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Development of an Onsite Performance Evaluation Method for Variable Refrigerant Flow Systems

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Abstract:

Variable refrigerant flow (VRF) systems have gradually expanded their market share over the past several decades. The systems have been installed not only in small-sized buildings but also in large-sized buildings instead of central air conditioning systems because of their high energy efficiency. As refrigerants directly exchange heat with the ambient air in the systems, it is generally difficult to evaluate their performance accurately. Also, because it requires a large-scale environmental test chamber to examine, it is impossible for users to evaluate the performance of the systems. In the present study, we developed an onsite performance evaluation method that reveals the operation performance of VRF systems. We succeeded in calculating the performance in real-time and with high accuracy within 10% on a high-performance microcomputer board and sending data to the cloud server via the Internet. This system was installed nationwide in various buildings with different uses and meteorological conditions and obtained data were analysed. As a result, actual conditions including unnecessary operations and performance degradation causes were clarified. We also examined an information providing method. Advice and messages which are based on the Nudge theory are sent to mobile devices and computers of users after data analysis to suggest better operational methods. Finally, an automatic control operation was carried out for energy-saving control operations and estimation of CO_2 reduction amount. According to the estimation we obtained, the reduction will be over 1 million tons by 2030 and the spread of this method will lead to energy conservation in the building sector. The present study was carried out under the title of "Low Carbon Technology Research and Development Energy Program" with the support of the Ministry of the Environment.

Keywords:

VRF systems, Performance Evaluation, Energy Conservation, Low-Carbon Technology.

1. Introduction

Greenhouse gas emissions reached 49 billion tons in 2010 according to the IPCC Fifth Assessment Report [1] and the emissions from the building sector exceeded 19%. Specifically, energy consumption from air conditioning systems is an important issue and its reduction potential is quite considerable.

VRF systems have considerably increased their shipments over the past few decades according to The Japan Refrigeration and Air Conditioning Industry Association [2]. The systems have been installed all sizes of buildings instead of central air conditioning systems because of their high energy efficiency, flexible design, easy installation and low initial costs [3-4]. As refrigerants directly exchange heat with the ambient air in the systems [5], it is generally difficult to evaluate their performance precisely. As a result, their management has not been paid attention to. Operating patterns are unknown and excessive installed capacities for avoiding complaints have been a major problem.

Therefore, it is important to enlighten users including building designers and operators by providing information of the precise performance and the actual energy consumption of the systems and encourage them to take action for energy-saving for reducing greenhouse gas emissions.

Daikin Industries, Ltd. supplies a preventive maintenance service by remote monitoring [6]. The service includes the collection and analysis of air conditioning operation data. When deterioration and abnormalities are detected, users will be informed, however, the service is limited to air conditioners made by Daikin.

In the present study, we built an onsite performance evaluation method that is applicable in all manufactures of VRF systems. Performance calculation in real-time and with high accuracy are realized. The method was applied to VRF systems in various buildings for a demonstration and obtained data were analysed. As a result, we clarified actual conditions including unnecessary operations and performance degradation causes. Additionally, we examined an information providing method. After data analysis, advice and messages which are based on the Nudge theory are sent to mobile devices and computers of users to suggest better operational methods and energy-saving designs. Finally, an automatic control device was installed for energy-saving control operations and CO_2 reduction amount are estimated which is over 1 million tons by 2030. The spread of this method will lead to energy conservation in the building sector and contribute to CO_2 reduction.

2. Performance evaluation method for VRF systems

2.1. Compressor Curve method

The CC method is a practical approach to calculate the capacity by multiplying the refrigerant mass flow of compressors by the specific enthalpy difference of indoor units. VRF systems typically employ scroll and rotary compressors. These compressors have their own refrigerant mass flow and energy consumption characteristics. For this reason, we focused on the refrigerant mass flow for performance evaluation.

The capacity calculation is shown in (1). Q indicates the actual thermal output and G_{comp} is the refrigerant mass flow. Delta h is the specific enthalpy difference between the inlet-air and outlet-air of the indoor unit as shown in Fig. 1. Delta *he* stands for the specific enthalpy difference of evaporator and *hc* for condenser.

The refrigerant mass flow is calculated using physical properties as shown in (2). ρ is the compressor suction density obtained by the calculation of temperature and pressure, V is the compressor displacement which is a characteristic value, N is the compressor revolution measured by power frequency and η is the volumetric efficiency.

As volumetric efficiency values were improved on a conventional study, it became possible to calculate air conditioning capacity with high accuracy.

$$Q = G_{comp} \times \Delta h \quad (1)$$

$$G_{comp} = \rho \times V \times N \times \eta \quad (2)$$

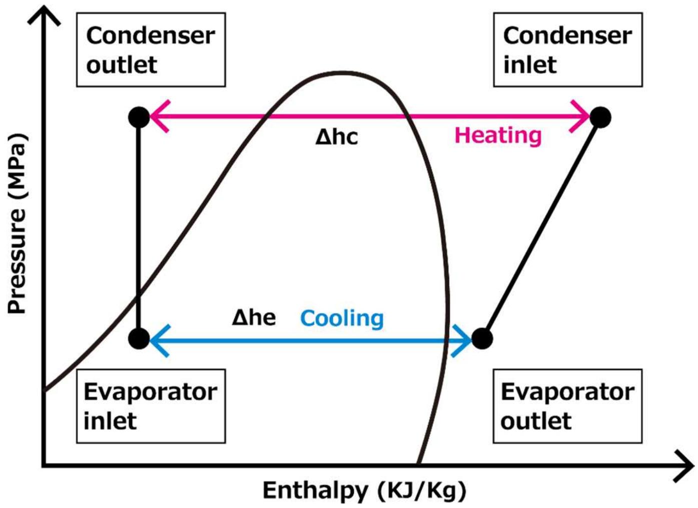


Fig. 1. Pressure-enthalpy chart.

3. Onsite performance evaluation system

3.1. Outline of the system

An outline of an onsite performance evaluation system is given in Fig. 2. It is a system that connects a control board of an outdoor unit to a microcomputer (Armadillo) and acquires actual operation data. The data is transmitted to the cloud server via the Internet. The data are physical property values including compressor revolution speed and refrigerant temperature and pressure values. Information on energy performance including refrigerant mass flow, air conditioning capacity, energy efficiency, load factor and installed capacity are calculated using the CC method.

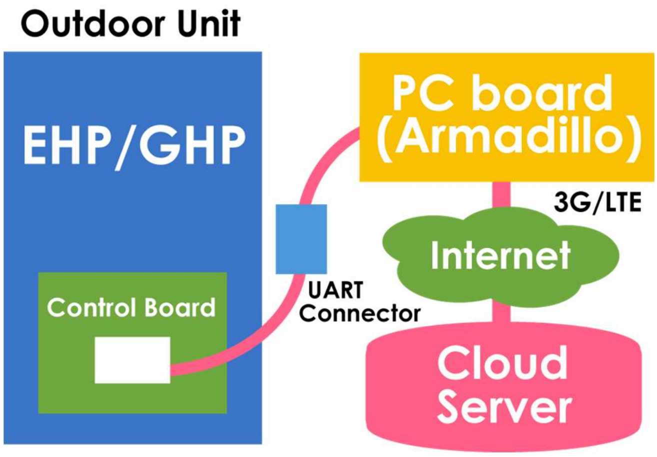


Fig. 2. Outline of the onsite performance evaluation system.

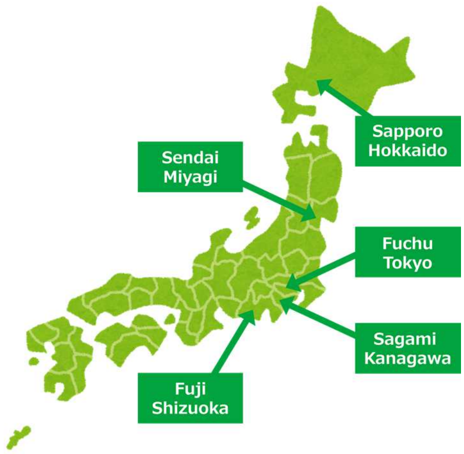


Fig. 3. Installation locations.

3.2. Demonstration of the system

This system was installed in Electric driven Heat Pumps (hereafter referred to as EHP) and nationwide in various buildings with different uses including offices and university buildings as shown in Fig. 3. Capacities of outdoor units are 8, 10 and 12HP and multiple indoor units are connected as shown in Table 1.

Table 1. List of installation sites

No	Prefecture	city	Use	Capacity	Outdoor unit	Indoor unit
1	Shizuoka	Fuji	Office	8HP	Single	3
2						3
3	Tokyo	Fuchu		12HP	Single	6
4				10HP*2	Multiple	9
5	Miyagi	Sendai		12HP	Single	6
6	Hokkaido	Sapporo		10HP	Single	4
7				10HP *4	Multiple	8
8				10HP, 8HP *2		5
9	Kanagawa	Sagami	University	12HP *2	Multiple	7
10				12HP, 10HP		8
11				12HP, 10HP		6
12				12HP	Single	3
13				10HP		3
14				12HP		3
15				12HP		3

3.3. Information providing method for energy conservation

As VRF systems have increased their market share because of easy settings and a large air conditioning capacity, management has not been done properly. Neither air conditioning heat quantities nor operating patterns are known. Fig. 4 shows the information providing method. Data on the cloud server are combined with weather data and they are sent to mobile devices and computers of general users and facility designers after data analysis to raise user's energy-saving consciousness. Examples of advice and messages are shown in 4.9. in the next chapter.

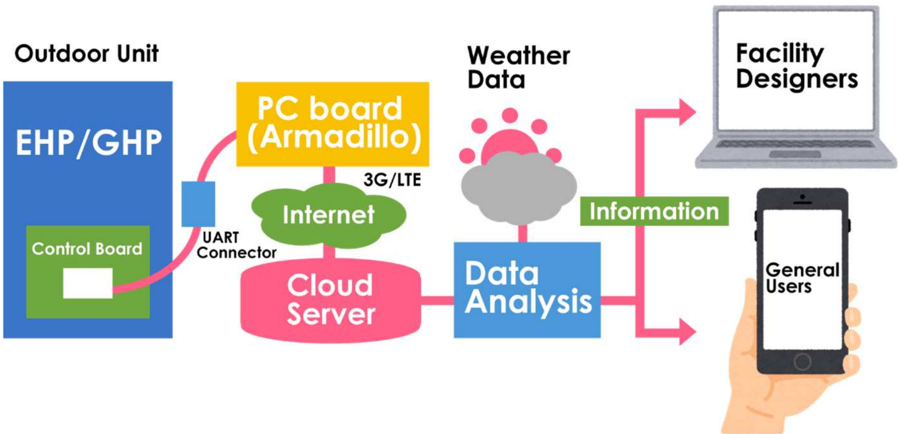


Fig. 4. Information providing method.

3.4. The Nudge theory

The Nudge theory is referred to examine what kind of messages will encourage users and building designers to take action for energy-saving. The theory was proposed by an American economist Richard H. Thaler. The phrase nudge theory, or nudge, is a behavioral science concept which states that positive reinforcement can influence the motivations and decision-making of a person or group of persons [7]. The six approaches, their explanations and examples of energy-savings in the present study are shown in Table 2.

Table 2. The Nudge theory and examples of energy savings

Approaches	Explanations	Examples of energy-saving in the present study
Incentives	Motivate remarkably	●Indicate peak power ●Emphasize loss
Understand mappings	Show the relationship between choices and results clearly	●Indicates energy conservation and savings by operation improvement ●Compare with rated operation
Defaults	Most people choose the defaults	Set to energy-saving mode at shipment
Give feedback	Report the results clearly	Expose the power consumption values with company names
Expect errors	Assume that mistakes will occur	●Detect extreme increase in air conditioning load ●Carry out inspections regularly
Structure complex choices	When choices are complicated, narrow down recommendations	●Recommend maximum power and inverter frequency controls

4. Validation by field data analysis

4.1. Definitions of terms

The data were collected every 5-second and aggregated in 1 hour. Data collection period is from August 1st to December 31st in 2017. All the data were considered for the analysis.

Terms of definitions are defined in (3) to (6) as follows:

COP = Rated capacity (kW) / Rated power consumption (kW) (3)

Cooling load factor = Total cooling capacity (kW) / Rated cooling capacity (kW) (4)

Heating load factor = Total heating capacity (kW) / Rated heating capacity (kW) (5)

Operating time of outdoor unit = Compressor running time (6)

4.2. Load factor frequency

Figs 5 and 6 show average load factors in the cooling and heating operations at all locations. Average load factor is 25.8% in the cooling operation and 22.2% in the heating operation. There are 3 outdoor units in Sapporo and average load factors are only 19.2% in the cooling operation and 14.9% in the heating operation. We found that installed capacity was excessive in Sapporo.

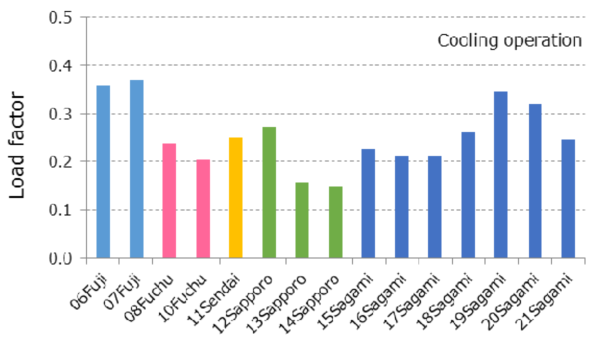


Fig. 5. Average load factor values (Cooling).

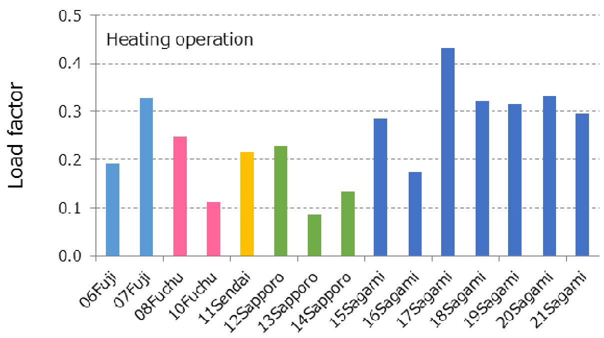


Fig. 6. Average load factor values (Heating).

4.3. Coefficient of performance

Figs 7 and 8 show average Coefficient of Performance values (hereafter referred to as COP) in the cooling and heating operations. The results show that Sapporo's average COP values which are 3.1 in the cooling operation and 2.4 in the heating operation are relatively lower than Sagami's average COP values which are 6.6 in the cooling operation and 7.0 in the heating operation.

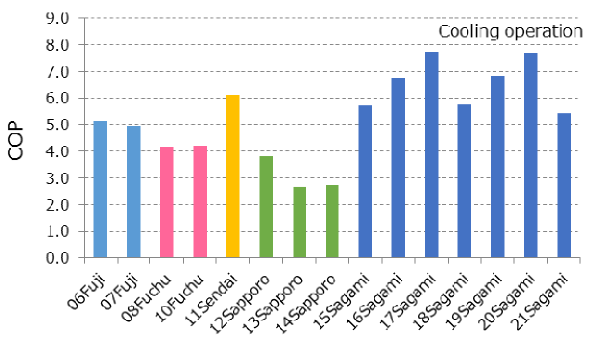


Fig. 7. Average COP values (Cooling).

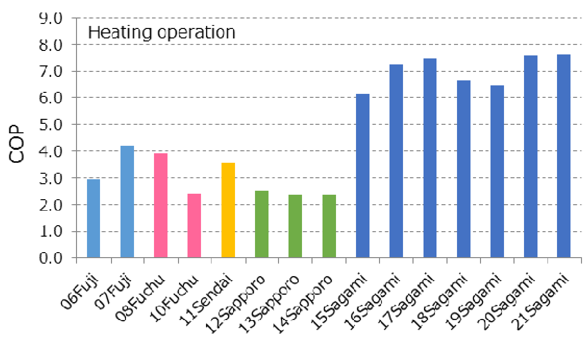


Fig. 8. Average COP values (Heating).

4.4. Temperature presets of indoor units

Figs 9 and 10 show average temperature presets in Sagami. There are 9 indoor units. All the indoor units are set to roughly 25 degrees Celsius during the cooling operation whereas pt_0 is set to 25.4 degrees Celsius which is 2 degrees higher than pt_5 in the heating operation. Inappropriate temperature settings are revealed.

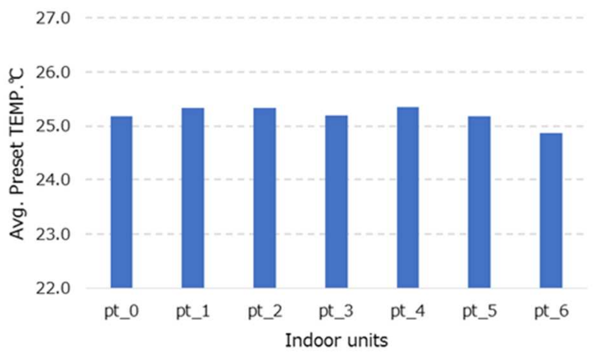


Fig. 9. Avg. temperature presets (Cooling).

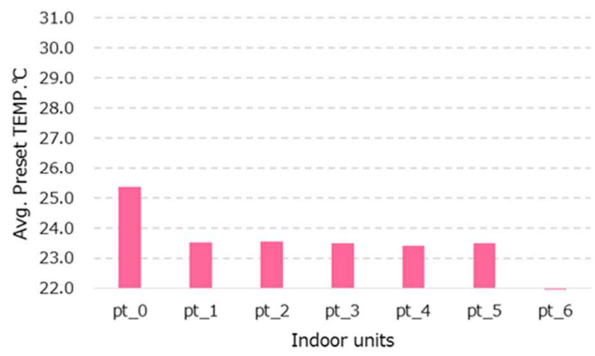
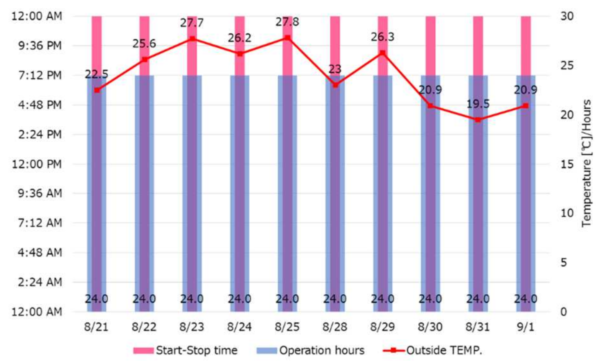


Fig. 10. Avg. temperature presets (Heating).

4.5. Operating hours

Figs 11 and 12 show the comparisons of outside air temperature, operation hours and start-stop time of operations in the cooling and heating operations in Sendai. Data from Aug 21st to Sep 1st and Dec 4th to 15th are analysed. Weekend data is not included as the office was not in operation. The results in the cooling operation show that the machine is operated continuously for the analysis period. Also, there is a possibility that the machine is operated all night on December 14th; an operation started at 7:37 a.m. on the 14th and it stopped at 8:44 p.m. on the 15th. Unnecessary operations are verified.



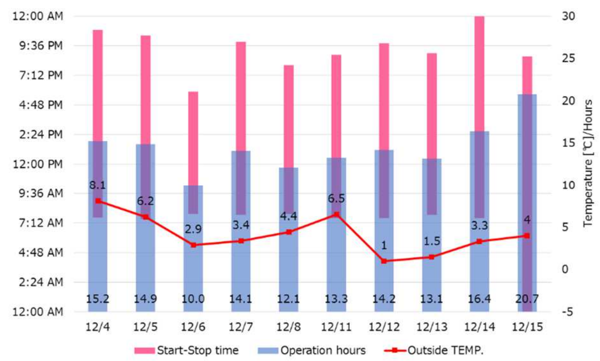


Fig. 11. Operating hours in Sendai (Cooling). *Fig. 12. Operating hours in Sendai (Heating).*

4.6. ON-OFF times of compressors

ON-OFF times of compressors and COP values and ON-OFF times at each point during the cooling and heating operations are shown in Figs 13 to 16. Average ON-OFF time intervals are shown in Table 3. Data is from August 21st to 25th and from December 18th to 22nd and the time is from 8 a.m. to 4 a.m. when the compressors were in operation. ONs and OFFs are repeated every 12-minute in Fuji and every 11-minute in Sendai. Sagami's time intervals are relatively longer. Except for Sagami in the heating operation, there is no obvious changes in COP values. Frequent ON-OFF times of compressors will lead to energy consumption increases and durability decreases of equipment, management should be applied.

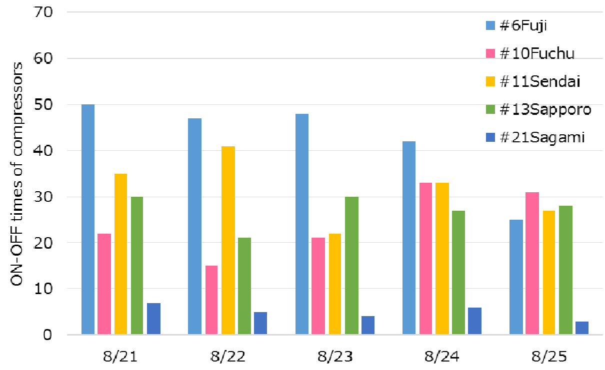


Fig. 13. ON-OFF times of compressors (Cooling).

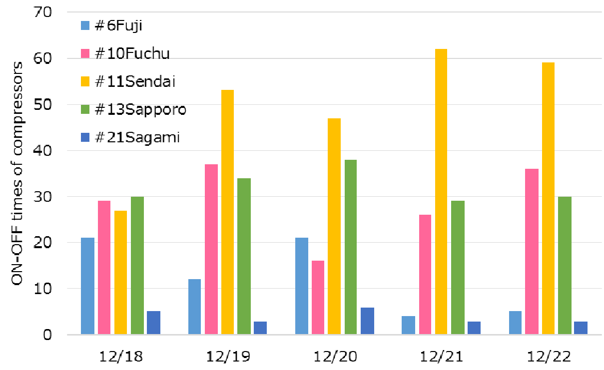


Fig. 14. ON-OFF times of compressors (Heating).

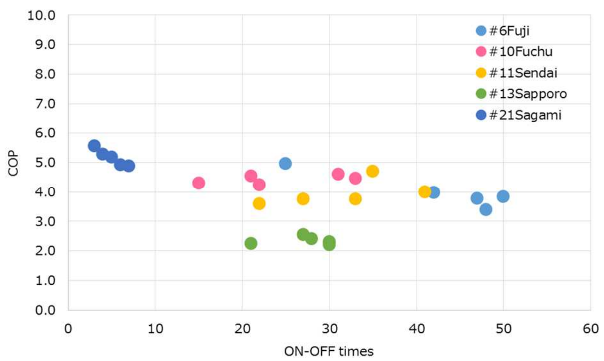


Fig. 15. COP and ON-OFF times (Cooling).

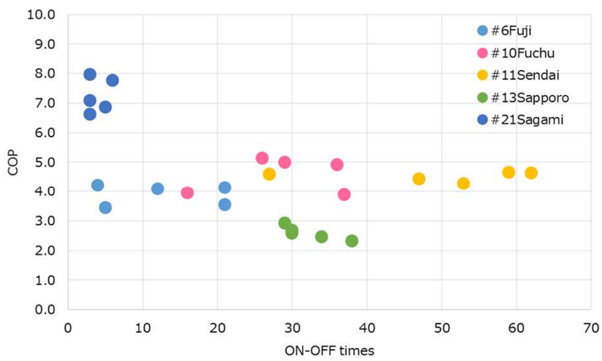


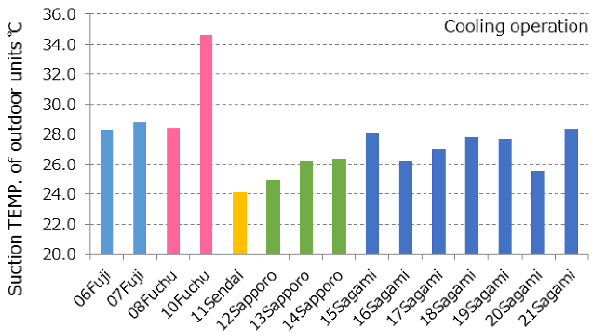
Fig. 16. COP and ON-OFF times (Heating).

Table 3. Average ON-OFF time intervals

Operations	#6Fuji	#10Fuchu	#11Sendai	#13Sapporo	#21Sagami
Cooling	12 min	21 min	16 min	18 min	105 min
Heating	60 min	18 min	11 min	32 min	131 min

4.7. Suction temperature of outdoor units

A short circuit is a major problem for air conditioners. Exhaust heat of outdoor units gets into the suction sides because of obstacles including walls and it causes low efficiency. Figs 17 and 18 show average suction temperature of outdoor units in both cooling and heating operations. As #10 in Fuchu records the highest suction temperature of 34.6 degrees Celsius, it is possible that there is an influence of a short circuit. Installation of exhaust hoods should be advised to users.



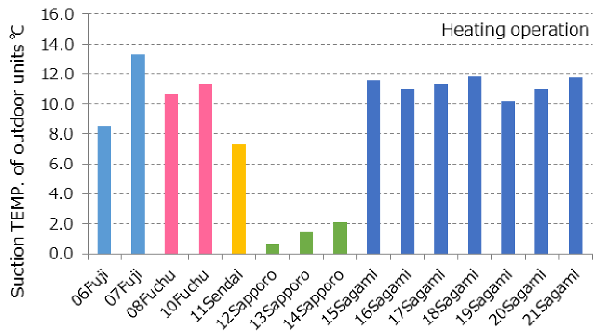


Fig. 17. Suction temperature of outdoor units (Cooling). Fig. 18. Suction temperature of outdoor units (Heating).

4.8. Power consumption per floor area

Figs 19 and 20 show average power consumption per floor area in the cooling and heating operations. Power consumption per floor area in #13 in Sapporo is the highest which is 16kWh/m^2 in the cooling operation and #8 in Fuchu which is 17kWh/m^2 is the highest in the heating operation. # 19 and 20 in Sagami are not in operation in the cooling operation. Warnings should be given to the users.

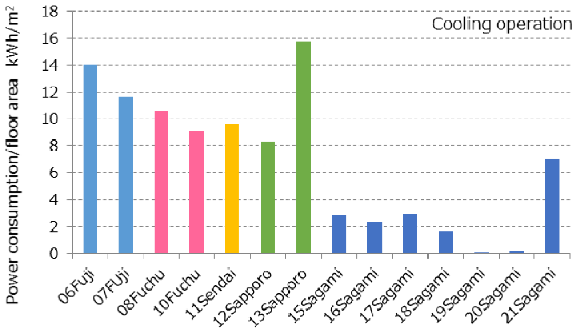


Fig. 19. Power consumption per floor area (Cooling).

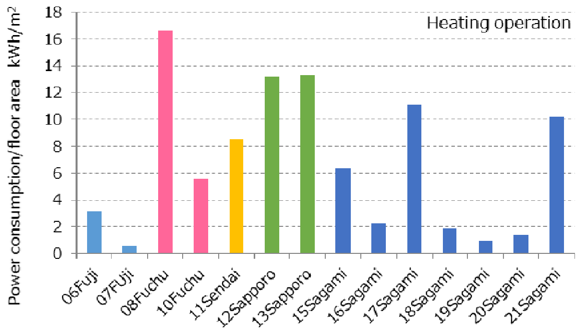


Fig. 20. Power consumption per floor area (Heating).

4.9. Results

The field analysis revealed various problems including low load and low efficient operations, inappropriate temperature settings, unnecessary operations, excessive installed capacities and a short circuit. Reporting these actual operations to users is a key to energy conservation. Examples of advice and messages to users taking the Nudge theory into consideration are shown in Table 4.

Table 4. Advice and messages to users using the Nudge theory

No	Results	Examples of advice/Messages to users
1	Low load factor	"Reconsider the air conditioning capacity at the next replacement."
2	Low COP	"Installed capacity of the air conditioner is excessive."
3	High/low temperature presets	"Temperature settings are too high. Please set to 26 degrees Celsius."
		"You are making a loss of $3 because of the high temperature presets."
4	Continuous operation	"Three hours have passed since the start of operation. "
		"The total operation time was 6 hours and 20 minutes yesterday. "
5	Frequent ONs and OFFs of compressors	"Compressors of the air conditioner started 58 times today. "
6	Short circuits	"As the outdoor unit installation environment is bad, consider installing an exhaust hood. "
7	High power consumption	"Save electricity as power consumption is high."

5. CO_2 reduction effect by the system

5.1. Energy-saving controls

It is possible to realize efficient operation of VRF systems by utilizing the data. An output control device is added for energy-saving controls. After obtaining data on the system, low efficient operation and excessive capacity are detected and send signals to the device for adjusting output. Energy-saving controls are applied for high efficient operations as shown in Fig. 21.

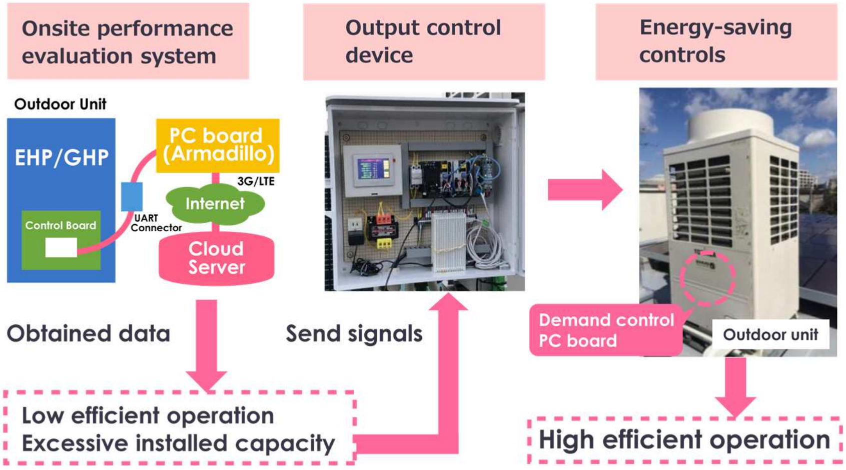


Fig. 21. Outline of energy-saving controls.

The experiment was carried out at a university's workshop in Sagami which has 3 outdoor units. Air-conditioning capacities are 12HP for AC1 and AC3 and 10HP for AC2. The experiment period is December 1st to 14th in 2017. According to COP evaluation, average COP values are 2.1 without the control and 3.1 with the control. Electricity is reduced when controls are ON as shown in Fig. 22 and Table 5. Average CO_2 reduction rate is 23.9%. CO_2 conversion factor is 0.486 kg-CO_2/kWh according to TEPCO [8].

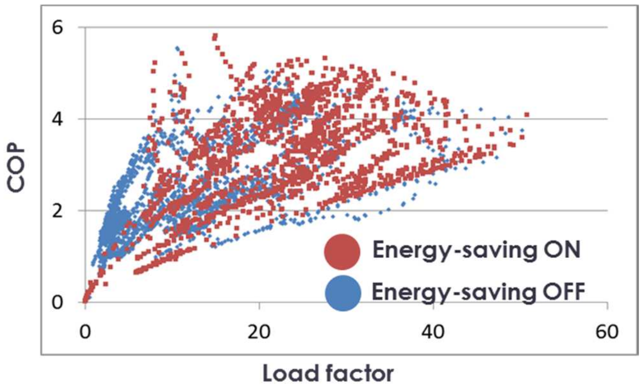


Fig. 22. COP and load factor in Sagami.

Table 5. Experimental results of energy-saving controls

Outdoor unit	Energy-saving ON			Energy-saving OFF			CO_2 reduction amount	Reduction rate
	Electric energy (kWh)	Outside TEMP. (℃)	Room TEMP. (℃)	Electric energy (kWh)	Outside TEMP. (℃)	Room TEMP. (℃)		
AC1	16.3	9.1	28.7	12.1	8.6	27.9	2.0	25.8%
AC2	3.5	10.7	26.2	2.7	10.1	26.7	0.4	22.9%
AC3	3.5	9.7	28.5	2.7	10.8	29.3	0.4	22.9%

5.2. Estimation of CO_2 reduction amount

Annual production of VRF systems is shown in Table 6. World demand is growing rapidly whereas Japan's demand is almost flat at about 130 thousand units according to The Japan Refrigeration and Air Conditioning Industry Association.

Table 6. Annual production of VRF systems

Year	2012	2013	2014	2015	2016
World total	994,000	1,104,000	1,180,000	1,156,000	1,312,000
Japan	125,000	126,000	134,000	129,000	131,000

Equations are shown in (7) to (11) for the CO_2 reduction amount calculation. Values used for the calculation are shown in Table 7. The full load equivalent operating time is 635 h/year in cooling operation and 500 h/year [9] in heating operation, and CO_2 conversion factor is 0.486 kg-CO_2/kWh. Also, we consider electric air conditioners with 36 kW-capacity (cooling rated power consumption 11.9 kW, heating 10.2 kW) for the calculation. Based on the result of energy-saving controls, it is calculated with a reduction rate of 20%. Additionally, reduction due to building renewal is not included and we consider the average lifespan of an air conditioner as 15 years [10]. Annual CO_2 reduction amount per unit will be 1.2 tons.

635 h/year * 11.9 kW = 7569.2 kWh/year (Cooling operation) (7)

500 h/year * 10.2 kW = 5095 kWh/year (Heating operation) (8)

7569.2 kWh/year +5095 kWh/year = 12664.2 kWh/year (Power usage) (9)

12664.2 kWh/year * 0.2 (20% reduction) = 2532.8 kWh/year (10)

2532.8 kWh/year * 0.486 kg-CO_2/kWh = 1.23 t-CO_2/year (11)

Table 7. Values used for the CO_2 reduction amount calculation

Operations	Cooling operation	Heating operation
Full load equivalent operating time	635 h/year	500 h/year
Air conditioning capacity (EHP 36 kW)	11.9 kW	10.2 kW
Reduction rate	20 %	
CO2 conversion factor	0.486 kg-CO2/kWh	

Accordingly, CO_2 reduction amount in 2018, 2025 and 2030 are estimated. The results are shown in Table 8 and (12) to (14). The predicted number of this device will be 13 thousand units in 2018, 468 thousand units in 2025 and over 1 million units in 2030 as we assummed 10% of the annual production in 2018 and 100% in 2027 (10% increases every year). As a result, the total CO_2 reduction amount will be 15 thousand t-CO_2 in 2018, 561 thousand t-CO_2 by 2025 and over 1.3 million t-CO_2 by 2030.

1.2t-CO_2/year * 13000 = 15600 t-CO_2 (12)

1.2t-CO_2/year * 468000 = 561600 t-CO_2 (13)

1.2t-CO_2/year * 1105000 = 1326000 t-CO_2 (14)

Table 8. Estimation of total CO_2 reduction amount

Year	2018	2025	2030
Predicted spread number of the system	13,000	468,000	1,105,000
CO_2 reduction amount/year/unit	1.2 t-CO_2	1.2 t-CO_2	1.2 t-CO_2
Total CO_2 reduction amount	15,600 t-CO_2	561,600 t-CO_2	1,326,000 t-CO_2

6. Conclusions

We discussed the development of an onsite performance evaluation method of VRF systems and approach to energy conservation. Our major conclusions are:

- The onsite performance evaluation method which calculates in real-time and with high accuracy within 10% was developed using the CC method.
- The field data analysis revealed various problems including low load and low efficient operations, inappropriate temperature settings, unnecessary operations, excessive installed capacities and a short circuit.
- The information providing method through mobile devices and computers were illustrated. Examples of advice and messages to users, building operators and designers using the Nudge theory were demonstrated.
- Energy-saving controls were carried out and CO_2 reduction amounts were obtained. Our estimation is 15,600 t-CO_2 in 2018, 561,600 t-CO_2 by 2025 and 1,326,000 t-CO_2 by 2030.

This study will definitely lead to energy conservation in the building sector and contribute to CO_2 reduction. In the next phases of this project, we intend to use this system as an energy censor of an indoor environment which improves air conditioning operations.

Acknowledgments

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Nomenclature

G refrigerant mass flow, kg/s

H specific enthalpy, kJ/kg

N compressor revolution, rps

Q capacity, kW

V compressor displacement, m^3/rev

Greek symbols

η volumetric efficiency

ρ density of refrigerant, kg/m^3

Subscripts

c condenser

comp compressor

e evaporator

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