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Operation Results and Utility of Dynamic Pricing Response Control-Applied VRF System in Summer Season

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Abstract Dynamic pricing refers to a system in which a tariff varies, according to a level of charging and applied time depending on time change. The power billing system used in the Korean Electric Power Corporation (KEPCO) is based on time of use (TOU) pricing, which is one of the dynamic pricing systems. This paper aimed to determine the operational results of a variable refrigerant flow system, to which a new control algorithm was applied, in order to respond to dynamic pricing, in summer and the utility of the new control. To do this, real measured data was acquired from a VRF system installed in a building for educational purposes, where dynamic pricing was applied for about 100 days during summer time. At the maximum load operation time period in TOU, the new control minimized operation within the indoor comfort range, an increase in refrigerant evaporation temperature in the indoor unit and the number of revolutions in a compressor in the outdoor unit was limited. As a result, power usage was decreased by 11%, and the operational cost by 14.6%. Furthermore, measurement results using the Predicted Mean Vote (PMV) model, that represented satisfaction of thermal environment, showed that 82.8% to 90.4% of the occupants of the building were satisfied during operation when the new control was applied.

Keywords: TOU (Time of Use), VRF system, Field Measurement, Energy Consumption

1. INTRODUCTION

1.1 Background and objectives of the study

Dynamic pricing refers to a billing system that varies charging level and applied time according to various conditions and circumstances, particularly time change. It can be divided into time of use (TOU), critical peak pricing (CPP), and real time pricing (RTP) according to a type of tariff scheme. Among them, the TOU pricing scheme divides a day into the maximum load time periods and non-maximum load time periods, and then applies a different tariff scheme according to power usage at the supplied time. In the maximum load time periods, a relatively higher tariff, and in the non-maximum load time period, a lower tariff than normal the power price is applied (Ashan, 2016, Kwon, 2010) The power tariff scheme used in Korea calculates a power charge based on the TOU scheme by combining a basic charge, which is contracted between KEPCO and the user based on the maximum demand power, and tax and power industry basis fund according to monthly usage.

Furthermore, KEPCO applies a different charge rate by season and load time period based on contracted power according to the building purpose on the basis of a single charge system, where a mean cost of power supply is applied equivalently to all time periods. KEPCO classifies buildings by building purpose to apply the power charge scheme. For example, buildings for educational purpose are divided into “A” and “B,” based on contracted power of 1,000kW, so that a different power charge is applied. The contracted power of most buildings in universities among educational purpose buildings is more than 1,000kW, and dynamic pricing according to the contracted power varies up to 3.5 times of the charge difference.

In general, buildings in universities are divided into lecture and research rooms, and since a cooling and heating operation time is not regular, an operation using a central heat source is inefficient. Thus, a variable refrigerant flow (VRF) system, which is a distributed heat source, has been widely employed, and an operating time and indoor setting temperature are limited to

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prevent an increase in operating costs and power usage due to excessive cooling and heating operations.

The present study has conducted research on actual buildings to investigate a performance of a newly developed dynamic pricing response algorithm (hereafter referred to DPR control), for the purpose of response to the TOU tariff scheme. Furthermore, the present paper is a follow-up to a study conducted by Kim (2015) in which was performance verification on the DPR control during winter period was studied. A different charge rate is applied between summer and winter seasons in the TOU tariff scheme. Thus, it is necessary to understand seasonal characteristics of the scheme. In this regard, the present study aimed to determine the energy usage and reduction effect of operating cost in the VRF system where new controls were applied through actual measurements during summer period, thereby presenting the analysis results and evaluation results due to the thermal environment.

1.2 Trend of existing research

A number of studies have been conducted on various control methods, for not only satisfaction on comfort felt by occupants, but also saving energy. Existing VRF control systems had limitations to satisfy the comfort of occupants since they employed a temperature control method of an indoor setting, and did not consider the control of occupants increasing energy usage, resulting in raising operating costs. To resolve this problem, a number of studies have been conducted on the development of a control algorithm of VRF systems, considering changes in temperature, humidity, and air flow, which were related to the indoor thermal environments among many factors that affected the comfort of the occupants. In a study on the development of cooperative comfort control algorithm for VRF systems by Kim (2011), temperature, humidity, and air flow were set as control variables, and a method that was controlled based on an index of comfort assessment and a percentage of dissatisfied value was discussed. In the present study, air conditioning control was conducted by reversely calculating a temperature, humidity, and air flow data when indoor conditions, measured through sensors, departed from a comfort range, and energy saving was induced via a method that maintained a current condition when indoor conditions were within the comfort range without running air conditioning control.

A comfort control algorithm, proposed by Moon (2015), calculated initial temperature and humidity conditions that can reach a thermal comfort range during cooling operation first through simulations. Afterward, Moon conducted a study on a method that executed a cooling operation to reach a calculated comfort range according to an indoor condition, which was located in one of three regions: a cooling region, a cooling and humidification region, and a humidification mode region.

A study on VRF system by Kim (2011) considered three factors such as temperature, humidity, and air flow, which were controllable in an air handling unit (AHU) among six environment factors in the PMV proposed in ISO 7730. There was a study on the development of a control algorithm by setting a comfort region in summer, after quantifying the above factors through survey of 36 occupants in a test chamber by changing the factors.

As described in the above, most existing studies developed control algorithms based on comfort regions, and focused on the induction of improvements on comfort and energy savings, by concentrating on the comfort feelings of occupants. In contrast, the DPR control applied in the present study is characterized by the development of a control algorithm to respond to the TOU dynamic pricing scheme employed in Korea, while satisfying the thermal comfort felt by occupants.

2. OVERVIEW OF DPR CONTROL

The DPR control consists of an indoor set temperature control, a maximum value control of revolution in inverter compressor (hereafter referred to as current limit), and a temperature control of refrigerant evaporation in indoor unit (hereafter referred to as refrigerant temperature control). Fig. 1 shows a conceptual diagram of the DPR control during summer operation, in which changes the indoor temperature and operating characteristics according to the DPR control are presented.

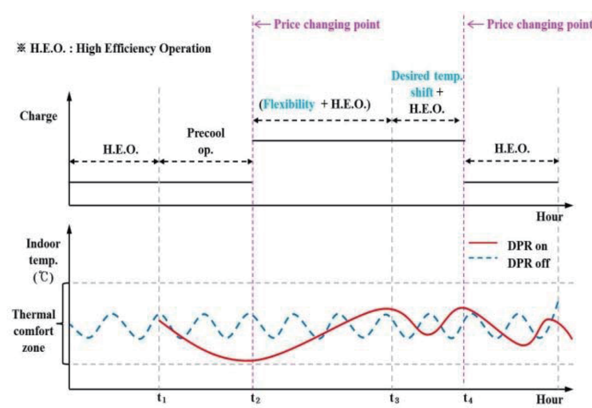

Figure 1. Conceptual diagram of DPR control during summer period

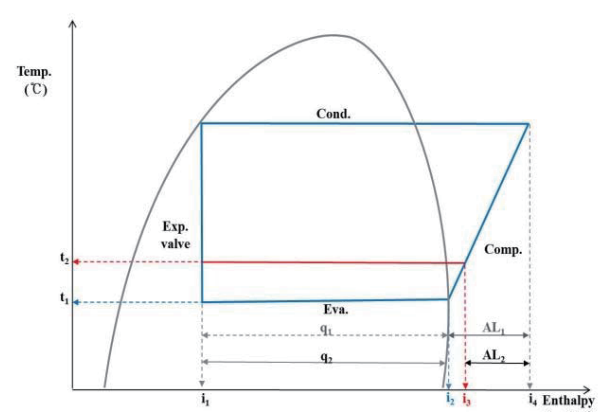

Figure 2. Changes in cooling cycle according to DPR control

$$AL_1 = i_3 - i_2 \quad AL_2 = i_3 - i_2$$

$$COP = \frac{q}{AL_1} < \frac{q}{AL_2} \tag{1}$$

First, during DPR-off operation, indoor temperature refrigerant temperature, and the number of revolutions of the compressor have the same values for daily operation times. However, a pre-cooling operation is conducted to lower the indoor set temperature lower than the reference temperature prior to a section of increasing power charge rate t_1–t_2 in Fig. 1, that is, the maximum load time period during DPR-on operation. Afterward, operation is temporarily suspended from t_2, but it is followed by a resulting distribution peak load, as indoor heat capacity due to pre-cooling resulted in a time lag(Lee et al., 2012, Lim et al., 2016). A cooling operation is re-started as soon as the comfort temperature range is not in the range after an indoor temperature is raised due to suspended operation. As described in the above, the characteristic of the DPR operation is to induce a reduction in energy usage in the VRF system through increasing a suspension time of cooling operations in the maximum load time period, and controlling an indoor temperature within a comfort range (hereafter referred to as flexible operation). Finally, an operation is back to normal from t_4 when an electricity charge rate is decreased.

Next, a high efficient operation is executed through current limit and refrigerant high-pressure control in the compressor in all sections, except for pre-cooling operation section during DPR control. The current limit is to control the maximum of number of revolutions in the inverter compressor within 100% to prevent an excessive number of revolutions in the compressor. The maximum value of the number of revolutions responds to the indoor load, and is operated in connection with the refrigerant temperature control. A refrigerant of higher temperature than the temperature of the existing refrigerant evaporation is fabricated in response to the indoor loads, through refrigerant temperature control. This is a control method utilizing an effect of reduction in the height of the cooling cycle, followed by increasing in the coefficient of performance(COP) in the VRF system as a refrigerant temperature increases as shown in Fig. 2. Equation 1 presents a comparison on each of COP according to refrigerant evaporation temperature.

3. TARGET BUILDING AND OPERATION METHOD

To verify the effect of the DPR control, actual measurements on a real building were collected, and the International Performance Measurement and Verification Protocol (IPMVP) Volume Ⅰ - Option C was applied. The IPMVP is an international protocol that proposes measurement and verification methods and standards on energy performance objectively. It is classified into Option A, B, C, and D according to characteristics and circumstances of the applied target. The present study targeted an overall system whose measurement scope was ranged from an indoor thermal environment, an indoor unit, and outdoor unit with the controller in the target building. Thus, it followed the standards in Option C.

The target building for performance evaluation on the control algorithm was a two-story building whose total floor area was 3,005m^2. It consisted of lecture rooms, laboratories, staff rooms, and research rooms for graduate students in G University, located in Tongyeong-si, Gyeongsangnam-do, Korea. The contracted power was 4,200 kW, and the following charging scheme was applied due to the TOU pricing scheme: high pressure A for educational purpose (B) and option 2. The power unit price and applied time during summer period are presented in Table 1.

The DPR control was operated every two days because the target building with the same condition could not be found. That is, the DPR control was activated on odd days while the DPR control was deactivated on even days and` normal operations were conducted (hereafter referred to as DPR on operation and DPR off operation). The reason for the alternating operation was to minimize the difference in operational characteristics due to outdoor conditions and operations during weekends and public holidays, regardless of the application of the DPR control, compared to operations divided on a weekly and monthly basis.

Fig. 3 shows an exterior of the building and floor plans of the ground and first floors. The existing VRF system consists of outdoor units of 87kW, 93kW, and 97kW capacity, and a total of 39 indoor units of 1-way and 4-way cooling operations.

To apply the DPR control algorithm to the VRF system in the target building, new controllers were installed as shown in Fig. 4 and power usage was measured according to whether the DPR control was applied or not through the power meter.

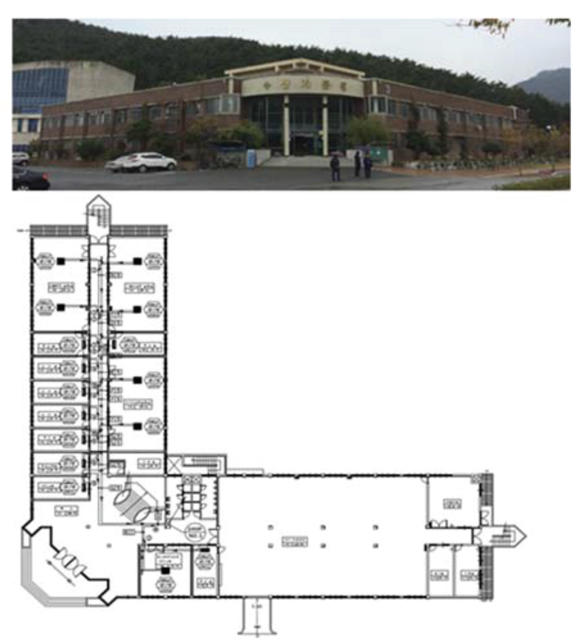

Figure 3. Exterior of the building (top) and 1st floor plan(bottom)

Figure 4. Current status of DPR controller installation

Table 1. TOU applied time and power charge rate during summer and intermediate season

Demand Charge (KRW/kW)	Energy charge(KRW/kWh)		
	Time period	Summer (Jun.~Aug.)	Fall (Sep.~Oct.)
6,980	off peak load	45.3	45.3
	mid load	90.0	59.7
	peak load	155.9	80.2

Table 2. Operation conditions during summer period

	Operation	Indoor temp	Refrigerant temp.	Current limit
DPR on	Odd days	25±1℃	Variable (8,11,14℃)	Variable (50~100%)
DPR off	Even days	25℃	Fixed (8℃)	Fixed (100%)

Table 3. Measurement items of data and intervals

Division	Indoor unit	Outdoor unit	Watt-hour meter	Others
Data measuring items	Indoor setting temp.	Partial load ratio	Electricity	Operation time of indoor unit
	Evaporator in and out temp.	Current limit ratio		
	Upper limit temp. of heating	COP		Thermo on time
	Lower limit temp. of cooling	Outdoor temp.		
Measuring interval	5 min.	5 min.	30 min.	1 Day

In the target building, cooling operations were performed from 08:00 to 24:00 on weekdays and weekends, and Table 2 presents operational conditions in summer according to whether the DPR control is applied or not. The indoor reference temperature during DPR operation was set to 25℃, that in pre-cooling was set to 24℃, and that during the maximum load operation time period it was set to 26℃, respectively. Furthermore, a current limit that affected the number of revolutions in the compressor directly was set to 50%–100%, and the refrigerant temperature was controlled to 8℃, 11℃, and 14℃ in response to indoor loads, respectively. In contrast, an indoor set temperature during DPR non- operation was set to 25℃, and current limit and refrigerant temperature control were set to fixed values as 100%, and 8℃. The measurement items of the collectors of data were indoor unit, outdoor unit, and power meter. The indoor and outdoor units were measured every five minutes, and power meter was measured in every 30 minutes. Table 3 present the measurement and data and intervals in detail.

4. OPERATION RESULTS AND ANALYSIS

DPR on and off operations were conducted for 101 days, from June 22 to September 30 in 2015 in the target building. The numbers of DPR on and off operation days were 51 and 50 days, respectively.

4.1 Measured results according to operation mode and discussion

Table 4 presents overall operation results during the summer season. The "operating time of indoor unit", which is one of the items in the table, refers to a time of cooling operations in residential space by occupants in each room, which combines the hours of all 30 indoor units. The "thermo on time" refers to the operational time of outdoor unit during cooling operation time of the indoor unit, which combines the hours of all 39 indoor units. The VRF system is structured with a single outdoor unit connected to multiple indoor units, in which indoor units without flow of refrigerant are found according to indoor load conditions, even if outdoor units were under operation.

Table 4. Measurement results during summer season

Division	DPR on	DPR off	Δ**	Saving rate(%)***
Electricity(kWh)*	7,252	8,155	903	11.1
Operation cost (10^3KRW)*	768	899	131	14.6
Operation time of Indoor unit(hour, A)	9,914	9,836	-78	-0.8
Operation time of Outdoor unit(hour)	1,215	1,245	30	2.4
Thermo on time (hour, B)*	5,244	5,812	568	9.8
Thermo on ratio (B/A,%)	51.0	55.6	4.6	8.2
COP	2.9	2.7	-0.2	-8.3
Indoor partial load(%)	40	42	2	-
Outdoor temp.(℃)	24.6	24.5	-0.1	-
Indoor temp.(℃)	26.0	25.8	-0.2	-
Current limit ratio(%)	58.4	100.0	-	-
Refrigerant temperature limit(℃)	11.9	8.0	-	-

*: Sum value of 36 days and others are mean value at each operation
**: Value of DPR off – DPR on
***: (Δ/DPR off value) × 100(%)

The thermo on time was to determine this. In addition, the "thermo on ratio" refers to a ratio of refrigerant circulation in each of the indoor units during cooling operation time, which is calculated by dividing the "thermo on time" by the "operating time of indoor unit". The operating time of outdoor unit also combines all operating hours of three outdoor units.

First, a mean outdoor temperature during 08:00 to 24:00 during cooling operations was 24.6℃ in DPR on operation, and 24.5℃ during DPR off operations, which indicated a difference in temperature between two operation modes of 0.1℃. This result is regarded as no significant difference in load according to outdoor temperature during the measurement period, as each of the operations were conducted under similar outdoor temperature conditions. Furthermore, the operating time of indoor unit was 9,914 hours during DPR on operations, and 9,836 hours during DPR off operations, which was nearly the same. That is, there was no significant difference in the cooling operational time overall in summer regardless of whether DPR controls were applied or not.

The power usage for the 50 days when DPR on and off operations occurred were 7,252kWh and 8,155kWh, and operating costs were 768,592 KRW and 899,591 KRW, which indicated that power usage and operating cost during DPR on operations were reduced by 11.1% and 14.6%, respectively compared to that during DPR off operation. During DPR on operations, the operating time of the outdoor unit was reduced by 2.4%, which was influenced by the DPR control characteristic that suspended the operation of the outdoor units temporarily during the maximum load operation time period. As a result, it influenced the reduction in power usage accordingly. A reduction rate of operating cost was 3.5% higher than that of the corresponding power usage. The reason for this was because operations were limited during the maximum load time period whose power charge rates were higher.

Furthermore, current limits and mean refrigerant temperatures during DPR on operation days were 58.4% and 11.9℃, and those during DPR off operation days were 100% and 8℃. Moreover, the COP during DPR on operation periods were 2.9, which was improved by 8.3% compared to 2.7 during DPR off operations. This was because highly efficient operations can be achieved with a refrigerant of high temperature that was increased by 3.9℃ and a reduction in power usage in the compressor due to about 40% reduced current limit thereby increasing the COP.

4.2 Results on DPR operation characteristics

In this section, the characteristics of DPR control operations are discussed, except for shortening the operating time of the outdoor unit according to DPR on operations, which was discussed in the above section. Fig. 5 shows refrigerant control temperatures according to whether DPR control is applied or not, and changes in refrigerant temperature accordingly.

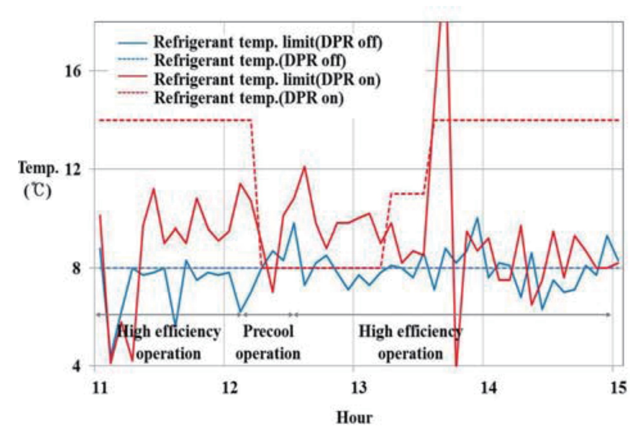

Figure 5. Changes in refrigerant temperature according to refrigerant temperature control

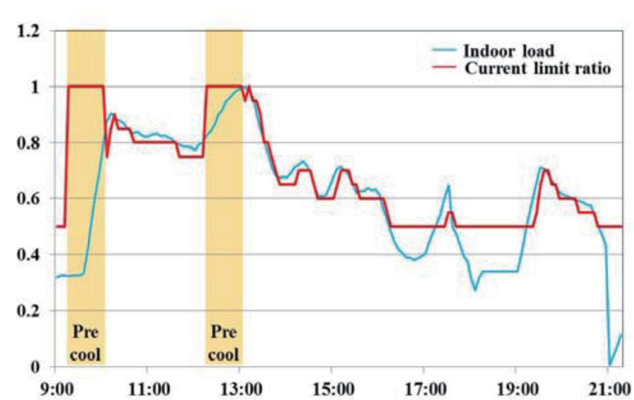

Figure 6. Setup of current limit ratio in the compressor according to indoor loads

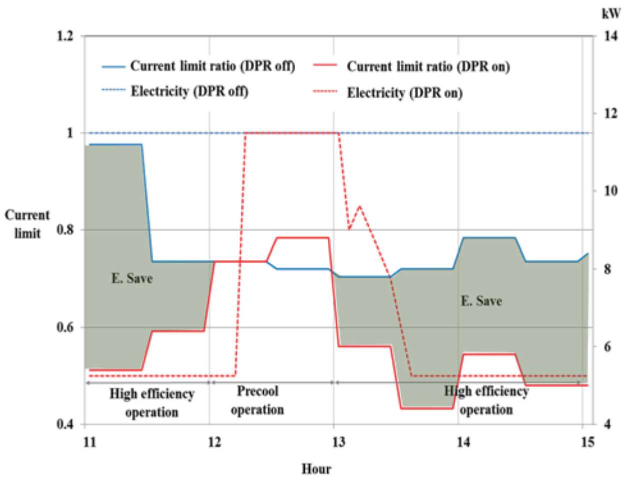

Figure 7. Current limit according to operation and comparison on power usage in compressor

The refrigerant control temperature during DPR off operations was 8℃, and actual refrigerant was fabricated to have a temperature around the control value. In contrast, a refrigerant temperature during DPR on operation was changed to 8℃, 11℃, and 14℃, and a refrigerant temperature was also changed accordingly. Thus, actual the refrigerant was fabricated to have a temperature of around 10℃ on average.

As described in the above, the number of revolutions in the compressor was set to 100% during the pre-cooling time period in DPR on operations regardless of indoor loads, and the current limit was controlled at 50% to 100%, in accordance with the indoor load at other periods of time. Fig. 6 shows a current limit ratio in the compressor calculated according to the indoor loads. Furthermore, the shaded part in Fig. 7 shows the current limit ratio and the comparison on power usage in the compressor refers to a reduction in power usage consumed in the compressor due to the current limit.

4.3 Measurement results of thermal environment

Table 5. PMV and PPD results

Operation Mode	DPR On		
Date	Aug.7th	Aug.9th	Aug.11th
PMV	0.76	0.53	0.47
PPD(%)	17.2	10.9	9.6
Operation Mode	DPR Off		
Date	Aug.8th	Aug.10th	Aug.12th
PMV	0.59	0.32	0.11
PPD(%)	12.3	7.1	5.3

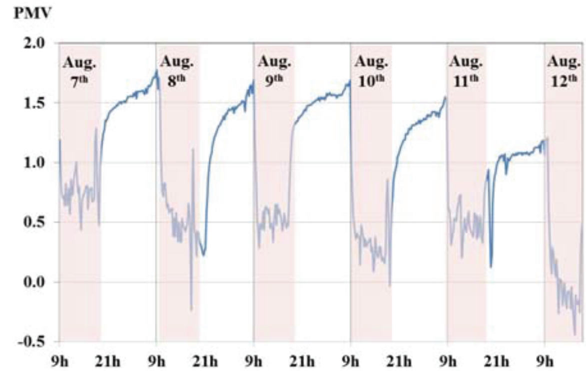

Figure 8. PMV value by operation

The indoor temperature measured during summer period was 24.6℃ during DPR on operations, which was increased by 0.1℃ compared to that of DPR off operations, which was 24.5℃. This was due to the flexible operations during the maximum load time as a result of the characteristics of the DPR control. Only the indoor temperatures were measured at the target building where the VRF system was applied. Since the measured indoor temperature was calculated by compensating a measured temperature in the indoor unit at the ceiling or controller attached to the side wall, it is unreasonable to evaluate an accurate thermal environment with these measured indoor temperatures. Thus, the thermal comfort of the occupants was measured separately using the PMV kit. The measurement period was from August 7 to 12, for six days, and PMV and the predicted percentage of dissatisfied (PPD) in Fig. 8 and Table 5 were created using the data measured between 09:00 and 17:00, which were normal business hours. According to a regulation range in the PMV of ISO 7730 and ASHRAE, when a PMV value was -0.5<PMV<0.5, 90% of occupants were satisfied, and when it was -0.85<PMV<0.85, 80% of occupants were satisfied(ASHRAE, 2013, ISO-7730). Based on this, the PPD was calculated using measured PMV values and Equation 2.

$$PPD = 100 - 95^{-(0.03353 \times PMV^4 + 0.2179 \times PMV^2)} \quad (2)$$

A daily mean of PMV during DPR on operations was 0.47–0.76 and that during DPR off operations was 0.11–0.59, which indicated that PMV during both operations were distributed within a range of 0 to +1. Furthermore, the satisfaction rate of thermal environments felt by occupants using PPD was 82.8–90.4% during DPR on operations, and 87.7–94.7% during DPR off operations, which indicated a satisfaction rate was decreased by about 4.5% by DPR control.

5. CONCLUSION

In this study, the DPR control was developed to reduce power usage and operating cost in the TOU tariff scheme where a different power charge rate was applied by load time period, and its operating results and utility were investigated after it was applied to an actual building. To do this, actual measurement data collected at an educational facility in a university where the VRF system was applied for 101 days during the summer operation period were utilized.

During DPR on operations, the indoor areas were pre-cooled prior to entering the maximum load time period, and then a method that reduced the operating hours of the outdoor units as much as possible through the flexible operation was employed, and techniques of current limit that controlled the number of revolutions in the compressor of the outdoor units, and increase refrigerant temperature in the indoor units to improve the COP of the equipment were applied. As a result, power usage and operating cost were reduced by 11.1% and 14.6%, respectively.

However, the problem of reduction in the satisfaction rate of indoor thermal environments due to flexible operation remained as the future research task. This is because a useful aspect of energy saving can only be valid only if energy saving does not negatively affect the indoor thermal environment. For the future study, a building size and purpose where the DPR on operation is useful will be identified, and a regression analysis will be conducted utilizing measured data obtained at the target building to extend the application of DPR control as well as the effect will be investigated.

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