

RESEARCH AND DEVELOPMENT OF INNOVATIVE ENERGY-SAVING CONTROLS OF NEXT-GENERATION MULTIPLE AIR-CONDITIONING SYSTEMS FOR BUILDINGS

Masafumi HIROTA, Professor, Department of Mechanical Engineering, Mie University, Kurimamachiya-cho, Tsu-city, Mie 514-8507, Japan

Yoshinari IWATA, Dr. Eng., Manager, Energy Applications R&D Center, Chubu Electric Power Co., Inc., Odaka-cho, Midori-ku, Nagoya 459-8522, Japan

Ichiro SAKURABA, Senior Research Scientist, Central Research Institute of Electric Power Industry, Nagasaka, Yokosuka 240-0196, Japan

Katsuaki NAGAMATSU, Research Engineer, Energy Applications R&D Center, Chubu Electric Power Co., Inc., Odaka-cho, Midori-ku, Nagoya 459-8522, Japan

Koichi SHINAGAWA, Environment & MEP Engineering Division, NIHON SEKKEI, INC., Shinjuku I-LAND Tower, 6-5-1, Nishi-shinjuku, Shinjuku, Tokyo 163-1329, Japan

Hiromasa KATSURAGI, Environment & MEP Engineering Division, NIHON SEKKEI, INC., Shinjuku I-LAND Tower, 6-5-1, Nishi-shinjuku, Shinjuku, Tokyo 163-1329, Japan

Hideaki HOSHINO, Environment & MEP Engineering Division, NIHON SEKKEI, INC., Shinjuku I-LAND Tower, 6-5-1, Nishi-shinjuku, Shinjuku, Tokyo 163-1329, Japan

Shin-ichi KASAHARA, Senior Researcher, Environmental Technology Laboratory, DAIKIN INDUSTRIES, LTD., 1304 Kanaoka-cho, Kita-ku, Sakai, Osaka 591-8511, Japan

Masahiro OKA, Senior Engineer, Sakai Plant, DAIKIN INDUSTRIES, LTD., 1304 Kanaoka-cho, Kita-ku, Sakai, Osaka 591-8511, Japan

Tomohiro YABU, Senior Engineer, Shiga Plant, DAIKIN INDUSTRIES, LTD., 1000-2 Otani, Okamoto-cho, Kusatsu, Shiga 525-8526, Japan

Abstract: The purpose of this study is to develop an innovative energy-saving A/C controller that can improve the energy efficiency of multi-split type air conditioning system for buildings (outdoor-air processing VRF system + heat recovery VRF system) operated under low thermal load conditions and/or simultaneous cooling and heating mode. This new A/C controller consists of the capacity optimization by the real-time prediction of the indoor thermal load based on the predictive functional control method, and the minimization of the capacity-control loss in simultaneous cooling and heating operations. We examined the energy-saving effect of the new A/C controller by the part-load performance tests made in a testing laboratory and by the field measurements of actual operations of the air conditioning system installed in an existent office building in two years. By careful comparisons of experimental data obtained with the conventional A/C controller and the new A/C controller, it was demonstrated that 170 % higher annual average COP was achieved by the air conditioning system with the developed new controller.

Key Words: Outdoor-air processing VRF system, Heat recovery VRF system, Energy-saving control, Part-load performance test, Field measurement

1 INTRODUCTION

In a business-related building, the energy used for air conditioning amounts to 30 % - 40 % of its total energy consumption. Therefore, the development of air conditioners with higher energy efficiency is crucial for the energy saving in buildings. In 2010, New Energy and Industrial Technology Development Organization (NEDO) in Japan started the research and development project on “Next-generation Heat Pump Systems”, which aimed for the development of innovative heat pump systems with 150 % higher COPs in comparison with conventional ones. The present paper reports on the development of a new energy-saving controller of the VRF system that was conducted as part of this NEDO project.

The use of a multi-split type air conditioner for buildings, i.e., VRF (Variable Refrigerant Flow) system, is now spreading to various business-relating buildings. Through the year, those air conditioners are mostly operated with indoor thermal loads lower than their rated capacities as shown in Fig. 1. In general, the energy efficiency of the VRF system deteriorates under low thermal load conditions less than its half capacity (Watanabe et al. 2008). Therefore, in order to achieve actually effective energy saving of the VRF system, it is important to improve its performance under low thermal load conditions. Moreover, in the heat recovery VRF system with simultaneous cooling and heating operations, heat exhausted from the cooling unit is utilized effectively in the heating unit in the simultaneous cooling/heating mode. Thus a higher energy-saving effect is expected with this system in principle. In its actual operations in a building, however, both hot and cold heats are exhausted simultaneously from the outdoor unit to secure the stable operation of the air conditioner. This causes unexpected deterioration of COP of the heat recovery VRF system.

The purpose of this study is to develop an innovative energy-saving A/C controller that can improve the energy efficiency of the VRF system operated under low thermal load conditions and/or simultaneous cooling/heating mode. We examined the energy-saving effect of the new A/C controller by part-load performance tests made in a testing laboratory and field measurements of actual operations of the VRF system in an office building. We aimed at realizing 150 % higher annual average COP with the new A/C controller and demonstrated that 170 % higher COP was achieved by the VRF system with the new controller.

2 AIR CONDITIONING SYSTEM TARGETED IN THIS STUDY

Figure 2 shows the air conditioning system targeted in this study. It is a multi-split type air conditioning system for buildings that consists of one outdoor-air processing VRF system and one heat recovery VRF system with simultaneous cooling/heating operation. It is installed on the second floor of an office building with a floor space of 600 m² located in Nagoya. The detailed specifications of this air conditioning system are shown in Table 1.

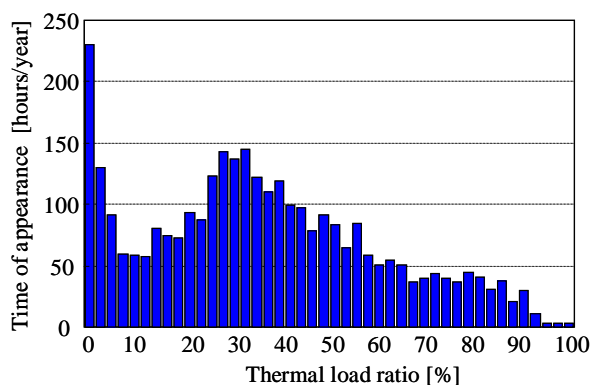


Figure 1: Actual Operating State of A/C

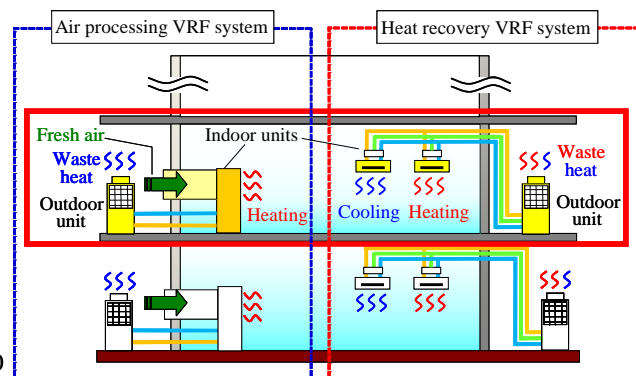
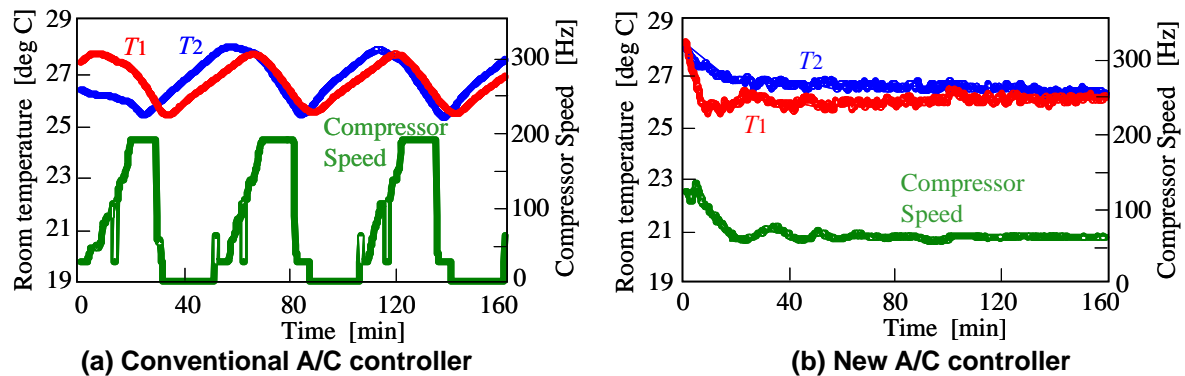


Figure 2: VRF Systems Targeted in This Study

Table 1: Specifications of the Air Conditioning System Installed in the Existent Office Building

Type of A/C	Rated cooling capacity	Rated heating capacity	Number of indoor units
Air processing VRF	45 kW	50 kW	2
Heat recovery VRF	100 kW	112 kW	14

**Figure 3: Comparison of Operating States of Compressor under Low Thermal Load Condition**

3 CONCEPTS OF THE NEW CONTROLLER FOR VRF SYSTEM

The new A/C controller mainly consists of the capacity optimization based on the real-time prediction of the indoor thermal load and the minimization of the capacity-control loss in cooling, heating and/or simultaneous cooling/heating modes. Details are explained below.

3.1 Capacity Optimization Based on Real-time Prediction of Indoor Thermal Load

In the conventional VRF systems, the indoor units have been controlled independently of the outdoor unit. In the indoor unit, the refrigerant flow rate is controlled by the expansion valve to keep the room temperature at a setting value, and the variation width of the capacity is quite limited. In the outdoor unit, the compressor speed is controlled to keep the evaporation or condensation temperature of the refrigerant, T_e or T_c , at a target value. Although T_e and T_c should be optimized to the thermal load, they are usually fixed irrespective of the operating condition of the air conditioner. Thus, under low thermal load conditions, mismatch arises between the controls of the indoor and outdoor units, and consequently the air conditioner repeats the operations with surplus capacities and stops as shown in Fig. 3(a). Such on/off operations of the compressor cause the serious deterioration of COP (Hirota et al., 2007).

In order to improve the performance of the air conditioner under low thermal load conditions, the compressor speed must be stabilized as shown in Fig. 3(b). We realized the stable operation of the compressor by the capacity optimization of the indoor heat exchanger based on the real-time prediction of the thermal load. Figure 4 shows its concept. We applied the predictive functional control (Richalet et al., 2009) to the capacity optimization of the indoor heat exchanger. PFC is one of the model predictive controls and superior to conventional control methods such as PID, but few PFC controllers have been implemented to VRF systems. In the new controller with PFC method, each indoor unit includes models of the temporal variation of the room temperature and the performance of the indoor heat exchanger expressed by following equations.

$$\rho_a C_p V_r \frac{dT_r}{dt} = Q_{hex} + Q_i + Q_o \quad (1)$$

$$Q_{hex} = f(T_r, T_e \text{ or } T_c, SH \text{ or } SC, G_a) \quad (2)$$

V_r and T_r are the volume and temperature in the room. Q_{hex} is the capacity of the indoor heat exchanger, Q_i and Q_o are thermal loads by indoor heat sources and by heat inflow from the outdoor environment, respectively. SH and SC are superheat and subcool of the refrigerant at the outlet of the indoor heat exchanger, and G_a is the air flow rate of the indoor unit.

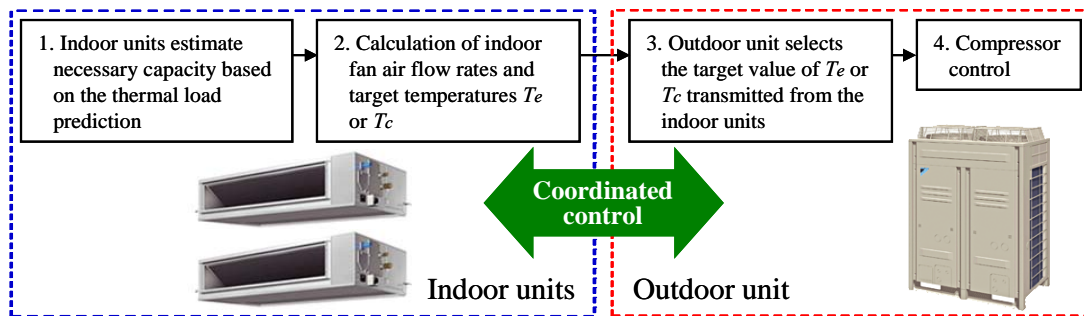


Figure 4: Concept of Capacity Optimization by Coordinated Control of Indoor and Outdoor Units

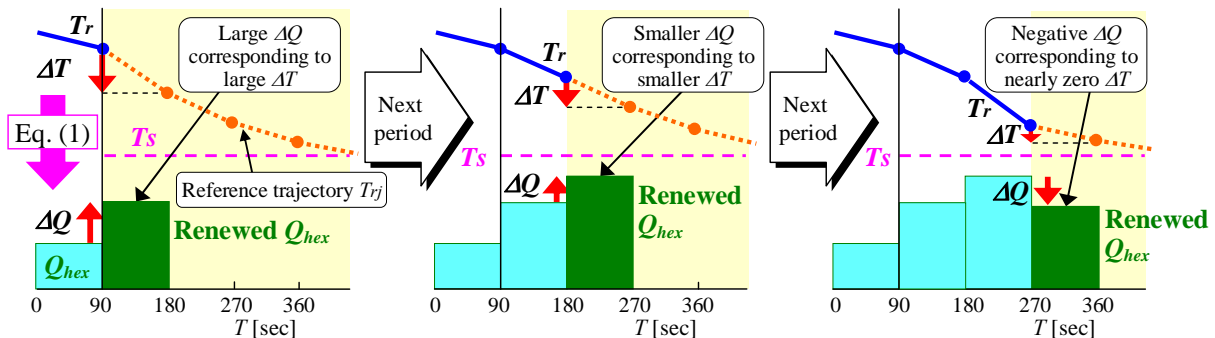


Figure 5: Capacity Optimization based on Predictive Functional Control Method

V_r is determined considering a floor space that corresponds to the rated capacity of the air conditioner and the number of indoor units. The initial values of Q_i and Q_o are determined based on the thermal loads calculated by the architectural design standards, but actual thermal loads may deviate from them moment by moment in the operation of the air conditioner. The new A/C controller stabilizes the compressor speed against such fluctuation of thermal loads based on PFC. The correlation for Q_{hex} is determined by the multivariable analysis of experimental and simulation data of the indoor heat exchanger. It should be noted that Q_{hex} in Eq. (2) shows the capacity of the indoor heat exchanger under the steady condition. Unsteady operations of air conditioners can occur in actual buildings, but the transient performance of the heat exchanger was not considered in this model for simplicity. In spite of this simplification, the new A/C controller could stabilize the compressor speed.

Figure 5 illustrates the scheme of the capacity optimization based on PFC. In this control method, each indoor unit has an ideal temperature trajectory (reference trajectory T_{rj} shown by orange lines in Fig. 5) to converge the room temperature at a setting value (T_s in Fig. 5) quickly and smoothly. T_{rj} is recalculated at every 90 seconds. The deviation value of Q_{hex} ($= \Delta Q$) that is required to bring the room temperature T_r closer to T_{rj} is calculated by substituting $\Delta T = T_r - T_{rj}$ for dT_r/dt in Eq. (1). When ΔT is large, ΔQ is increased accordingly as shown in the first period of Fig. 5. The time constant of T_r response to the change of Q_{hex} identified from the data of preliminary experiments is also considered in determining ΔQ .

Target T_e or T_c and optimum G_a corresponding to renewed Q_{hex} are calculated by Eq. (2), but there is a degree of freedom in setting them for the same Q_{hex} . The new A/C controller always tends to increase G_a of each indoor unit in order to raise T_e (or lower T_c). This is more energy saving because the reduction of the energy consumption of the compressor by raising T_e (lowering T_c) is larger than the increase of energy consumption of the indoor fan by increasing G_a . In the cooling mode, if ΔQ calculated from Eq. (1) is positive, the A/C controller first increases the fan speed to attain the optimum G_a calculated by substituting renewed Q_{hex} for Eq. (2). If the fan speed reaches the upper limit, the A/C controller then lowers T_e and the decrease of T_e is also calculated by Eq. (2). On the other hand, in $\Delta Q < 0$, the controller raises T_e first. The expansion valve controls the refrigerant temperature at the outlet of the indoor heat exchanger so that its best performance can be obtained.

In the outdoor unit, the minimum T_e or the maximum T_c calculated in the indoor units is selected and the compressor speed is controlled at the necessary value. By these coordinated controls of the indoor and outdoor units, the high-low pressure difference of the refrigerant is reduced and the energy consumption of the compressor can be decreased. Moreover, the intermittent operations of the compressor under low thermal load conditions can be suppressed effectively. Consequently we can expect the improvement of COP with the new A/C controller in comparison with the air conditioner with the conventional controller.

3.2 Minimization of Thermal Loss in Simultaneous Cooling/Heating Mode

In an ideal operation of the simultaneous cooling/heating mode of the heat recovery VRF system, heat is transferred between the indoor units operating in cooling mode and heating mode, and only surplus or insufficient heat is exhausted or absorbed in the outdoor heat exchanger. In the conventional A/C controller, the lower limit of the adjustable thermal capacity in the outdoor heat exchanger is set at somewhat larger value ("C" in Fig. 6(a)) to avoid the frequent switching between the condenser and the evaporator in the outdoor unit that may occur under nearly balanced indoor cooling and heating loads. As a result, surplus hot and cold heats are exhausted in the outdoor heat exchanger simultaneously as shown in Fig. 6(a), and large heat loss lowers the COP in the simultaneous cooling/heating mode.

In the new A/C controller, the flow rate of the refrigerant in the outdoor heat exchanger is minimized to reduce the lower limit of the adjustable capacity ("D" in Fig. 6(b)) by the coordinated control of the electric valve and the fan in the outdoor unit. As a result, the heat exhausted from the outdoor heat exchanger is decreased as shown in Fig. 6(b) and COP is improved in comparison with the conventional A/C controller. The heat balance in the simultaneous cooling/heating mode of the heat recovery VRF system is shown in Table 2.

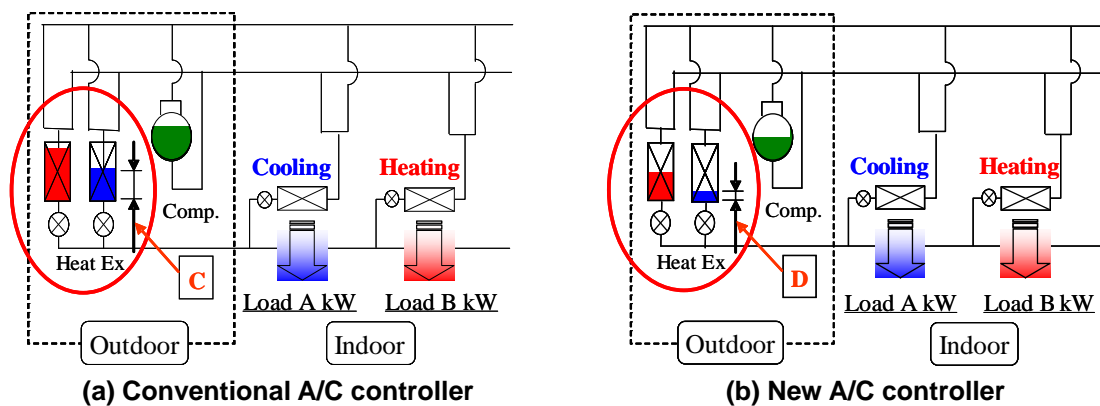


Figure 6: Minimization of Thermal Loss in Simultaneous Cooling/Heating Mode

Table 2: Heat Balance in Simultaneous Cooling/Heating Mode of Heat Recovery VRF System

	Conventional controller	New controller
Difference of cooling/heating capacities in indoor units	A - B (A > B)	A - B (A > B)
Capacity to be controlled in outdoor unit	A - B	A - B
Minimum evaporation capacity in outdoor unit	C	D (<< C)
Condensation capacity in outdoor unit	A - B + C	A - B + D

4 EVALUATION OF ENERGY-SAVING EFFECT OF NEW A/C CONTROLLER BY PART-LOAD PERFORMANCE TESTS

4.1 Tested Air Conditioners

First we evaluated the energy-saving effect of the new A/C controller by the part-load performance tests made in the test facility of Chubu Electric Power, in which the performance

Table 3: Specifications of the Air Conditioning System for Part-load Performance Tests

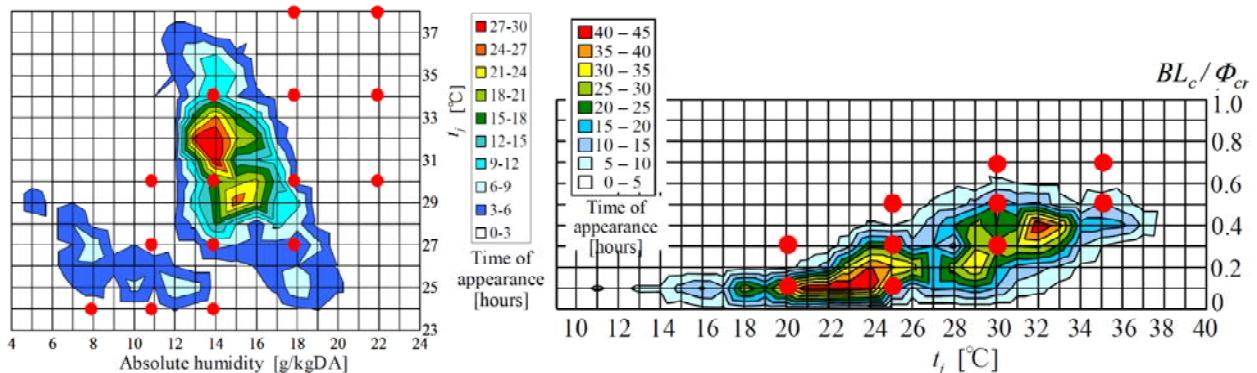
Type of A/C	Rated cooling capacity Φ_{cr}	Rated heating capacity Φ_{hr}	Number of indoor units	Indoor fan motor
Air processing VRF	45 kW	50 kW	2	AC
Heat recovery VRF	56 kW	63 kW	5	AC, DC (new)

of an air conditioner with a rated cooling capacity up to 168 kW and a rated heating capacity up to 200 kW can be measured by the air-enthalpy method (Nakayama et al. 2011). The specifications of the VRF systems provided for this test are shown in Table 3. We at first measured the performances of the marketed VRF systems with the conventional A/C controller. Then, the controller was replaced by the new controller developed in this project, and the performances of the VRF systems were measured again. Here it should be noted that, in the VRF systems with the conventional A/C controller, the fans in the indoor unit are powered by AC motors (AC indoor fans), while the new A/C controller can exhibit its full energy-saving performance with the DC indoor fans that can control the air flow rate more precisely. In the field measurements made in the existent office building, however, AC indoor fans were used irrespective of the A/C controllers due to the limitation of replacement works of the indoor units. Hence, as for the heat recovery VRF system with the new A/C controller, we measured the performances using two kinds of indoor unit with AC fans and DC fans.

4.2 Test Conditions

In the preliminary study, we measured the operating states of the air conditioners installed in the office building shown in Fig. 2 and temperature and humidity of outdoor air around it from December 2010 to November 2011. The test conditions of the part-load performance tests were determined based on those field data. In the outdoor-air processing VRF, the capacity and COP were determined by the dry-bulb temperature t_j and absolute humidity of outdoor air in its actual operation in the building. Thus, the part-load performance tests were conducted taking t_j and absolute humidity of outdoor air as parameters. The flow rate and temperature of blown air were fixed at specified values. In the heat recovery VRF, COP changed depending on t_j and the thermal load ratio BL_c/Φ_{cr} or BL_h/Φ_{hr} , where BL_c (BL_h) and Φ_{cr} (Φ_{hr}) denote the indoor cooling (heating) load and rated cooling (heating) capacity of the air conditioner, respectively. In the simultaneous cooling/heating mode, COP was influenced by t_j and the combination of BL_c/Φ_{cr} and BL_h/Φ_{hr} . Therefore, the part-load performance tests of the heat recovery VRF system were conducted changing t_j and BL_c/Φ_{cr} and/or BL_h/Φ_{hr} .

The test conditions of the air conditioners were determined so that they covered the major range of the actual operating conditions measured in the office building. Figure 7(a) shows the cooling performance test conditions of the outdoor-air processing VRF system. The abscissa and ordinate show the absolute humidity and t_j of outdoor air, respectively, and time (hours) of their appearance in a year is shown by a colour map. The test conditions are plotted by red symbols on this map. Figure 7(b) shows the relationship between the time of



(a) Outdoor-air Processing VRF System **(b) Heat Recovery VRF System**
Figure 7: Operating States of A/C in Cooling Season and Conditions of Performance Tests

Table 4: Conditions of Part-load Performance Tests
(a) Outdoor-air processing VRF system

Cooling performance test						Heating performance test								
t_j [°C]	Absolute humidity [g/kg]					t_j [°C]	Absolute humidity [g/kg]							
	22	18	14	11	8		7.5	6.6	5.7	4.3	3.7	3	2	
38	0	0	-	-	-	13	0	0	0	0	-	-	-	
34	0	0	0	-	-	9	-	-	0	0	-	0	-	
30	0	0	0	0	-	5	-	-	-	0	-	-	-	
27	-	0	0	0	-	3	-	-	-	-	0	0	0	
24	-	-	0	0	0									

(b) Heat recovery VRF system

Cooling performance test					Heating performance test			
t_j [°C] DBT/WBT	Cooling load ratio BL_c/Φ_{cr}				t_j [°C] DBT/WBT	Heating load ratio BL_h/Φ_{hr}		
	10%	30%	50%	70%		10%	30%	50%
20 / -	0	0	-	-	0 / -1	0	0	0
25 / -	0	0	0	-	6 / 2	0	0	0
30 / -	-	0	0	0	12 / 7	0	0	-
35 / -	-	-	0	0				
Simultaneous cooling / heating performance test								
BL_c/Φ_{cr}		10%	10%	20%	35%	35%	10%	20%
BL_h/Φ_{hr}		10%	35%	20%	10%	35%	20%	35%
t_j [°C] DBT/WBT	3 / 0	0	0	-	-	-	0	0
	10/6	0	0	0	0	0	0	0
	17/13	0	-	-	0	0	-	-

appearance of t_j and BL_c/Φ_{cr} in a year measured with the heat recovery VRF system in the office building and conditions of its cooling performance test. In the actual office building, this VRF system was working under the cooling load ratio less than 50 %. In the simultaneous cooling / heating mode, a positive correlation was observed between BL_c/Φ_{cr} and BL_h/Φ_{hr} , and the air conditioner was working under the conditions of $BL_c/\Phi_{cr} < 50\%$ and $BL_h/\Phi_{hr} < 50\%$ similar to the case of cooling operation. The test conditions are summarized in Table 4.

4.3 Results of Part-load Performance Tests

4.3.1 Outdoor-air processing VRF system

In the part-load performance tests of the outdoor-air processing VRF system, we measured COPs and capacities taking t_j and absolute humidity as parameters. Here, COPs shown in this paper are defined based on the electricity consumed by both the indoor and outdoor units. COPs measured with the conventional A/C controller and the new A/C controller are compared in Fig. 8. In the new A/C controller, cooling COPs are higher than those of the conventional controller at high t_j , but this relation is reversed at low t_j . The new controller can decrease the cooling capacity according to drop in t_j to lower level than the conventional controller. As a result, the electricity consumption of the indoor fans accounts for relatively large percentage in the total electricity consumption compared to the conventional controller at low t_j . Since the electricity consumption of the indoor fans is constant in both controllers, this lowers COPs of the new controller at low t_j . In the heating operations, improvement of COPs with the new A/C controller is observed under all test conditions as shown in Fig. 8(b).

4.3.2 Heat recovery VRF system

COPs of the heat recovery VRF system measured in the part-load cooling performance test and heating performance test are shown in Fig. 9. The results obtained with the conventional A/C controller, new A/C controller + AC indoor fans, and new A/C controller +

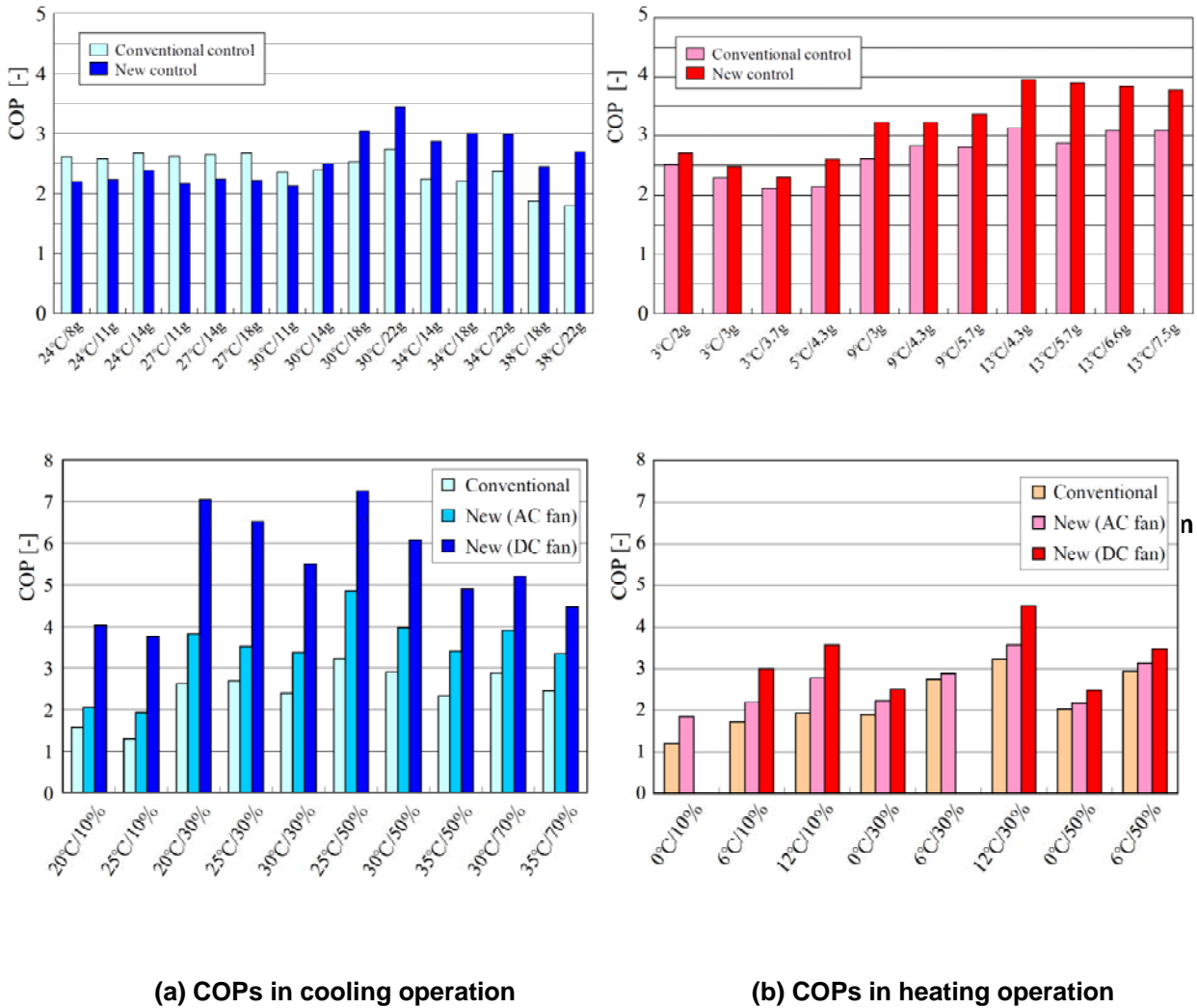


Figure 9: Results of Part-load Performance Tests of Heat Recovery VRF System

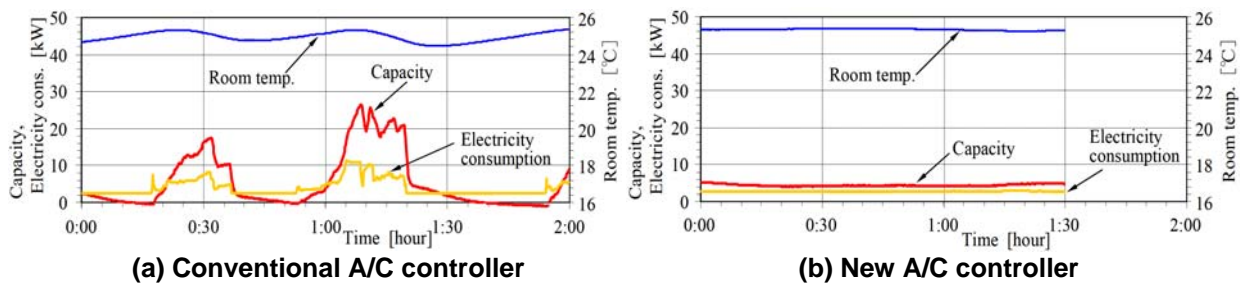


Figure 10: Example of Trend Curves ($BL_c/\Phi_{cr} = 10\%$)

with the conventional one under all test conditions. In particular, higher increase ratios of COPs are observed in a relatively low cooling load range with the new A/C controller + DC indoor fans. This superiority of the DC indoor fan is attributed to its precise controllability of air flow rate and low heat generation. Heating COPs are also increased by the new A/C controller, but their increase ratios are not as high as those observed in the cooling operation. In this study, the measured COPs were expressed as a function of t_i and BL_c/Φ_{cr} or BL_h/Φ_{hr} (denoted as COP surface) for convenience of the calculation of the annual average COP.

Figure 10 shows the temporal variations of the cooling capacity, electricity consumption and room temperature measured with each A/C controller under the low cooling load of $BL_c/\Phi_{cr} = 10\%$. In the conventional A/C controller shown in Fig. 10(a), the intermittent operation of the

compressor and the fluctuation of the room temperature are observed. The operation of the compressor is stabilized with the new A/C controller in Fig. 10(b).

Figure 11 shows COPs measured in the simultaneous cooling / heating mode, which were

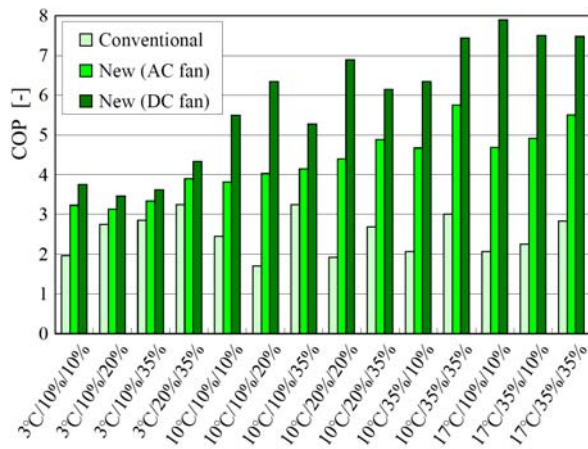


Figure 11: COPs Measured with Heat Recovery VRF in Simultaneous Cooling / Heating Mode

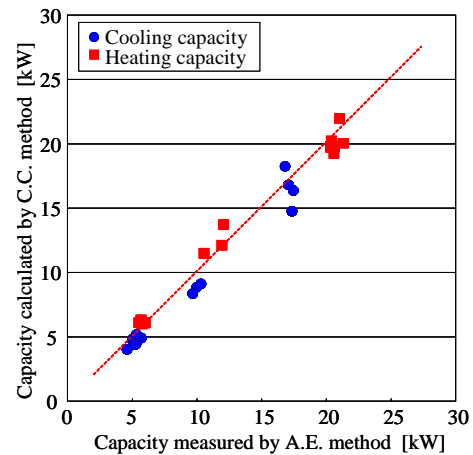


Figure 12: Comparison of Capacities Measured by A.E. and C.C. Methods

calculated based on the sum of cooling and heating capacities and the total electricity consumption of the air conditioner. Remarkable improvement of COPs is observed with the new A/C controller under relatively high t_i condition, and DC indoor fan has superiority over the AC indoor fan similar to results described above.

4.4 Verification of Compressor-curve Method

As a preparation for the field measurements of capacities of VRF systems, the reliability of the compressor-curve method was examined in the part-load performance tests. Figure 12 shows a comparison of time-averaged capacities measured by the air-enthalpy method and those calculated by the compressor-curve method in the simultaneous cooling/heating mode. They agree with each other within an average difference of 5%, and similar results were obtained for other modes of the heat recovery VRF and the outdoor-air processing VRF.

4.5 Evaluation of Energy-saving Effect of New A/C Controller

Based on the results of the part-load performance tests, the annual average COP of the air conditioning system shown in Fig. 2 was estimated, which was defined as the ratio of the annual thermal load to the annual electricity consumption. As for the outdoor-air processing VRF system, COPs and capacities measured in the performance tests were expressed as functions of t_i and absolute humidity of outdoor air. They were combined with the time of appearance of t_i and absolute humidity in a year (Fig. 7(a) for the cooling operation) to calculate the annual thermal load and electricity consumption. Since we could not measure the performance of the outdoor-air processing VRF with the new A/C controller + DC indoor fans, its annual average COP was estimated taking decrement of the electricity consumption of the indoor fan motors into account. The annual average COP of the heat recovery VRF system was calculated based on the time of appearance of t_i and thermal load ratio in a year (Fig. 7(b) for the cooling operation) and the COP surface of each operation mode.

At first, we explain the thermal load processed by each air conditioner in the office building. Figure 13 shows the monthly integrated capacities of each air conditioner for each operation mode measured from January to December in 2012. The annual heating capacity of the outdoor-air processing VRF is about five times its annual cooling capacity. The heat

recovery VRF system is operated in the simultaneous cooling / heating mode from January to June. This means that the cooling load arises locally in the office even in midwinter.

Figures 14 and 15 show the annual average COPs and annual electricity consumptions of each air conditioner estimated based on the results of part-load performance tests and operating conditions measured in the office building. The results of the annual average

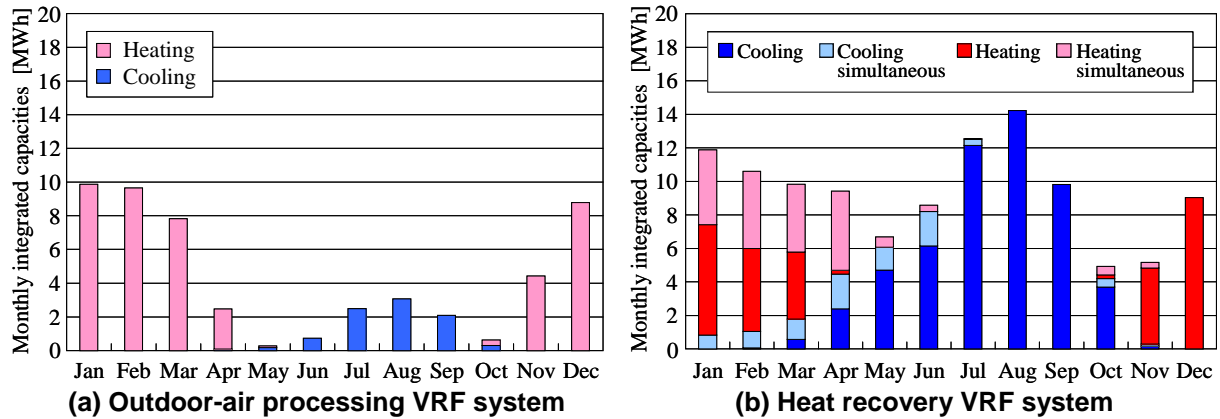


Figure 13: Capacities of Each Air Conditioner Integrated Monthly for Each Operation Mode

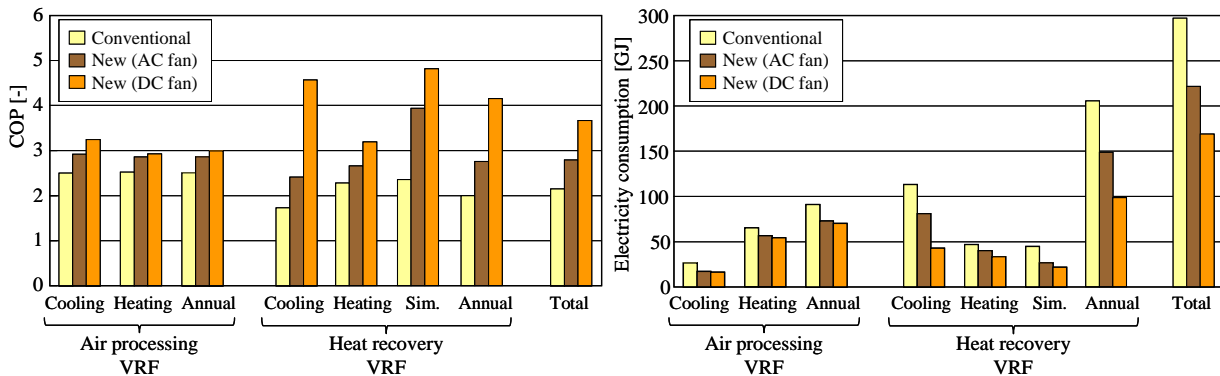


Figure 14: Annual Average COPs

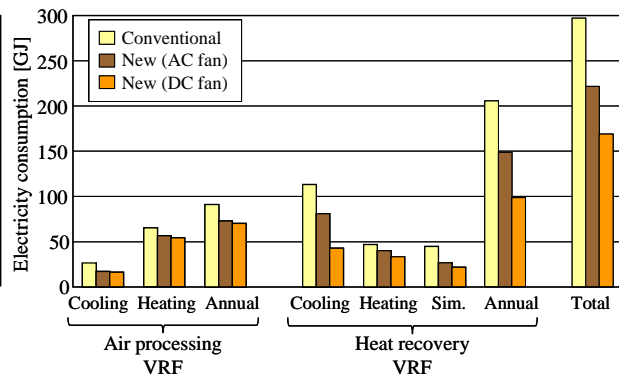


Figure 15: Annual Electricity Consumptions

Table 5: Annual Average COPs Predicted Based on Part-load Performance Tests

A/C controller	Annual average COPs			Increase ratio of annual average COPs		
	Air processing	Heat recovery	Total	Air processing	Heat recovery	Total
Conventional	2.50	1.98	2.14	Base	Base	Base
New + AC fan	2.86	2.74	2.78	14%	38%	30%
New + DC fan	2.99	4.13	3.65	19%	108%	71%

COPs are summarized in Table 5. The annual average COP of the air-conditioning system increases by 30% and 71% with the new A/C controller combined with AC indoor fans and DC indoor fans, respectively. As a result, the annual electricity consumption can be decreased by 23% and 42% with the new A/C controller. Therefore, it is expected that 150 % higher annual average COP, which is the final target of this R & D project, can be achieved with the combination of the new A/C controller and the DC indoor fans.

5 EVALUATION OF ENERGY-SAVING EFFECT OF NEW A/C CONTROLLER BY FIELD MEASUREMENTS IN EXISTENT OFFICE BUILDING

5.1 Results of Field Measurements

In this study, the operating state of the air conditioning system with the conventional A/C controller installed in the office building shown in Fig. 2 was measured from December 2010

to November 2011. Then, the controller was changed to the new A/C controller and the operating state was measured again from January to December in 2012 to evaluate its actual energy-saving effect. The specifications of the air conditioners are shown in Table 1, and their capacities were measured by the compressor-curve method. Since the indoor units were unchanged in 2012, the new A/C controller was combined with the AC indoor fans.

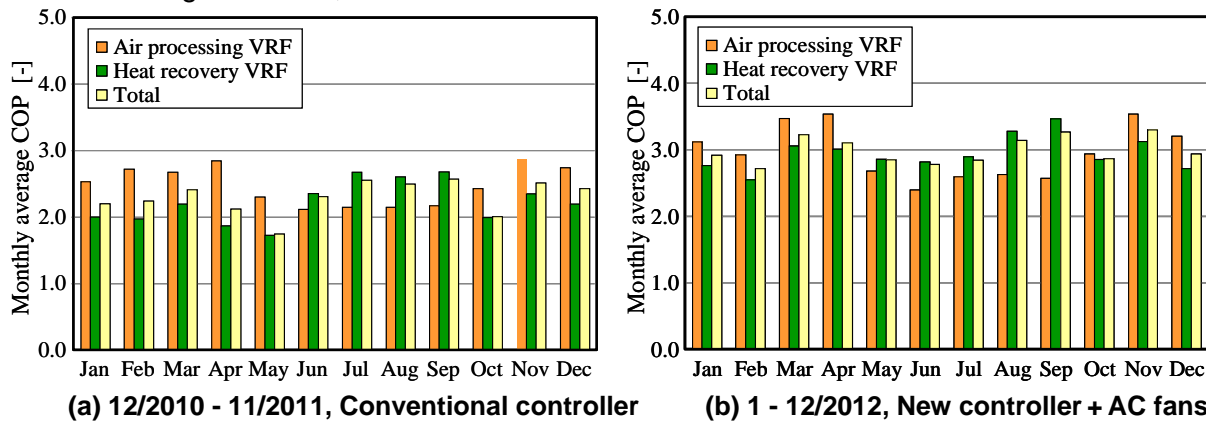


Figure 16: Monthly Average COPs Measured in the Existent Office Building in Two Years

Figure 16 shows the monthly average COPs measured in the office building for two years. COPs are generally improved by the new A/C controller. The annual average COP of the air conditioning system with the conventional A/C controller was 2.40, and that with the new A/C controller was 2.98. Thus, the increase ratio of the annual average COP was 24%.

In the field measurements, the operating states of the air conditioners and meteorological conditions around the building may differ depending on the test year. In order to evaluate the energy-saving effect of the new A/C controller correctly, those differences of the operating conditions must be compensated. In this study, we compensated the field data measured with the conventional A/C controller using the results of the part-load performance tests. At first, we calculated the monthly average COPs of the conventional A/Cs using their COP surfaces and operating conditions from December 2010 to November 2011. Then, by the same method, we calculated the monthly average COPs of the conventional A/Cs operated under the conditions from January to December in 2012, and their change ratios were determined for each month. By using these change ratios of COPs, we estimated the monthly average COPs of the conventional system operated in the actual building from January to December in 2012. With this compensation of the field data, the annual average COP of the air conditioning system with the conventional controller operated in 2012 was estimated to be 2.28 and the increase ratio of the COP with the new controller was 31%. This result agrees well with that predicted by the part-load performance tests (Table 5).

5.2 Effect of DC Indoor Fans

As described in chapter 4, the new A/C controller can exhibit its full energy-saving performance by the combination with the DC indoor fans, but AC indoor fans were used in the field test of the new A/C controller. In this study, monthly and annual average COPs of the air conditioning system with the new A/C controller + DC indoor fans were estimated based on the results of the part-load performance tests. For the heat recovery VRF system, the increase ratio of COP ($= \text{COP with DC fans} / \text{COP with AC fans}$) was expressed as a function of t_j and BL_c/Φ_{cr} or BL_h/Φ_{hr} as shown in Fig. 17. By combining this result with COPs measured in the building in January - December 2012, COPs of the heat recovery VRF system with the new A/C controller + DC indoor fans were estimated. For the outdoor-air processing VRF system, we considered only the decrement of the electricity consumption of the indoor fan motors as described in 4.5. Figure 18 shows the comparison of the monthly average COPs, and Table 6 shows the annual average COPs and their increase ratios. By

combining the new A/C controller with the DC indoor fans, the annual average COP of the air conditioning system increases to 3.85. This result demonstrates again that 170 % higher annual average COP can be achieved by replacing the conventional A/C controller + AC indoor fans with the new A/C controller + DC indoor fans.

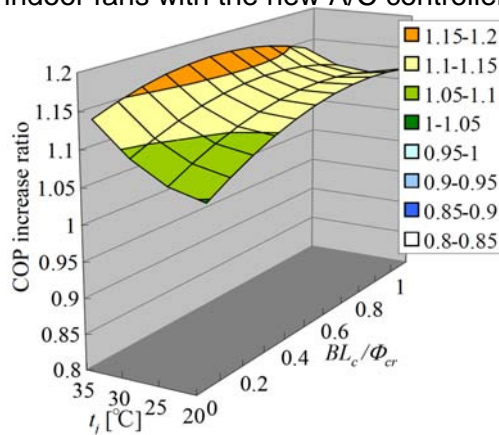


Figure 17: COP Increase Ratio by Use of DC Indoor Fans (Cooling Operation)

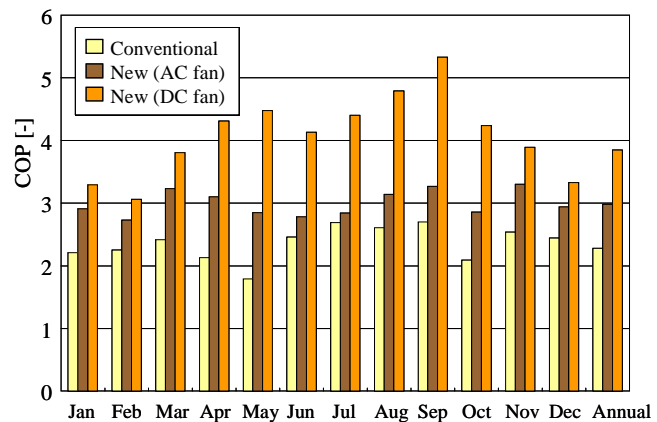


Figure 18: Comparison of Annual and Monthly Average COPs Measured in Office Building

Table 6: Annual Average COPs Measured in Existent Office Building

A/C controller	Annual average COPs			Increase ratio of annual average COPs		
	Air processing	Heat recovery	Total	Air processing	Heat recovery	Total
Conventional	2.58	2.16	2.28	Base	Base	Base
New + AC fan	3.08	2.94	2.98	19%	36%	31%
New + DC fan	3.23	4.23	3.85	25%	96%	69%

6 CONCLUDING REMARKS

We developed an innovative energy-saving A/C controller that consists of the capacity optimization based on the capacity optimization by the real-time prediction of the indoor thermal load with PFC, and the minimization of the capacity-control loss in simultaneous cooling and heating operations. This new controller was installed in the multi-split air conditioning system for buildings (outdoor-air processing VRF + heat recovery VRF), and its energy-saving effect was examined by the part-load performance tests in a test laboratory and field measurements in an existent office building. It was demonstrated that 170 % higher annual average COP can be achieved by this new A/C controller. This new A/C controller will be installed in the air conditioners that will be put on the market by DAIKIN INDUSTRIES.

The results obtained by this study attribute to the research and development project on “Next-generation Heat Pump Systems” of NEDO.

7 REFERENCES

Hirota M., Watanabe C., Furukawa M., and Nagamatsu K. 2007. “Evaluation of Annual Performance of Multi-type Air-Conditioners for Buildings - 1st Report: Annual Energy Consumption of EHP-,” *Trans. of the JSRAE*, Vol. 24, No. 4, pp. 303-314. (in Japanese).

Nakayama H., Iwata Y., Sakuraba I., Nagamatsu K. and Tokuda M. 2011. “An overview of energy-saving heat pump test facility “Heat Pump Lab”,” *Proc. 10th IEA Heat Pump Conference*, Tokyo, Japan, 3.16, on CD-ROM.

Richale J. and O'Donovan D. 2009. *Predictive Functional Control: Principles and Industrial Applications*, Springer, Berlin.

Watanabe C., Nagamatsu K., Nakayama H., Hirota M. and Ohashi E. 2008. "A New Test and Evaluation Method of Annual Energy Efficiency of Multiple Air-Conditioners for Buildings," *Proc. 9th IEA Heat Pump Conference*, Zürich, Switzerland, 3.19, on CD-ROM.