Application of the thermal comfort index as a control logic of VRF system and analysis of its performance by field measurement

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Abstract. Variable refrigerant flow (VRF) systems are known for their high energy performance and the installation of VRF systems in buildings is increasing. However, most studies have focused on improving the mechanical efficiency of VRF systems and there has been little research on energy efficient control strategies considering the thermal comfort of occupants. In this study, the application of the thermal comfort index as a control logic of VRF system was analyzed by field measurement. Indoor thermal environment and energy consumption characteristics according to control strategies such as set-point temperature and thermal comfort range in VRF system were analyzed. In this paper, the system configuration and the measurement results will be described.

1. Introduction
According to the Korea Meteorological Administration, in Korea, the average number of heat waves in 2018 was the highest 31.4 days since 1973 and it recorded the highest temperature in most regions of Europe as well as in Asia including Korea. [1]. It is becoming difficult to spend the summer without the cooling system, and as the outdoor temperature gradually rises during the summer, the cooling load increases, which is concerned about excessive use of energy due to cooling operation. Among the cooling systems, the Variable Refrigerant Flow (VRF) system is a multi-heat pump that connects a number of indoor units to a single outdoor unit and controls the flow rate of refrigerant for cooling or heating using the Electronic Expansion Valve (EEV) [2]. The VRF system has the advantage of reducing energy consumption by about 30 to 40% compared to Variable Air Volume (VAV), which is the central air-conditioning system [3]. In addition, VRF systems are widely used for cooling and heating of small-medium-sized buildings such as schools, offices and hospitals due to ease of responding partial loads, control of each zone and ease of installation. The VRF system market of Korea is growing with an annual growth rate of 15 to 20% and VRF system market is growing globally with about 24% of VRF system in global commercial air-conditioning market as well as in Korea [4, 5]. Accordingly, the use of the VRF system is concerned about increase of the energy consumption. In order to prevent excessive consumption of energy from using the VRF system in buildings during summer, there is a regulation limiting indoor set temperature. In Korea, indoor cooling temperature is regulated at 26°C or higher and indoor cooling temperature is regulated at 28°C or higher in public
institutions for building energy conservation and reasonable use [6]. However, although regulating the indoor set temperature may reduce the excessive energy consumption according to the use of the VRF system, cannot ensure the comfort of occupants.

Agneiyay, S. et al. [7] referred that increased cooling set-point temperature could reduce energy consumption but negative impacts of potential thermal discomfort from increased cooling set-point might include fatigue and sleepiness as well as decreased productivity. There is not specific point where occupants start to feel thermal discomfort when increasing the cooling set-point and people could feel thermally comfortable when considering temperature, humidity, airspeed, etc. Park et al. [8] studied that the set indoor temperature was changed to 26°C and 27°C in the office where the VRF system was installed to analyze comfort sense by occupants’ survey. When changing the room set temperature from 26°C to 27°C, the energy consumption decreased by 3.7% but the rate of the comfort of the occupants decreased by 10%. Increased indoor cooling set temperature can reduce energy consumption, but it can cause thermal discomfort of occupants because the occupants feel hot according to increasing indoor temperature. Therefore, it is necessary to control the VRF system considering the two aspects together, which are energy saving and thermal comfort.

Therefore, the method of control the VRF system using thermal comfort index was studied to consider the energy saving and thermal comfort. There is a method of controlling the indoor environment by using PMV (Predictive Mean Vote), which is an index of the thermal comfort in numerical range suggested by P.O. Fanger [9]. Most studies have proposed the PMV control that the indoor set temperature was calculated using the factors(mean radiant temperature, relative humidity, air velocity, clothing insulation and metabolic rate) that determine the PMV value based on reverse equation[10, 11]. However, the control method using PMV, a typical thermal comfort index, has the disadvantage of having a large number of necessary data and complicated computational processes. In addition, the PMV controls from the literature reviews resulted that although the thermal comfort of occupants was satisfied, the effect of energy saving was not obvious compared to the conventional set temperature control because the comfort indoor temperature was recalculated by reverse equation.

In addition to the PMV, a method of controlling the VRF system according to the comfort zone in the psychrometric chart has been suggested. The indoor temperature and the humidity are controlled to be maintained in the comfort zone defined by ASHRAE[12]. Kim et al. [13], Moon et al. [14] proposed a control method in three modes according to the indoor environment condition by setting a comfortable range based on the new standard effective temperature (SET *) and the relative humidity. R.Z. Freire et al. [15] proposed control method by optimizing the comfort range based on dry bulb temperature and relative humidity.

However, the control methods by thermal comfort index in literature reviews are insufficient for the control method in actual buildings because the control method has been mainly verified through the simulation tool or the experiment in the testbed. Therefore, in this study, we propose a control algorithm based on a thermal comfort index that can be applied to a VRF system installed in actual building and the effect of thermal comfort improving and energy saving is analyzed compared to the set-point control which is a conventional control method of VRF system. The significance of this study is as follows.

First, based on the ASHRAE comfort zone, we developed a comfort control algorithm by deriving the comfortable range that the occupants feel comfortable through experiment. In ASHRAE, indoor comfort ranges of summer and winter are suggested based on operative temperature and humidity ratio [12]. The comfort control algorithm based on the ASHRAE comfort zone does not require a lot of data and it can be intuitively controlled according to the indoor environment condition without complicated calculation processes. Therefore, it is easy to apply to the actual VRF system. Second, we applied the comfort control algorithm to the actual VRF system using IoT technology and monitored the information of the indoor temperature, humidity and the energy consumption according to use of the VRF system through the remote management system. The application of the comfort control algorithm to the VRF system using IoT technology will be a method for efficient energy management as well as maintaining a comfort indoor environment of the building.
2. Control algorithms

2.1. Set-Point Control

Set-point control is a general method to control VRF system. Based on a certain temperature, supply air temperature and airflow rate are controlled. In this study, the set-point temperature is tested at 25°C. The set-point temperature reflects the results of preliminary survey on thermal and comfort sensation of occupants.

Figure 1 and Figure 2 are graphs showing the survey results of thermal sensation votes (TSV) and comfort sensation votes (CSV) under the control of set-point temperature of 26°C and 25°C. In set-point 26°C control, occupants in the target space responded at a rate of 47% to 'discomfort', which was higher compared to set-point 25°C control. The reason for the increased discomfort in set-point 26°C control is that the ratio of 'hot' is increased by 18% compared to set-point 25°C control.

Therefore, in this study, the indoor set temperature of the set-point control was set to 25°C considering the aspect of occupants’ comfort based on the evaluation results of thermal sensation and comfort sensation.

![Figure 1. TSV according to set-point temperature](image1)

![Figure 2. CSV according to set-point temperature](image2)

2.2. Comfort Range Control

When comfort range control algorithm based on ASHRAE comfort zone in summer (operative temperature 24-27°C, humidity ratio 0.012 kg/kg’ below) is applied to actual VRF system, the system uses only dry bulb temperature as the control variable. So it difficult to reflect indoor humidity change in control in real time. Therefore, only the operative temperature was considered as the control variable of the comfort range control algorithm applied to the actual VRF system in this study and the operative temperature range of 25-26.5°C was derived from the experiment of the subjects. In addition, the blowing mode was applied to generate airflow by operating only indoor units without operating the outdoor unit according to the control range in order to maintain occupants’ comfort and save energy consumption. The outline of the comfort range control algorithm proposed in this study is as follows.
2.2.1. **Control variable: operative temperature.** The operative temperature is an index that comprehensively considers the effects of dry bulb temperature, air velocity and radiant temperature. Since the existing VRF system recognizes only the dry bulb temperature as the return air temperature, the calibration value for dry bulb temperature was derived through preliminary experiments. Figure 3 is a graph showing the measured dry bulb temperature, the calculated mean radiant temperature and the operative temperature by Box Plot. Based on these results, a calibration value of dry bulb temperature + 0.5°C was derived.

2.2.2. **Control range.** T. Hoyt et al. [16] referred that indoor environments controlled to narrow temperature ranges do no result in higher occupant satisfaction than environments with wider ranges. Based on the ASHRAE comfort zone in summer (operative temperature 24-27°C) The control algorithms were derived by setting the lower and upper limits of the control range reflecting the evaluation results of occupants’ thermal, comfort sensation and PMV calculation. As a result, the control range is 25-26.5°C of operative temperature.

2.2.3. **Blowing mode.** Air movement has significant cooling effect, which encourages the use of elevated air speed to widen the acceptable range of thermal conditions [17]. In warm environments, air movement has the potential to conserve energy while maintaining occupants' comfort [18]. Therefore, in this study, the blowing mode was applied when the indoor operative temperature reaches at 25°C, only the indoor unit operate without the outdoor unit until at 26.5°C according to the control range. When the indoor operative temperature reached at higher than 26.5°C, outdoor unit operate again for cooling.

3. Field measurement

3.1. **Target space**
In this study, the control algorithms were equipped in the VRF system installed in the office space of Asan central library in Korea. Table 1 summarizes the target space to be tested. The floor area is about 260m² and the VRF system consists of one outdoor unit and four indoor units. The total number of occupants is 18 including 5 men and 13 women.

![Figure 3. Box plot of indoor environment](image)
3.2. System configuration

The application of control algorithm to VRF system and the outline of remote management system are as shown in Figure 4. The control system consists of sensors and VRF systems based wired/wireless, Internet of Things (IoT) server and Direct Digital Control (DDC) controllers. The DDC controller sends and receives various data such as temperature, humidity of space and power of VRF system as well as controls the VRF system. IoT server saves and analyzes data collected through DDC controller based on Building Automation and Control Networks (BACnet).

In this study, The DDC controller is connected to existing VRF system installed in building, and the comfort range control algorithm is applied. The DDC controller send control signals to the VRF system through Modbus RS485 communication mode and receive data of system, indoor environment (temperature, relative humidity) and energy consumption of VRF system. Through IoT server, the VRF system is controlled, the status of the system is monitored and the collected data is analyzed. In addition, remote control of VRF system in the target space is made possible in mobile environment by synchronizing mobile device such as tablet PC with IoT server PC.

Table 1. Information of target space

| Target building | Asan Central Library, 229, Nambu-ro, Asan-si, Chungcheongnam-do, Republic of Korea |
|-----------------|-----------------------------------------------------------------|
| Location        | Office on 4th Floor                                             |
| Size            | Area: 259.2m², Height : 2.7m                                     |
| Occupants       | Male 5, Female 13 (Clothing insulation 0.5clo, Metabolic rate 1.1met) |
| Schedule        | 08:00 ~ 20:00                                                   |
| System          | VRF System (Outdoor unit 1EA, Indoor unit 4EA)                  |

![Figure 4. System configuration](image)
3.3. Measurement conditions
In this study, the control cases which are set-point control and comfort range control were performed in the target space for about 3 weeks. The measurement conditions are shown in Table 2. Each case was tested under the same conditions except for control variables, control value / range and control mode. In consideration of the night time, the VRF system operated 4 indoor units from 8:00 to 18:00 and 2 indoor units from 18:00 to 20:00.

4. Analysis of results
4.1. Indoor environment
Figure 5 and Figure 6 show the change of the indoor air temperature and the EEV opening rate for each control method under the same weather conditions. The result shows that the indoor air temperature of each control changes according to the control value or control range. In Set-Point Control, indoor air temperature is maintained at 25°C ± 0.3°C. In Comfort Range Control, indoor air temperature is maintained at 25-26.5°C. Comfort Range Control is controlled to be about 1.0-1.5°C wider than Set-Point Control. It can be seen that the EEV opening rate also changes with the indoor air temperature. Since set-point control maintains the indoor air temperature at a constant temperature (25°C), the EEV opening rate changes frequently based on set-point value. In Comfort Range control, in order to lower the indoor air temperature from 26.5°C to 25°C, the EEV opening rate is larger than the Set-Point Control, but the EEV opening rate is not changed frequently because the indoor air temperature is maintained according to the range.

![Figure 5. Indoor air temperature according to Set-Point Control](image_url)
4.2. Thermal comfort

4.2.1. Surveying occupants. The surveying occupants is a result of thermal comfort felt by those who are working in a particular space, the target space. Table 3, Figure 7 show information of occupants such as the height, weight and age. The survey was conducted for each control and the occupants did not know about the control information and evaluated the indoor environment. The evaluation results of occupants’ TSV and CSV with Set-Point Control and Comfort Range Control are shown in Figure 8 and Figure 9. In the case of Set-Point Control, the results of the preliminary test(Set-Point 26°C) were also shown. In the results of TSV, the percentage of ‘neutral’ to the Comfort Range control was 53%, which is higher than the set-point control. In the results of CSV, 91% of respondents answered 'Comfortable' to Comfort Range control and the comfort sensation was improved compared to Set-Point control. The reason for the improved comfort sensation is due to the increase in the ratio of thermally neutral sensation. In the Set-Point Control, according to the constant temperature (25°C or 26°C), occupants feel ‘cold’ or ‘hot’ sensation. On the other hand, the Comfort Range Control has gradually increased or decreased the indoor air temperature according to the control range, so that the temperature range that the occupants can thermally accommodate has been widened, which means that the ratio of ‘neutral’ has increased.

4.2.2. PMV and PPD. The PMV and Predicted Percentage of Dissatisfied (PPD) were calculated based on the measured indoor thermal environment factors [19]. Figure 10 to 12 show the results of PMV and PPD of Set-Point Control and Comfort Range Control. PMV is distributed in the range of -0.5 ~ 0 in Set-Point 25°C and 0 ~ +0.5 in Set-Point 26°C. However, In the Comfort Range Control, PMV is distributed in the range of -0.5 to +0.5 and the range of PMV variation is wider than Set-Point Control.

4.3. Energy consumption

Figure 13 is a graph showing energy consumption and outdoor temperature according to use of VRF system. The average energy consumption is 26.67kWh/day for Set-Point Control and 17.72kWh/day for Comfort Range Control. Therefore, in the Comfort Range Control, it is shown that the energy can be reduced by about 34% compared to the Set-Point Control. The reason for the energy saving is that the ratio of operating the outdoor unit is reduced. In the Comfort Range control, only the indoor unit was operated without operating the outdoor unit according to the control range, thus saving energy compared to the Set-Point Control.
Table 3. Characteristics of occupants

|       | Number | Height     | Weight      | Position and Activity |
|-------|--------|------------|-------------|-----------------------|
| Male  | 5      | 170.5±6.5cm| 69.5±6.0kg  | Seated, typing        |
| Female| 13     | 160.2±10.0cm| 51.0±7.0kg  |                       |

Total response number 78

Figure 7. The age group of occupants

Figure 8. The results of TSV(Thermal Sensation Votes)

Figure 9. The results of CSV(Comfort Sensation Votes)

Figure 10. PMV and PPD of Set-Point 25°C

Figure 11. PMV and PPD of Set-Point 26°C
Figure 12. PMV and PPD of Comfort Range Control

Figure 13. Energy consumption and outdoor temperature

5. Conclusions

In this study, the control algorithm for thermal comfort and energy saving is applied to the VRF system and the validity of the control algorithm is verified through the field measurement. Based on the operative temperature by ASHRAE comfort zone, a comfortable range was derived from preliminary test and applied to the VRF system installed in the office space through IoT technology. The comparison and analysis of the conventional method of VRF system control (Set-Point Control) and the Comfort Range Control in this study were conducted in terms of indoor environment, thermal comfort and energy consumption. The results are as follow.

- In the Comfort Range control, since the indoor temperature is controlled according to the control range, the temperature range that the occupants can thermally accommodate has been widened, and the percentage of the occupants feeling thermally 'neutral' has increased. Compared to the Set-Point Control, in the Comfort Range Control, the blowing mode was possible to maintain occupants’ comfort sensation even under a relatively high temperature condition.
- As results of the energy consumption according to VRF system usage, energy consumption is less than Set-Point control in Comfort Range Control. The reason for this is that the indoor units only operate according to the control range.
- Based on the above results, when the Comfort Range Control algorithm purposed in this study is applied in actual VRF system, it is able to improve comfort by maintaining thermally neutral state because the indoor environment is controlled according to the temperature range. In addition, by reducing the operation of outdoor unit of VRF system, it is possible to save energy.
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