PERFORMANCE EVALUATION OF VRF SYSTEMS -2ND REPORT: EXPERIMENTAL EVALUATION OF TRANSIENT DRIVING-

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Abstract: VRF (Variable Refrigerant Flow) system is the air conditioning system that has some indoor units. This system is widely used for the building because it can be easily equipped with the building, and save the space and cost. So far, the air-conditioning system is mainly evaluated at the rated point using COP. But recently it is demanded to improve the annual efficiency of the air conditioning system. For VRF systems, it is difficult to grasp their performance because the indoor units are driven separately in the different unsteady state indoor conditions, and the refrigerant flow and control method are very complex.

Key Words: VRF system, COP, APF, multi unit, unsteady state

1 INTRODUCTION

In the 1st report, we tested the performance of VRF system utilizing the equipment on the market. Comparing with the rated performance and the test results, we concluded that the rated performance has the reducibility. Also, from the comparison of the performance test and the thermal load test, we confirmed that the efficiency of the system lowered since the electricity use of the system increased. This variation needs to be considered in control logic of VRF system.
In this paper, we report the results of the experiment of VRF system transient driving considering the condition of the practical operation and evaluate the system performance.
1 the outdoor temperature test
Since the outdoor temperature changes greatly throughout the year in Japan, there is a long term when the outdoor temperature falls below T1 (35ºC). Thus, we did an experiment changing the outdoor temperature condition, and we evaluated its effect on the system.
2 the latent load variations
Either JIS or ISO standards does not consider the latent load at the rated output. Specifically, the latent load of outdoor air depends on the combination of VRF system and the ventilation system in the building services design. Thus, we did an experiment changing the latent load condition, and we evaluated its effect on the system.
3 Variations of the running indoor unit number
It is known that the indoor unit operation changes dynamically by the individual control of the air condition. Thus, we did an experiment varying the running indoor unit number, and evaluated its effect on the system.

Moreover, we did a simulation (EnergyPlus 6.0) of the general office building. We discuss the overall evaluation of the experiments and the simulation. We focused on the building load in this simulation, which doesn't contain VRF system modules.

The equipment and the facility of the experiments are the same as in the 1st report.

2 METHODS

2.1 EXPERIMENT

Table 1 shows the condition of outside temperature test. The tests were operated by testing thermal load performance mode.

Table 1: Condition (Effect of outside temperature)

<table>
<tr><th>Type of test*</th><th>Indoor air Temperature of entering side (°C)
D.B.T./W.B.T</th><th>Outdoor air Temperature of entering side (°C)
D.B.T./W.B.T</th><th>Compressor Control</th></tr>
<tr><td>Cooling
C4 100% Cooling Load
C5 50% Cooling Load</td><td rowspan="3">27
19</td><td>35
24</td><td>Transient</td></tr>
<tr><td>Cooling
C7 100% Cooling Load
C8 50% Cooling Load</td><td>30
20</td><td>Transient</td></tr>
<tr><td>Cooling
C9 100% Cooling Load
C10 50% Cooling Load</td><td>25
18</td><td>Transient</td></tr>
<tr><td>Heating
H4 100% Heating Load
H5 50% Heating Load</td><td rowspan="2">20
15</td><td>7
6</td><td>Transient</td></tr>
<tr><td>Heating
H7 100% Heating Load
H8 50% Heating Load</td><td>12
11</td><td>Transient</td></tr>
<tr><td colspan="4">*The experimental run number is a sequential number from 1st report</td></tr>
</table>

Table 2 shows the condition of latent load test. The tests were operated by testing thermal load performance mode.

Table 2: Condition (Effect of latent load)

<table>
<tr><th rowspan="2">Type of test*</th><th>Indoor air Temperature of entering side (°C)
D.B.T./W.B.T</th><th rowspan="2">Outdoor air Temperature of entering side (°C)
D.B.T./W.B.T</th><th rowspan="2">Compressor Control</th></tr>
<tr><th>Sensible Heat Factor [-]</th></tr>
<tr><td rowspan="2">Cooling
C4 100% Cooling Load
C5 50% Cooling Load</td><td>27
19</td><td rowspan="4">35
24</td><td rowspan="2">Transient</td></tr>
<tr><td>0.85</td></tr>
<tr><td rowspan="2">Cooling
C11 100% Cooling Load
C12 50% Cooling Load</td><td>27
-</td><td rowspan="2">Transient</td></tr>
<tr><td>1.00</td></tr>
<tr><td colspan="4">*The experimental run number is a sequential number from 1st report</td></tr>
</table>

Table 3 shows the condition of Indoor unit operation change test.

Table 3: Condition (Effect of Indoor unit operation change)

Type of test*	Indoor air Temperature of entering side (°C) D.B.T./W.B.T	Outdoor air Temperature of entering side (°C) D.B.T./W.B.T	Compressor Control
Cooling **C13** 4 units →2 units →4 units	30 22	35 24	Transient
Heating **H9** 4 units →2 units →4 units	17 11	7 6	Transient
*The experimental run number is a sequential number from 1st report			

2.2 SIMULATION OF GENERAL OFFICE BUILDING IN TOKYO

We assumed the environment of the general office building in the simulation. Simulating the recent higher interior gain load, we set the interior gain load as 30 W/m^2. Table 5 shows the simulation schedule, the APF assumption schedule regulated in JIS 8616.

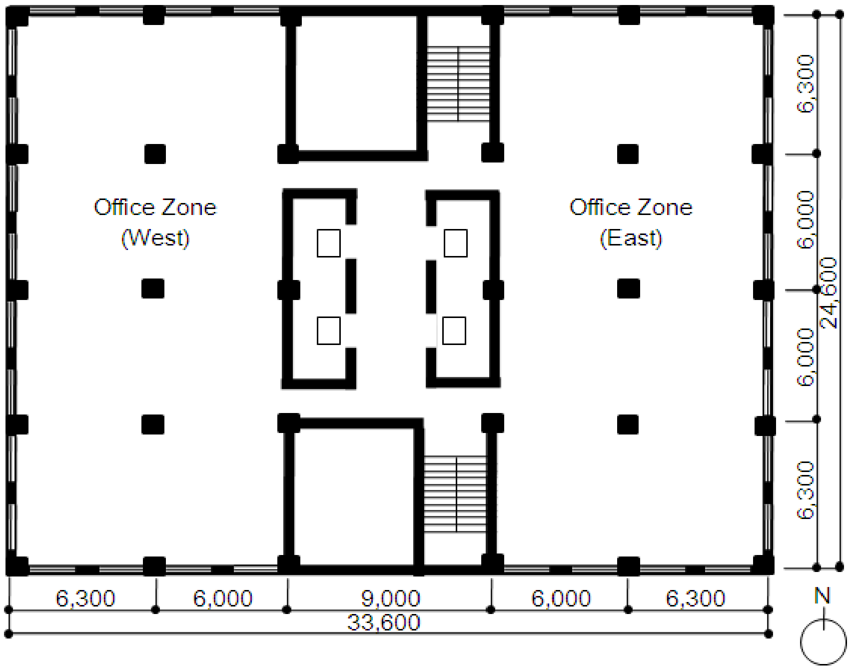

Figure 1: Simulated Building Layout

Table 4: Simulation condition

LOCATION	TOKYO
Indoor temperature set point summer/winter	27℃/20℃
USE	Office
Simulated Room	Office zone (West) Figure 3
Specification of External Wall and Grazing	Wall: Plaster board 12[mm], Air gap 60[mm], 25[mm], Concrete 150[mm], Tiles 7[mm]
	Grazing 8mm + Blind
Occupancy	0.2people/m^2
Gain(Light, Other)	30W/m^2
Amount of air introduction	6m3/m2･h

Table 5: Simulation schedule

Cooling operation	5/22-10/8, weekday ,8:00-20:00
Heating operation	11/23-2/9, weekday ,8:00-20:00
Occupancy	9:00-12:00, 100%,13:00, 50% 14:00-17:00, 100%, 18:00, 50% 19:00, 25% 20:00-8:00, 0%
Gain(Light, Other)	9:00-12:00, 100%,13:00, 70% 14:00-18:00, 100%, 19:00-20:00, 50%, 21:00-8:00, 0%
Amount of air introduction	$6m^3/m^2 \cdot h$

3 RESULTS AND DISCUSSION

COPr is a calculated value of published specification of the system in the 1st report.
We kept the experiment until thermal load reached the steady cycle when there is a cyclic variation. We then sum all thermal output and electric power, respectively, throughout several cycles. And coefficient of performance at experiment (COPj) was derived from eq. (1)-(4). Kr is the piping length coefficient that considers the piping heat loss.

$$\Phi_{ij} = \frac{q_{\mathrm{mi}}\left(h_{\mathrm{a1}} - h_{\mathrm{a2}}\right)}{v'_{\mathrm{n}}\left(1 + w_{\mathrm{n}}\right)} \tag{1}$$

$$P_{tj} = P_{ij} + P_{oj} \tag{2}$$

$$K_r = func\left(l_{pipe}, h_{pipe}\right) \tag{3}$$

$$COP_{\mathrm{j}} = \frac{\sum_{\mathrm{t=0}}^{\mathrm{t=cycle}} \Phi_{ij.t}}{\sum_{\mathrm{t=0}}^{\mathrm{t=cycle}} P_{tj.t}} \cdot \frac{1}{K_r} \tag{4}$$

Nomenclature

- Φ_{ij} : total capacity at experiment, W
- *ha* : air enthalpy, $J \cdot kg^{-1} \cdot K^{-1}$
- *qmi* : air volume, m3/s
- *v' n* : specific volume, m3/kg
- *wn* : absolute humidity, kg/kg(DA)
- *Pi* : indoor unit electric power, W
- *Po* : outdoor unit electric power, W
- *lpipe* : piping length, m
- *hpipe* : piping height difference, m
- *K r(c)* : correction factor for piping at cooling, 0.969
- *K r(h)* : correction factor for piping at heating, 0.989
- COP_j : coefficient of performance at experiment, [-]
- COP_r : coefficient of performance at publication, [-]

3.1. RESULTS OF OUTSIDE TEMPERATURE TEST

3.1.1 RESULTS OF EXPERIMENT

Table 6 shows the temperature and the system input are under the effect of the outside temperature experiment. Result of 50% load condition is not included, because part of the indoor unit was driven on-off.
According to the result of Table 6, comparing with the cooling loads C7 and C4, the electric consumption decreased since the constant speed type compressor happen to stopped.

Table 6: Temperature and compressor input

Measuring Point	C4	C7	C9	H4	H7
	100%CoolingLoad			100%HeatingLoad	
Temperature of air entering indoor side (°C) dry-bulb wet-bulb	 26.6 17.8	 28.9 21.1	 28.2 20.2	 20.2 14.1	 20.1 17.5
Temperature of air entering outdoor side (°C) dry-bulb wet-bulb	 34.8 24.1	 30.0 20.0	 25.0 18.0	 7.0 6.0	 12.1 11.1
Temperature of heat exchanger surface indoor side (°C) Unit Average	12.3	16.0	14.7	37.4	36.4
Temperature of heat exchanger surface outdoor side (°C)	42.2	34.4	30.1	0.7	6.2
System input (kW)	9.42	6.25	5.59	9.71	7.68
Compressor ON/OFF Variable Speed by Inverter Constant Speed	 ON ON	 ON OFF	 ON OFF	 ON ON	 ON ON
Result of load factor (%)	102	92	92	102	95

Figure 2 shows the variation of COP. As a reference, we also show the results of the cooling and heating loads at 50% of capacity. The cooling load without the constant speed type compressor showed the higher COP gain than that of the heating load. We had the same result at the load of 50% capacity.

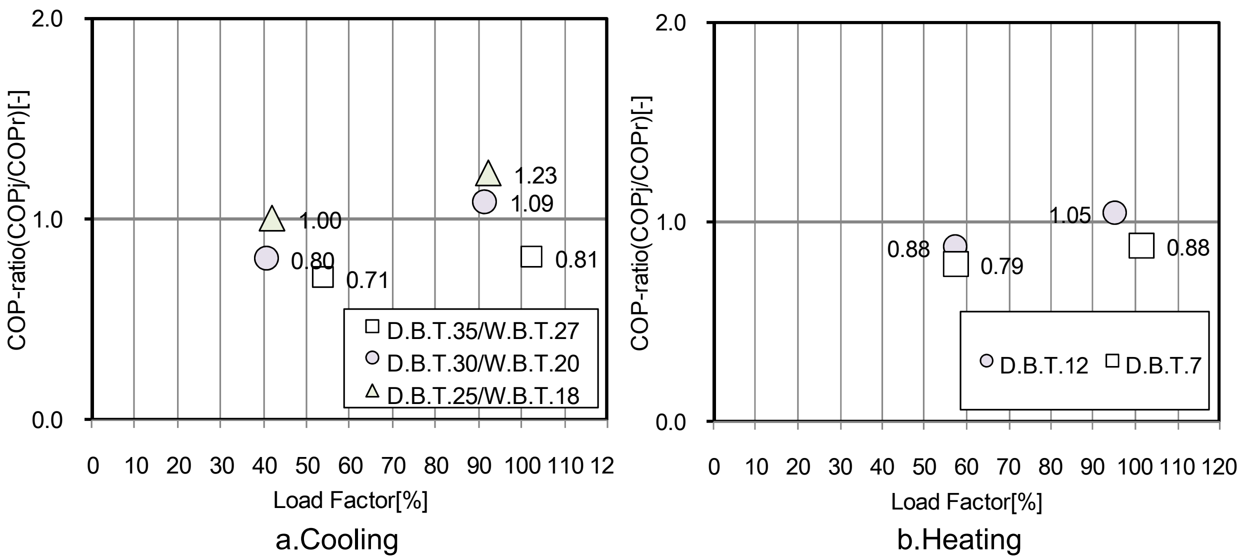

Figure 2: Results of the system performance

From these results, there is a tendency that the electric consumption of the cooling load decreases when the outdoor temperature lowers, that results in the COP gain.

3.1.2 RESULTS OF SIMULATION

Figure 3 shows the simulation result of EnergyPlus+6.0. JIS 8616 treats the relationship of the outdoor temperature and the building load as proportion. The building load average value of the simulation approximately matched to that of the building load model at cooling in JIS 8616.This could happen only if the entire outdoor air was handled by VRF system. When you handled only the interior load, the correlation of the outdoor temperature and the load tended to decline.

In the heating, the building load factor was small in the simulation and very different from the JIS model. That is because we assumed the higher interior gain load to represent the recent office environment in the simulation.

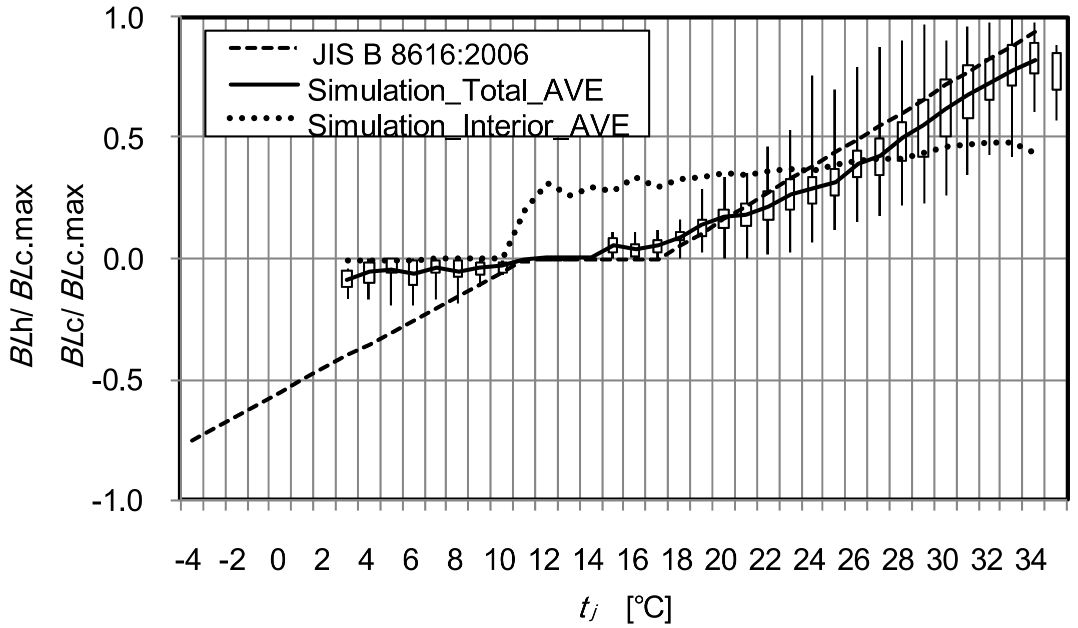

Figure 3: Outdoor temperature and building load

Table 7: Outdoor temperature and building load appearance

Temperature [°C]	13 ~ 15	16 ~ 18	19 ~ 21	22 ~ 24	25 ~ 27	28 ~ 30	31 ~ 33	34 ~ 36
BL Appearance[h] (with Energy Plus)	7	37	190	325	274	281	222	21
Energy Plus BL	0.00	0.06	0.16	0.26	0.38	0.56	0.73	0.82
JIS BL	0.00	0.02	0.17	0.33	0.50	0.67	0.83	0.97

Table 7 shows the frequency of the outdoor temperature and the building load. According to Figure 2, we knew that COP tended to gain when the outdoor temperature was mild. Since the term with the mild outdoor temperature occupies most of the year, we can expect to run the system with higher COP throughout the year. Although, it could occur that the system drives on-off for decreasing the building load while the outdoor temperature is mild.

3.2 RESULTS OF LATENT LOAD TEST

3.2.1 RESULTS OF EXPERIMENT

According to the result of Table 8, comparing with the cooling loads of C4 (SHF=0.85) and C11 (SHF=1.00), the system input of C11 decreased. Thus, it could be said that the compressor output grows because of the increase of the latent load. It could be guessed that the increase of the compressor output was relatively small in the experiment because it was controlled by the variable speed type compressor.
We excluded the results of the cooling load at 50% capacity since the system was driven on-off.

Table 8: Temperatures and System input

Measuring Point	C4	C11
	100%CoolingLoad	
Temperature of air entering indoor side (°C) dry-bulb wet-bulb	 26.6 17.8	 27.1 16.8
Temperature of air entering outdoor side (°C) dry-bulb wet-bulb	 34.8 24.1	 34.9 23.9
Temperature of heat exchanger surface indoor side (°C) Unit Average	12.3	11.6
Temperature of heat exchanger surface outdoor side (°C)	42.2	40.9
System input (kW)	9.42	8.19
Compressor ON/OFF Variable Speed by Inverter Constant Speed	 ON ON	 ON ON
Result of load factor (%)	102	95
Result of SHF[-]	0.87	0.99

Figure 4 shows the variation of COP. As a reference, we also show the result of the cooling load at 50% capacity. Those are the experimental average value.
At C11 which the electric consumption of the system decreased, COP was 5 points higher than that of C4. But the experiment at C4 (SHF=0.85) showed higher COP under the load of 50% capacity. That was because the system was driven on-off, and the system had the latent load at the SHF=1.00.

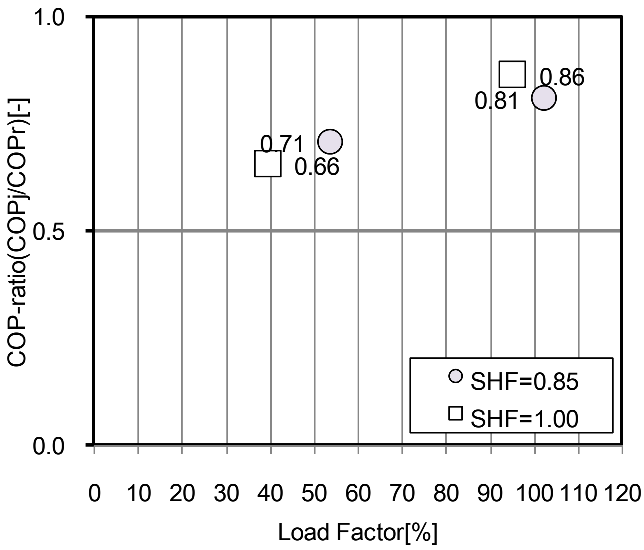

Figure 4: Characteristic

3.2.2 RESULTS OF SIMULATION

According to the results of the experiment, the system electric consumption tends to increase when the latent load grows. We then simulated the tendency of the latent heat amount in the building load.
Figure 5 shows the results of the simulation. The building load increases because of the increase of the latent load of the outdoor air. The latent load changes greatly if you design the VRF system to handle the outdoor air. Either JIS or ISO shows us the method to evaluate

VRF system COP under the increase of the latent load. In the future, those methods need to be considered in assuming annual COP.
On the other hand, since there is only human originated latent load to handle, identification of SHF (sensible heat factor) and the latent load would be easier when only handling the interior load.

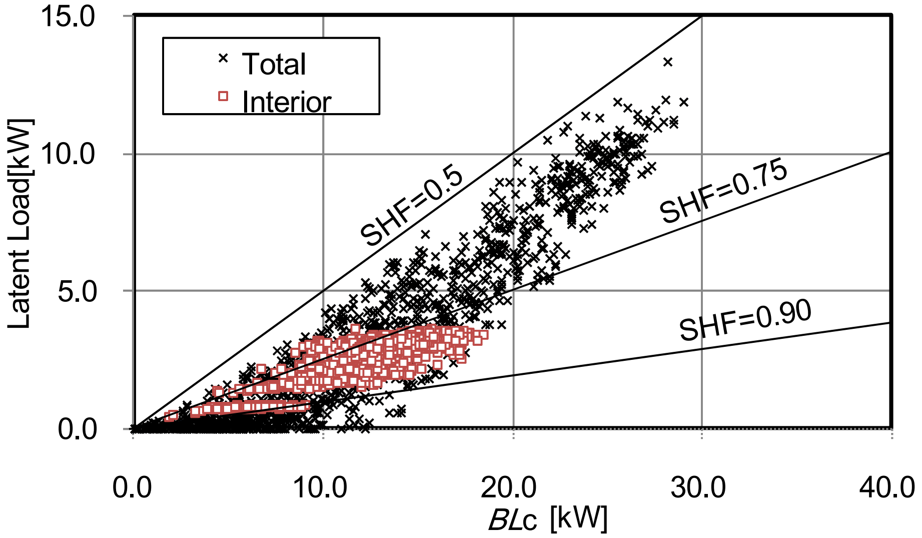

Figure 5: Latent load and building load

3.3 RESULTS OF INDOOR OPERATION CHANGE TEST

Figure 6 shows the result of the indoor unit variation test at the cooling load. Though COP changes greatly for 10 min. at the transient driving after the number of the indoor unit changed, the difference between before and after the number change was within 10%.

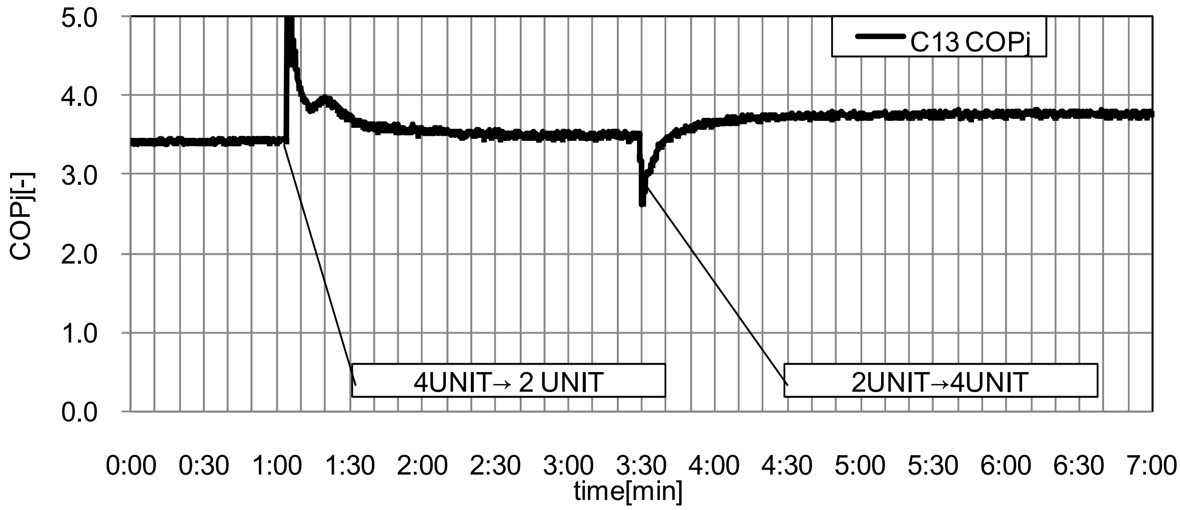

Figure 6: COPj (Cooling)

Figure 7 shows the result of the indoor unit variation test at the heating load. Though COP changes greatly for 10 min. at the transient driving after the number of the indoor unit changed, the difference between before and after the number change was within 10%.

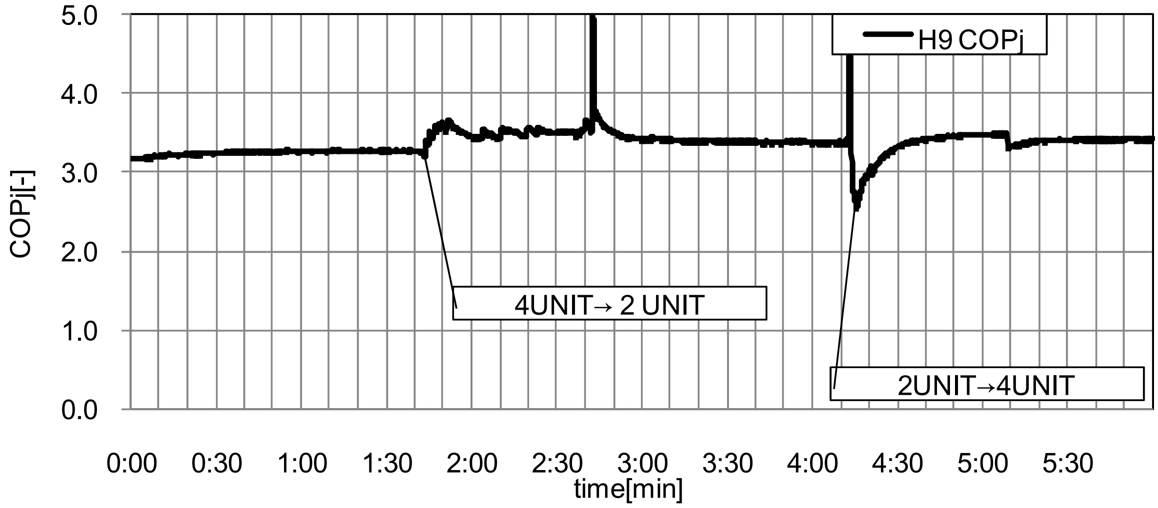

Figure 7: COPj (Heating)

VRF system, especially the multi-unit type, people in the room can control individually by the unit controller. It is not studied much about the effect of those controls on the system COP yet. In our experiment, we shifted the indoor unit from 4 to 2, however, the system running situation would be more dynamic in the practical operation.

4 CONCLUSIONS

According to the outdoor temperature test, the system tends to drive with high COP when the outdoor temperature is mild. However, the on-off driving of the system is worried under that condition since the building load also lowers.

According to the latent load test, the system electric consumption increases when the ratio of the latent load is high.

According to the test varying the indoor unit number, though COP changes for 10 min. at the transient driving after the number of the indoor unit changed, the difference between before and after the number change is not big.

We tested the equipment on which the variable speed type compressor is mounted. At the outdoor temperature test, the system shows higher COP under the rating condition by running the variable speed type compressor mainly. At the latent load test, the system handles the increased electric consumption of the latent load by controlling the variable speed type compressor. And that resulted in the reduction of the system electric consumption. With the newest variable volume type system, it is important to balance the volumes of the constant speed type compressor and the variable speed type compressor.

According to the building load simulation, we confirmed that JIS regulates the building load model under the assumption of heat extraction of the outdoor air load. When you design the building as VRF system handles the outdoor air load, the latent load to be handled tends to vary greatly. For now, JIS does not consider the latent load, though, this matter will be important in designing the heat exchanger of indoor unit.

In this paper, we report the results of the load test and the building load simulation. As a result, we conclude that it is important to clarify the building load and feedback the result to the system development for the use of VRF system with the higher COP.