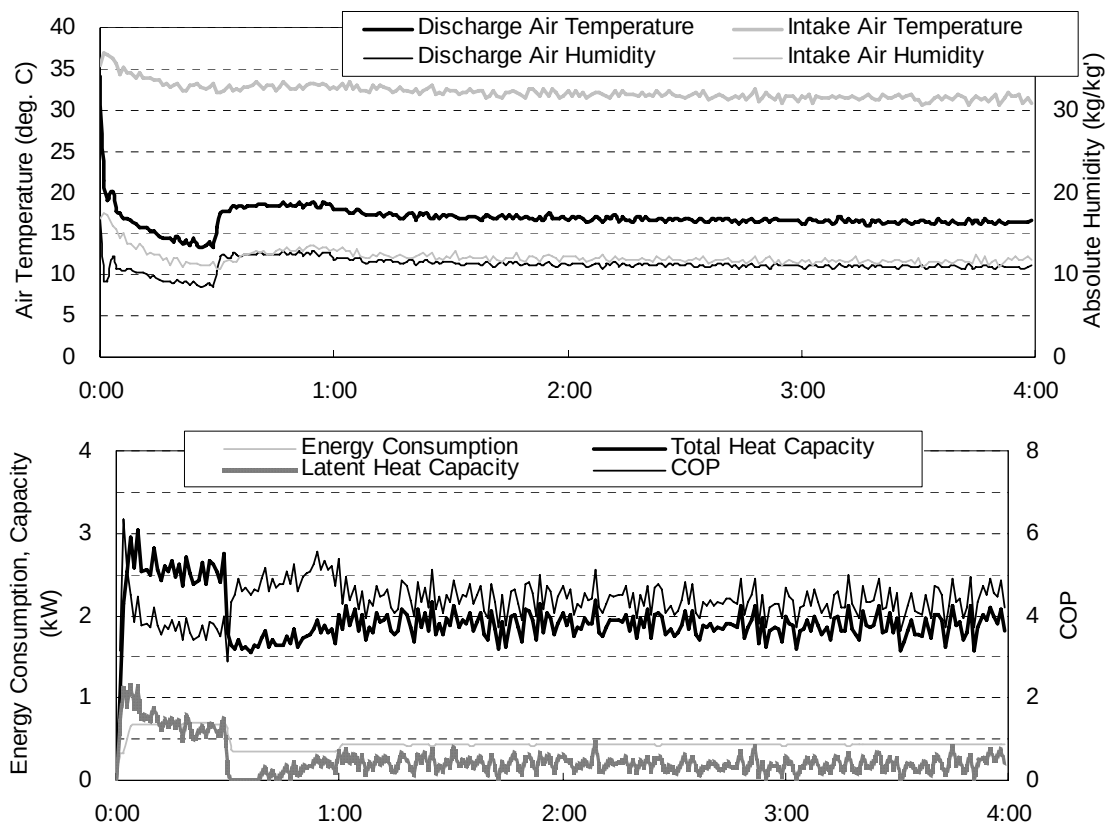
Figure 5 shows the relationship between energy consumption and sensible cooling capacity. The results were categorized according to the outdoor temperature and the indoor humidity.

Under the range of the energy consumption from 140 to 250 W, the operation was intermittent.

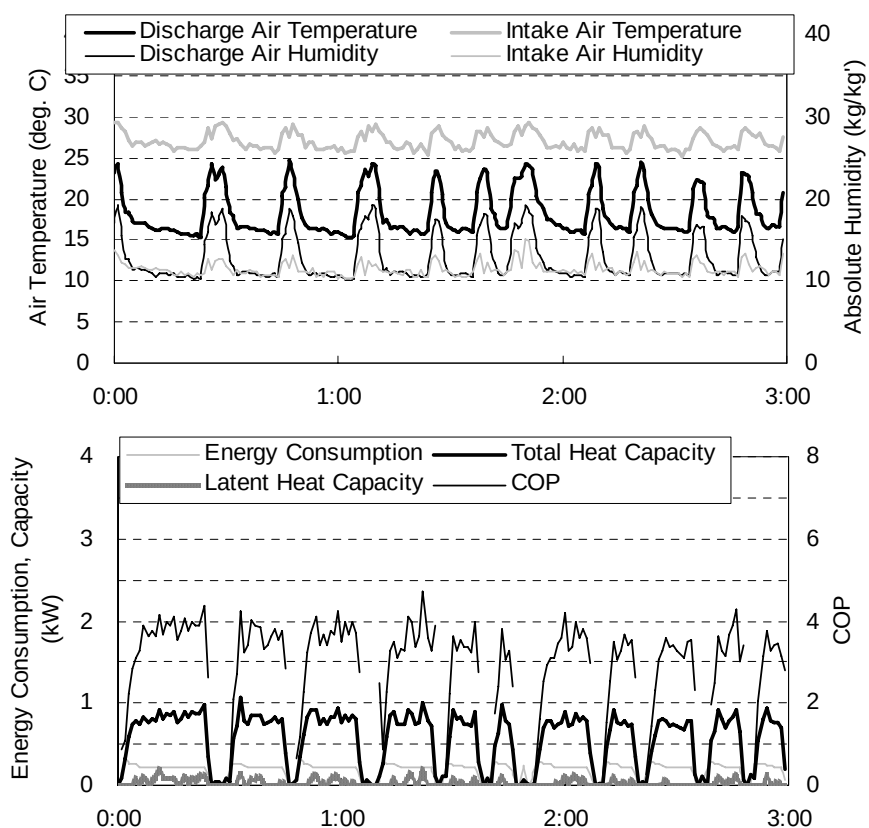
Comparing the data under the condition where the outdoor temperature was different and the humidity was same 40 % (see A, B and C in the figure), the lower the outdoor temperature was, the higher the efficiency was.

Comparing the data under the condition where the indoor relative humidity was different and the outdoor temperature was same 35 °C (see a, b and c in the figure), the higher the relative humidity was, the lower the sensible heat capacity was. The reason why the sensible cooling capacity depended on the indoor relative humidity is that the condensation temperature decreased according to the increase of the latent cooling capacity when the indoor relative humidity was high, and consequently the sensible cooling capacity decreased.

However, the sensible cooling capacity did not depend much on the indoor relative humidity and considering that it is generally difficult to calculate the latent heat load by simulations, there will be possibility to calculate the energy consumption for cooling based only on the sensible cooling load.



(a) Setting 1 (in Table 2 (b)) (Cooling load was large.)



(b) Setting 7 (in Table 2 (b)) (Cooling load was small.)

Figure 4: Test Results (Outdoor 35°C 40% and Setting Temperature 27°C)

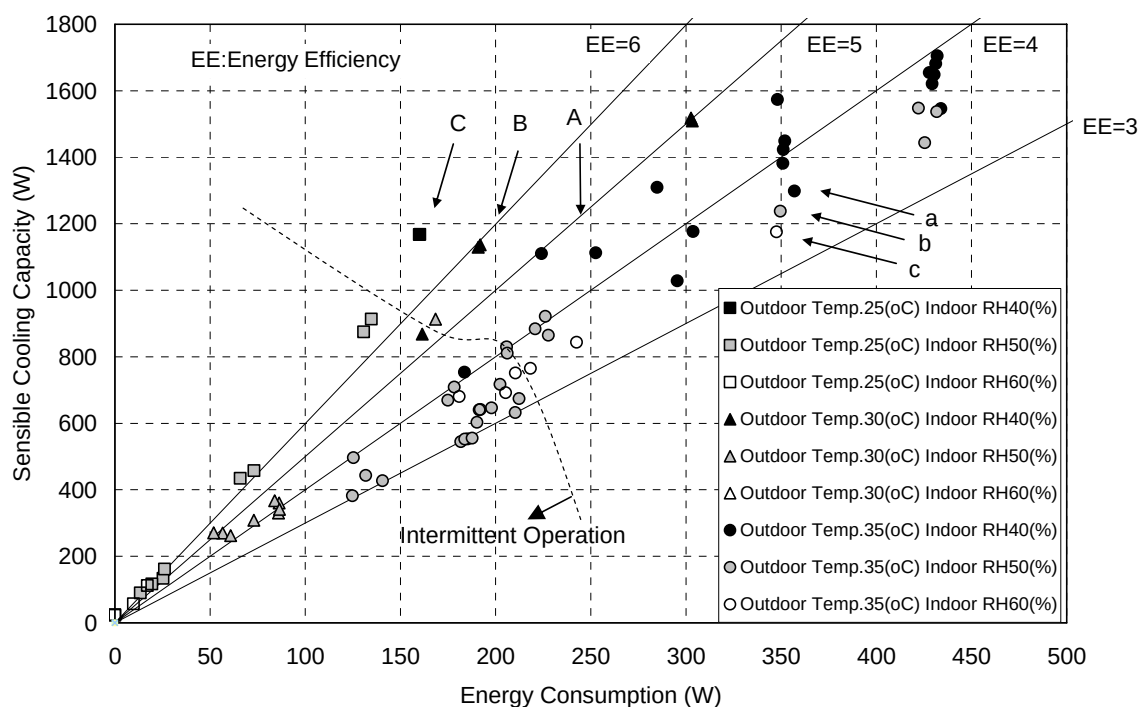


Figure 5: Relationship between Energy Consumption and Sensible Cooling Capacity

Figure 6 shows the relationship between the energy consumption and the latent cooling capacity.

Comparing the cooling capacity under the condition where the latent cooling capacity was different and the outdoor temperature was same 35 °C (see A, B and C in the figure), the latent cooling capacity depended much on the indoor relative humidity.

Meanwhile, the latent cooling capacity was small during an intermittent operation. The reason for this may be that when the cooling capacity was low the condensation temperature increased, it was approximately equal to or higher than the dew point temperature of the intake airflow and water in the intake airflow hardly condensed.

3.2.2 Heating

Figure 7 shows the relationship between the energy consumption and the heating capacity.

Comparing the results under the condition where the outdoor relative humidity was 90% (see A, B, C and D in the figure), the higher the outdoor temperature was, the higher the heating capacity was. Under the range of the energy consumption from 150 to 200 (W), the intermittent operation could be observed and accordingly the efficiency decreased to 2.0.

When the outdoor temperature was below 2 °C and the energy consumption was high (in the experiments of setting 1 to 2), defrosting operation could be observed. The reason why the defrosting operation was often observed only when the energy consumption was high seemed to be that the condensation temperature drops and a lot of water in the intake airflow condensed at the external unit.

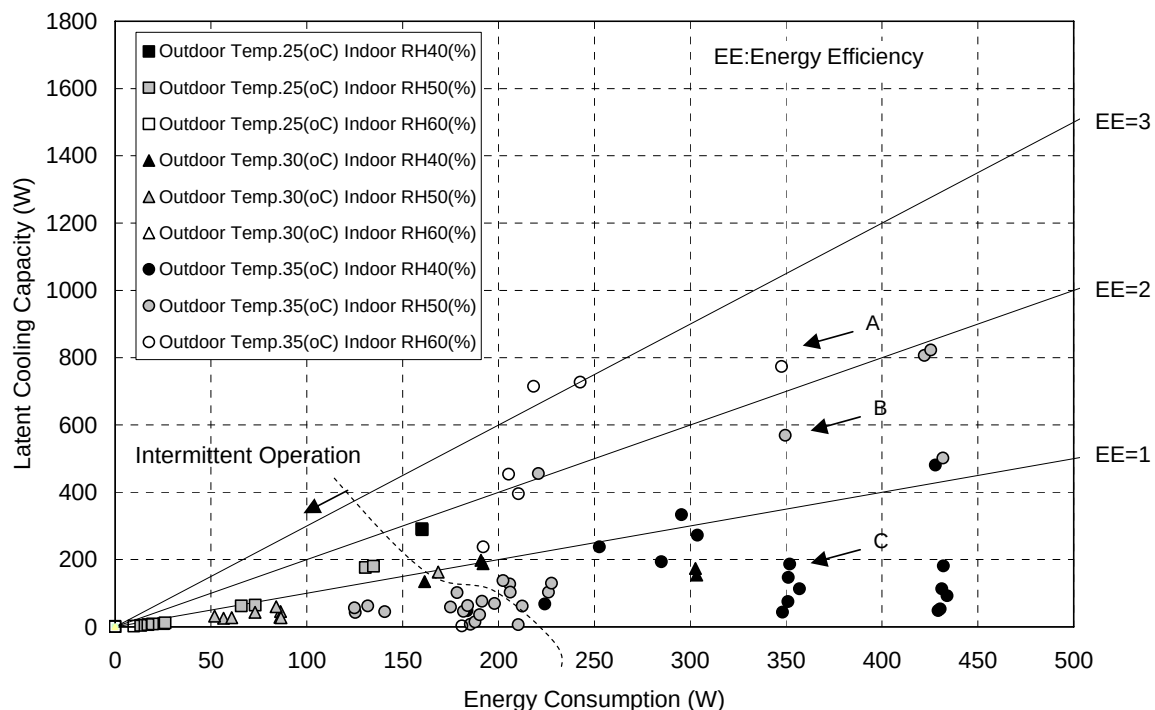


Figure 6: Relationship between Energy Consumption and Latent Cooling Capacity

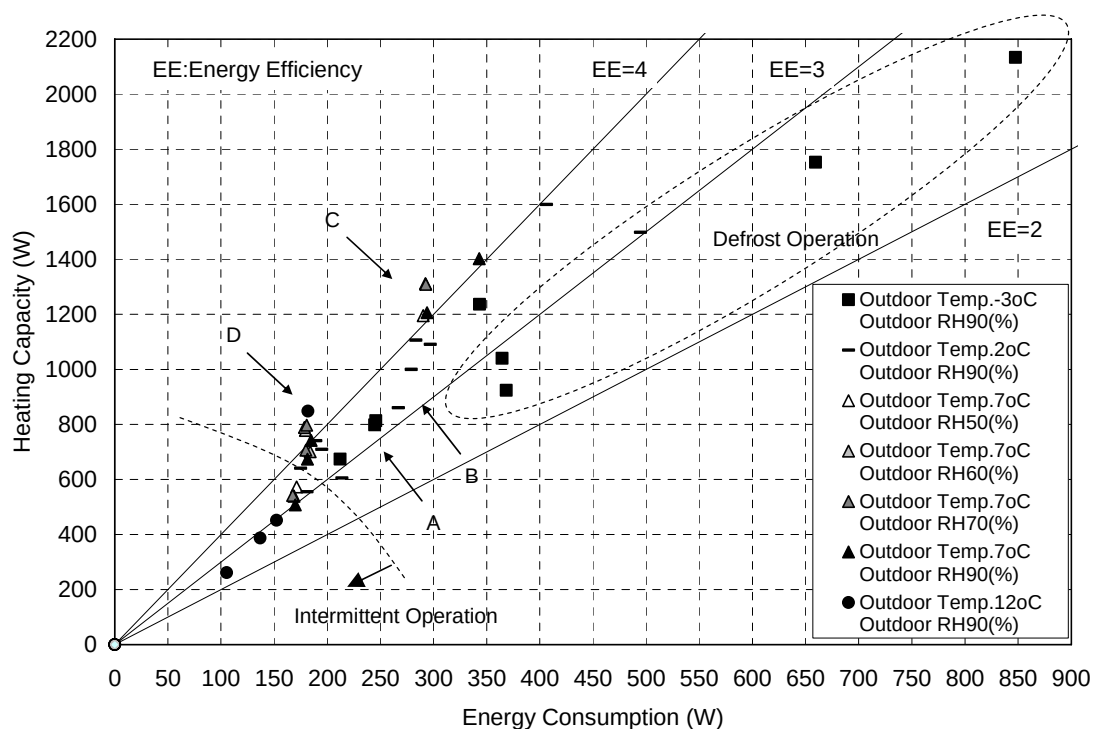


Figure 7: Relationship between Energy Consumption and Heating Capacity

4 CORRECTION COEFFICIENT BY OUTDOOR AND INDOOR TEMPERATURE

The results of the tests show the dependence of the heating and cooling capacity on the indoor and outdoor temperature and humidity. There was a report (JIS C9612) concerning the effect of heating and cooling capacity on the outdoor temperature. We referred the literature and we made correction coefficients shown in Table 3, assuming that both the effect of the outdoor temperature for heating and the effect of the indoor temperature for cooling were similar and that both the effect of the outdoor temperature for cooling and the effect of the indoor temperature for heating were similar, because the refrigerating cycle for heating is the reverse operation for the refrigerating cycle for cooling, although the literature reported only the effects of the outdoor temperature for heating and cooling.

In order to compare the results under the identical conditions concerning the indoor and outdoor temperature, by using the correction coefficient mentioned above, we corrected the test results of the energy consumption and the heating and cooling loads to the value under the rated condition where the outdoor temperature 35 °C and the indoor temperature 27 °C for cooling, and the value under the rated condition where the outdoor temperature 7 °C and the indoor temperature 20 °C for heating.

The corrected results are shown in Figure 8 and Figure 9. Because it is difficult to clear the influence of the indoor humidity for cooling and the outdoor humidity for heating and the influence of the intermittent operation, we categorized here the results based on the humidity difference and the operation.

As see the results for cooling in Figure 8, the lower the energy consumption was, the higher the efficiency was. However in the intermittent operation, the efficiency decreased. The figure shows that the continuous operation changes into the intermittent operation at the energy consumption approximately 200 W. Considering the minimum energy consumption for cooling is 75 W (see the specification in Table 1), this approximately 200 W, the minimum energy consumption at the continuous operation, depended on control software in the machine.

As see the results for heating in Figure 9, the efficiency did not depend on the outdoor humidity and it was constant regardless of the energy consumption in the tested region. The intermittent operation could be seen at the region where the energy consumption was below approximately 170 W, which seems to be also controlled by software in the machine, although the minimum energy consumption for heating is 75 W. And the efficiency decreased in the intermittent operation.

Table 3: Correction Coefficient

	Heating		Cooling	
	Indoor Temp.	Outdoor Temp.	Indoor Temp.	Outdoor Temp.
Ratio of variation of energy consumption (%/°C)	1.4%	1.3%	1.3%	1.4%
Ratio of variation of heating and cooling capacity (%/°C)	-1.3%	2.6%	2.6%	-1.3%

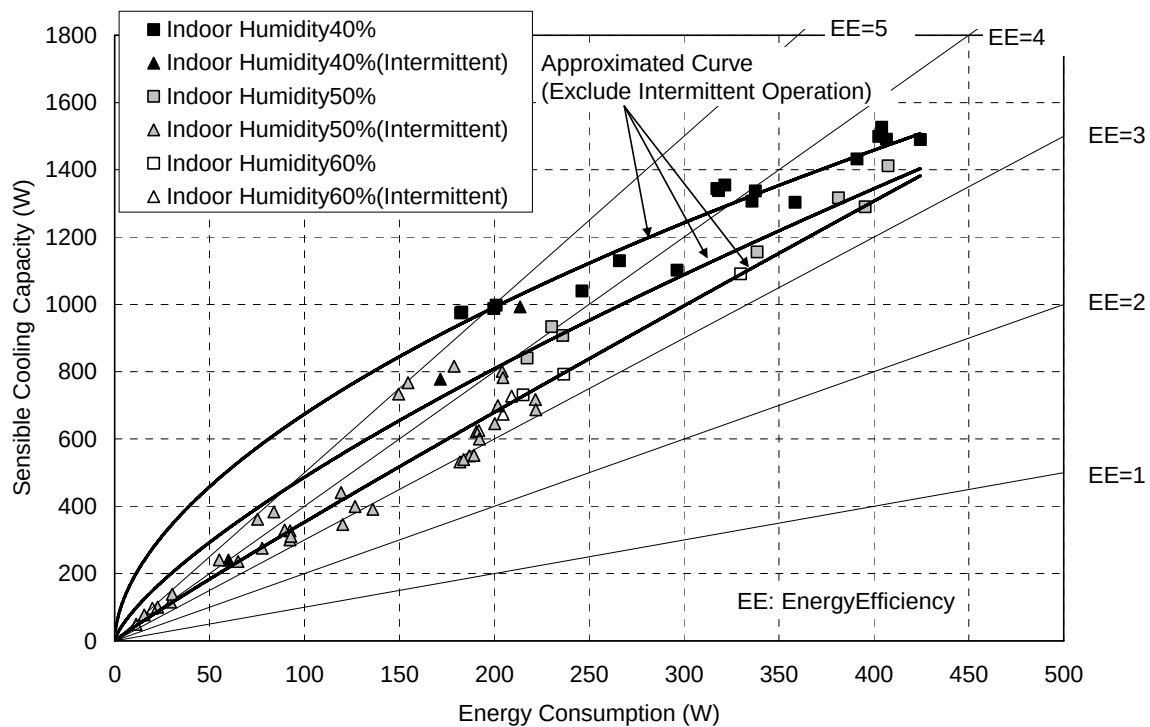


Table 8: Corrected Energy Consumption and Sensible Cooling Capacity

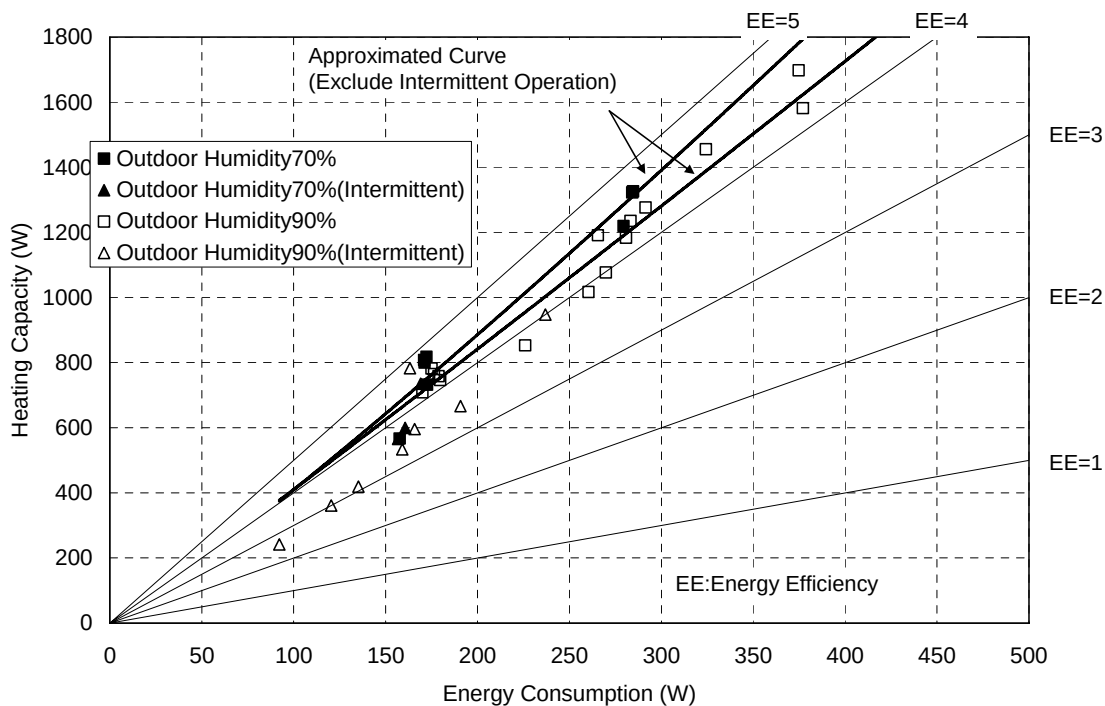


Table 9: Corrected Energy Consumption and Heating Capacity

5 CONCLUSION

In this paper, we discussed the effect of the indoor and outdoor temperature and humidity, and the operation mode on heating and cooling capacity and energy consumption, and the summary is as follows:

- 1) In the tested machine, intermittent operation was observed under the region where the energy consumption was below approximately 200 W for cooling and was below approximately 170 W for heating. And the region did not depend on the minimum energy consumption in the catalogue value and seems to depend on software control of the operation.
- 2) We clarified the effect of the external temperature for heating on the sensible heating capacity.
- 3) During cooling operation, the sensible cooling capacity depended a little on the indoor relative humidity.
- 4) During cooling operation, the latent cooling capacity depended much on the indoor relative humidity. On the other hand, during the intermittent operation, the latent cooling capacity was small and it depends little on the indoor relative humidity.
- 5) During heating operation, when the outdoor temperature was below approximately 2 °C and the heating capacity was large, defrosting operation was observed.
- 6) We discussed the effect of the indoor and outdoor temperature on the cooling and heating capacity, we decided corrected coefficients and we made the approximated curve for heating and cooling respectively.

The following study for the calculation of seasonal energy consumption is necessary.

- 1) determination of energy efficiency curve, and the test method based on which we can determine the energy efficiency curve,
- 2) determination of the range of intermittent operation, and decrease in the efficiency on the intermittent operation,
- 3) determination of the condition of defrosting operation for heating, and decrease in the efficiency on the defrosting operation, and
- 4) the influence of the indoor humidity on the latent cooling capacity.

6 REFERENCES

ISO 5151 Non-ducted Air Conditioners and Heat Pumps – Testing and Rating for Performance

JIS C9612 – 2005 Room Air Conditioners.

JIS B8615-1 – 1999 Non-ducted Air Conditioners and Heat Pumps – Testing and Rating for Performance