A Study on the Energy Saving Potential of Adaptive Temperature Control of a VRF System in an Office Building in Guangzhou

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Abstract. Under traditional VRF system control, room air temperature is maintained through multiple levels fan speeds (either user-specified or automatic), and regulating the opening of the electronic expansion valve based on the temperature difference between return air and the indoor setpoint temperature. This approach often requires a very low evaporating temperature, leading to energy wastage. Moreover, in regions like Guangzhou with hot summers and mild winters, keeping indoor temperatures excessively low during cooling seasons further increases energy consumption. To address these issues, this study proposes an adaptive control strategy for VRF systems based on automatically reset the supply air temperature, evaporating temperature, condensing temperature, and indoor temperature setpoints. Through a case study of an office building in Guangzhou, it demonstrates that the adaptive control leads to an energy savings of 34.74% compared to the existing control method.

Keywords: Variable Refrigerant Flow System, Adaptive temperature control, Energy saving.

1 Introduction

In today's society, efficient HVAC equipment alone is insufficient to achieve high levels of building energy performance, as control strategies play a crucial role[1]. With the rapid development of the VRF industry and the ongoing promotion of building energy conservation in China, "energy saving" has become a focal point of research in the field. The VRF air conditioning system, also known as the variable refrigerant flow direct expansion system, is a new type of air conditioning system characterized by its compact structure, flexible operation, high comfort levels, and energy-saving capabilities even during low-load operation[2]. Therefore, VRF air conditioning systems have been widely adopted in both commercial and residential buildings. Domestic sales of these products have exceeded 60 billion RMB, capturing over 50% of the centralized air conditioning market in China [3]. Therefore, reducing

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the actual operational energy consumption of VRF systems and enhancing their efficiency is crucial for advancing nationwide energy conservation efforts and achieving the goals of "peak carbon emissions and carbon neutrality" set by the country.

The control technology of VRF systems is complex. In order to achieve high level reduction in energy consumption during the operation of VRF air conditioning systems while ensuring the thermal comfort of indoor occupants, this paper proposes an adaptive temperature control strategies by automatically resetting the indoor air temperature setpoint, supply air temperature setpoint, evaporating setpoint and condensing temperature sepoint of the VRF air conditioning systems. The building and VRF system model were developed under the EnergyPlus environment and validated with the onsite energy consumption data. Then the energy consumption and under the new control strategy was obtained through simulation and compared with the existing energy consumption and the new control strategy was proved to be able to effectively reduce the building energy consumption and improve the overall system performace.

2 Method

The study focuses on an office buildings in Guangdong Province, located in the southern part of China, and characterized by hot summers and warm winter climate. EnergyPlus software is utilized to simulate the energy consumption of Variable Refrigerant Flow (VRF) systems during the cooling season. The study involves establishing relationships between indoor air temperature setpoint, supply air temperature setpoint, evaporating temperature setpoint, condensing air temperature setpoint and outdoor air temperature. To enhance the system energy performance, the study proposes optimizing the performance of VRF systems by optimizing the temperature of the refrigerant during the evaporation process (corresponding to the saturation temperature at the compressor suction pressure), and lowing the condensing temperature as possible, while the same time satisfying the occupants' thermal comfort.

Based on this energy-saving principle, the study utilizes the VRF simulation module developed within the building dynamic energy simulation software EnergyPlus to simulate the energy consumption of the baseline model. The research investigates the variation in energy consumption of VRF air conditioning systems in Guangzhou during the cooling season by considering the indoor air temperature, evaporating temperature, condensing temperature as they vary with the outdoor air temperature, using the enthalpy diagram of the vapor compression refrigeration cycle and known building cooling loads.

2.1 Energy consumption simulation principle of the VRF system

When using EnergyPlus to calculate the energy consumption of a basic model of a VRF system, it is essential first to model each component of the VRF system. This includes indoor units, outdoor units, condensers, evaporators, fans, compressors, and other relevant components. Additionally, the software typically incorporates structural parameters of the building, meteorological data, and performance curves specific to the VRF system. This paper utilizes the "Air Conditioner: Variable Refrigerant Flow" object within EnergyPlus to model the entire VRF system. This object includes 10 system performance curves specifically for the cooling module, enabling comprehensive simulation and evaluation of the entire VRF system's performance. The "Coil: Cooling: DX" and "Coil: Heating: DX" objects are used to define cooling and heating coils for VRF systems. All system performance curve coefficients are based on the custom curve coefficients provided in EnergyPlus example files[4].

2.2 Calculation of cooling capacity and COP of VRF system

When performing thermodynamic calculations using a vapor compression refrigeration cycle, in addition to using T-s (temperature-entropy) diagrams related to the working fluid, the most convenient tool is the pressure-enthalpy ($lgp - h$) diagram, also known as the log P-h diagram[5].The $lgp - h$ diagram uses enthalpy of the refrigerant as the horizontal axis and pressure as the vertical axis, with pressure represented logarithmically to conserve space. The diagram includes six clusters of state parameter lines for the refrigerant: constant enthalpy (h), constant pressure (p), constant temperature (T), constant specific volume (ν), constant entropy (x), and constant quality (x)[5] (Fig.1).

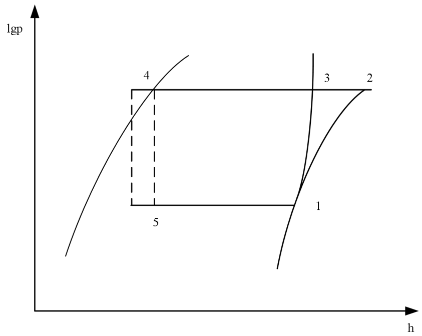

Fig. 1. $lgp - h$ diagram of the refrigeration cycle

From Figure 1, it can be observed that points 1-2 represent the adiabatic compression process of the refrigerant in the compressor, where points 1 and 2 lie on the same isentropic line. Points 2-3-4 depict the constant-pressure cooling process of the refrigerant in the condenser, while 4-5 represents the adiabatic throttling process of the refrigerant through the expansion valve. Finally, 5-1 signifies the constant-pressure evaporation process of the refrigerant in the evaporator. Therefore, based on the condensing and evaporating temperatures, the parameters of the main state points can be determined, and the process lines can be drawn accordingly. Energy consumption analysis of the vapor compression refrigeration cycle is described by the following equations.

The coefficient of performance (COP) can be obtained by:

$$COP = \frac{q_{cooling-capacity}}{w_{Total\ input\ electrical\ power}} \#(1)$$

where $q_{cooling\text{-}capacity}$ is the refrigeration capacity, in kJ/kg; $w_{Total\ input\ electrical\ power}$ is the net cycle work consumed, in kJ/kg.

The refrigeration capacity can be calculated as :

$$q_{cooling-capacity} = h_1 - h_5 \#(2)$$

The net cycle work consumed:

$$w_{Total\ input\ electrical\ power} = h_2 - h_1 \#(3)$$

The condensing heat release ($q_{Condensation\ heat}$) can be calculated as:

$$q_{Condensation\ heat} = h_2 - h_4 \#(4)$$

Therefore:

$$COP = \frac{h_1 - h_5}{h_2 - h_1} \#(5)$$

where h_1 to h_5 are the enthalpy of the refrigerant at state 1 to 5, in kJ/kg.

The refrigerant mass flow (m) can be written as:

$$m = \frac{Q_{Cooling-load}}{q_{Condensation\ heat}} \#(6)$$

where $Q_{Cooling-load}$ is the cooling load of the building, in kJ/h.

The compressor power can then be calculated as:

$$W = \frac{m * w_{Total\ input\ electrical\ power}}{3600} \#(7)$$

3 Model

3.1 Building model

The front view of the building model is shown in Figure 2. Sketchup software is used to build the typical office building model. The total construction area of the building is 266.28 m^2, with height of 4.2 m, shape coefficient of 0.25, and total window to wall area ratio of 0.24. The air tightness level of the exterior doors and windows is 6[6]. The thermal inertness index D is less than 2.5. The thermal design parameters of roof, exterior wall, exterior window and SHGC (solar heat gain coefficient) are 0.429 $W/m^2 \cdot K$, 0.741 $W/m^2 \cdot K$, 2.4 $W/m^2 \cdot K$ and 0.3, respectively.

The indoor cooling temperature setpoint is set to be 26℃ with relative humidity no higher than 70%, and wind speed no higher than 0.3m/s[7].Design working hours include Monday to Friday from 7am to 6pm, excluding public holidays. The building personnel density is designed to be 10 m^2/person with fresh air volume of 30 m^3/per person, lighting density of 9 W/m^2, equipment density of 15 W/m^2, and indoor personnel heat gain of 117W/person.

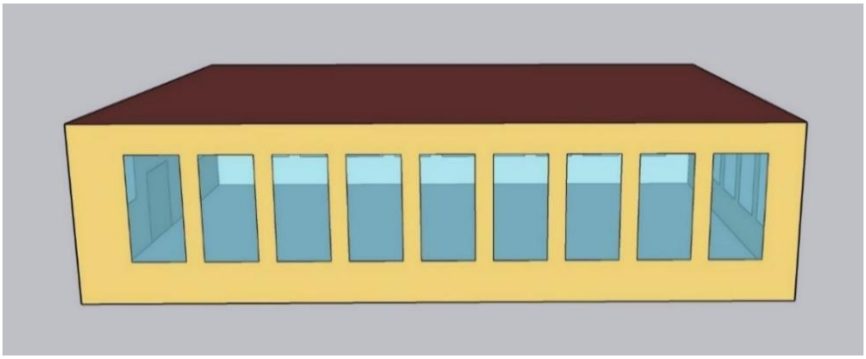

Fig. 2. Front view of the building model

Figure 3 presents the hourly variation of the outdoor air temperature throughout the year. The outdoor air temperature is in the range of 4.8ºC to 37.5ºC with obvious seasonal and daily changes.

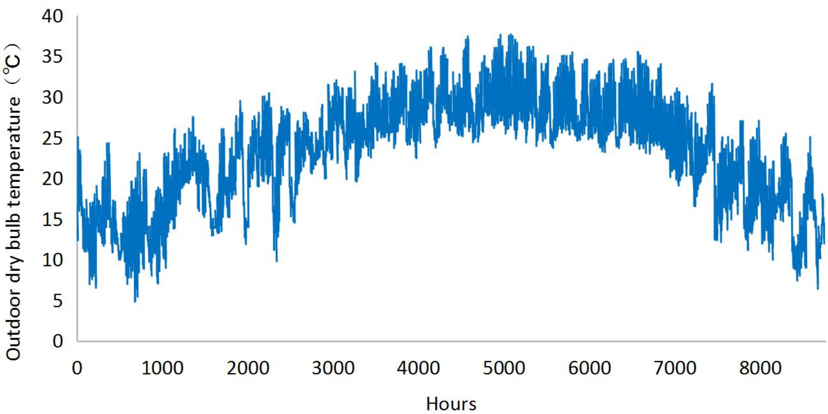

Fig. 3. Hourly outdoor dry bulb temperature in Guangzhou throughout the year

3.2 Adaptive thermal comfort model

Adaptive thermal comfort models help improve occupant comfort, save energy and reduce carbon emissions, improve building design and operational efficiency, and promote health and productivity. The thermal adaptation model is a linear regression model of the correlation between indoor thermal neutral temperature and outdoor temperature. Compared with the PMV model, it takes more consideration of the active interaction of people on the environment, and can better describe the thermal comfort of the transitional season in hot summer and cold winter areas [8].

Guangzhou is located in the hot summer and warm winter area. The ideal working temperature of the adaptive thermal comfort model applied in this paper is defined as in equation (8)[9]. Where T_n represents the ideal temperature setpoint of the adaptive thermal comfort model, and T_{out} represents the outdoor dry bulb temperature. In order to save energy, this paper will modify the adaptive thermal comfort model according to the ideal working temperature of the adaptive thermal comfort model, limiting the indoor temperature setpoint to be equal or greater than 26 ℃. Figure 4 shows the hourly variation of temperature setpoint according to the adaptive thermal comfort model.

$$T_n = 0.554T_{out} + 10.278\#(8)$$

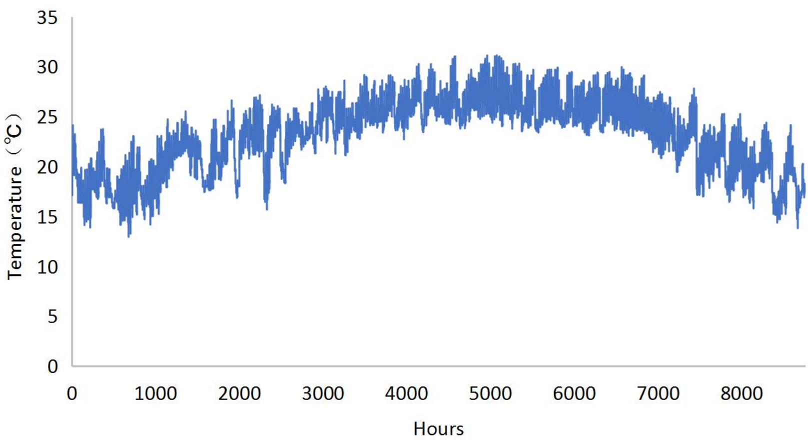

Fig. 4. Variation of adaptive thermal comfort model temperature setpoint in Guangzhou

3.3 Variation of supply air temperature with outdoor air temperature

If there is a reasonable correlation between the supply air temperature and the outdoor temperature, the air conditioning system can be adjusted more effectively, thereby reducing unnecessary energy consumption, but also ensuring the comfort condition of the indoor environment, thus avoid over cooling or overheating.

A linear supply air temperature variation model is developed according to the adaptive thermal comfort model. A linear model is a type of model commonly used in statistics and machine learning to describe the relationship between dependent and independent variables. In this study, the relationship between air supply temperature and outdoor air is assumed to be linear, and the supply temperature setpoint can be calculated as:

$$T_{s-cooling} = 13 + a * (T_{out} - T_b) \# (9)$$

where T_b is the base temperature, in ºC and a is the regression coefficient, dimensionless.

3.4 Variation of evaporating and condensing temperature with outdoor air temperature

For the steam compression refrigeration cycle, energy saving can be achieved by increasing the refrigerant evaporating temperature when the room set temperature and condensation temperature remain unchanged. By increasing the opening of the electronic expansion valve opening level and adjusting the compressor speed, the pressure difference between the inlet and outlet of the expansion valve is reduced, the evaporation pressure is increased, the evaporating temperature of the refrigerant is increased, the density of gaseous refrigerant is increased, the flow of gaseous refrigerant inhaled by the refrigeration compressor is increased, and the difference in the enthalpy of refrigerant at the inlet and outlet of the evaporator also increases, thus the refrigeration capacity of the VRF system is increased [10].The refrigeration efficiency of the refrigeration cycle increases with the increase in evaporation temperature.

A simple correlation is develop between the evaporating temperature and the supply air temperature.

$$T_{evaporation} = T_{s-cooling} - 5 \# (10)$$

Similarly, by reducing the condensation temperature of VRF system, the performance and efficiency of the system can also be improved, and the energy consumption of the system can be reduced. Reducing the condensation temperature can lead to the increase of the condensation efficiency of the refrigerant in the condenser, making it easier for the refrigerant to change from gaseous to liquid, thus reducing the loss of compressed power in the refrigeration cycle. At the same time, since reducing the condensing temperature will reduce the compression power requirement in the refrigeration cycle, the total energy consumption of the system can be reduced.

A simple model between the condensing temperature with outdoor air temperature is developed as below:

$$T_{condensation} = T_{out} + 5 \# (11)$$

4 Results and Discussion

Results on the hourly cooling load of the building, model validation, room air temperature variation and energy performance of the VRF system are presented in this section.

4.1 VRF system model establishment in Energyplus

Figure 5 displays the hourly thermal load variation of the office building during the cooling season of the year, which reflect the actual operation of the VRF system. The cooling season lasts from April to November. On weekdays, the load of the office buildings typically gradually increases in the morning, reaching its peak value as work hours approach, generally between 9 and 11 a.m. Later, during the midday break, the load will decrease somewhat, but not to the level of non-working hours. In the afternoon, the load will rise again until the end of the day.

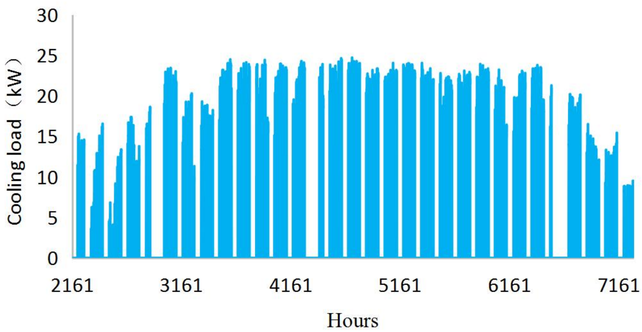

Fig. 5. Hourly load change in building interior

4.2 Model verification

The outcomes of the VRF energy consumption through simulation was compared with the actual onsite reading data on June 11, 2024 from 9:00AM to 17:00AM and presented in Figure 6. It can be observed that there is very good agreement between the simulated results and onsite reading data. There are still small errors possibly caused by the uncertainty of personnel and the uncertainty of indoor equipment operation during the actual operation of the system.

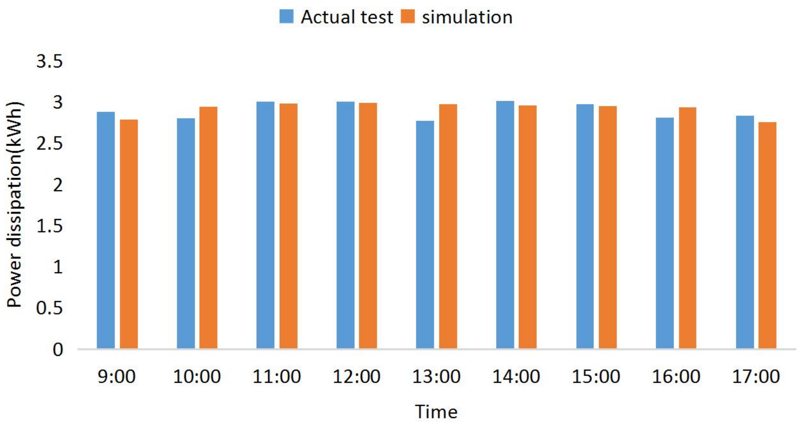

Fig. 6. Comparison of hourly system energy consumption on June 11

4.3 Comparative analysis of simulation results under different control strategies

Figures 7 and 8 present the variation of indoor air temperature of the building under existing control (with constant temperature setpoint of 26ºC) and under adaptive thermal comfort control during the cooling season. Similar trends were observed, however, larger fluctuation on the temperature range was found for the adaptive thermal comfort control as it allows the indoor temperature setpoint to vary with the outdoor air temperature.

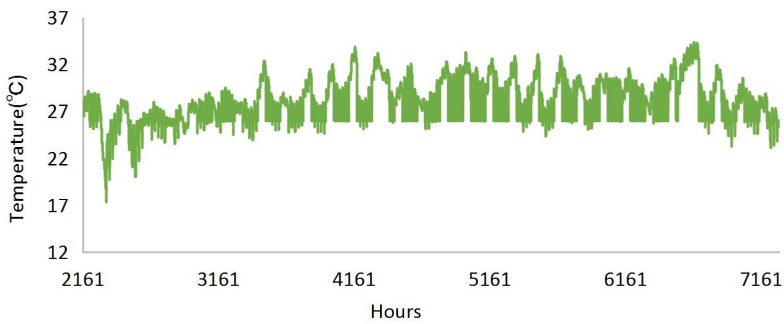

Fig. 7. Hourly variation of the indoor air temperature under existing room temperature control

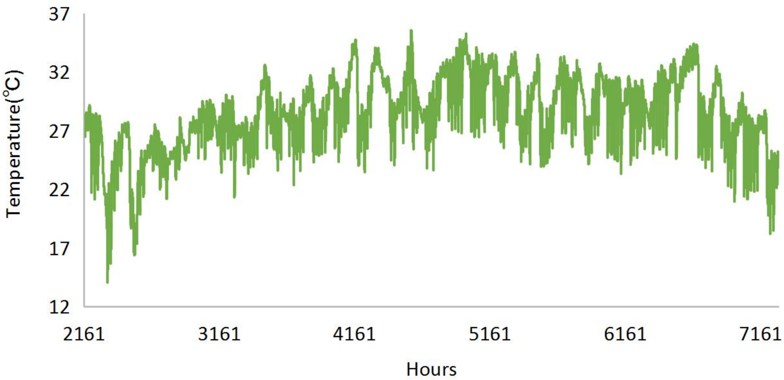

Fig. 8. Hourly variation of the indoor air temperature under adaptive thermal comfort control

The total power consumption of the VRF system under existing control and adaptive thermal comfort control were found to be 7814.88 kWh and 7455.57 kWh (62.64kWh/m^2), respectively. The adaptive thermal comfort control leads to an energy saving of 4.61% compared with the existing control.

Figures 9 and 10 demonstrate the cooling electric power demands of the VRF system under existing control and under adaptive thermal comfort, variable evaporating and condensing temperature control, respectively. By varying the indoor room air temperature, evaporating and condensing temperature the total energy consumption was finally reduced to 5105.67kWh. A total energy savings of 34.66% was achieved.

Figures 11 and 12 presents the associated variation of COP of the VRF system. I can be observed that the system COP was improved by about 1/3, especially under the part load condition.

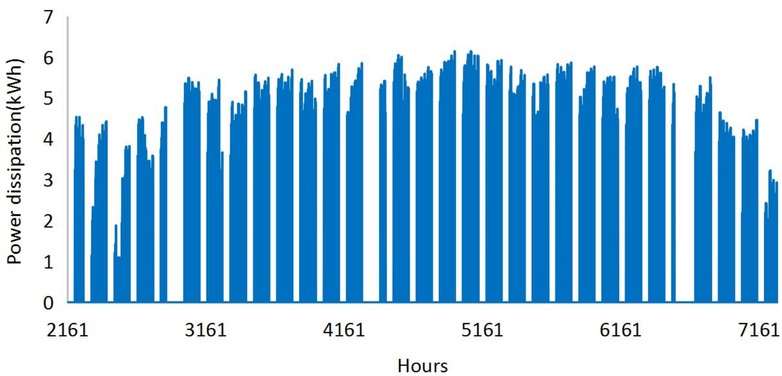

Fig. 9. Cooling electric power demand of the VRF system under existing control

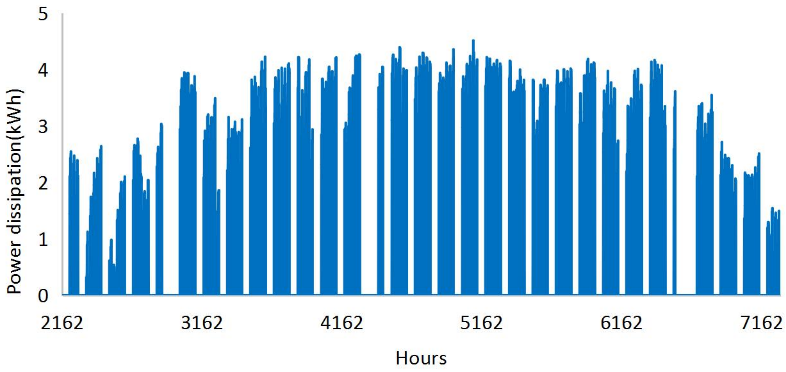

Fig. 10. Cooling electric power demand of the VRF system under adaptive thermal comfort, variable evaporating and condensing temperature control

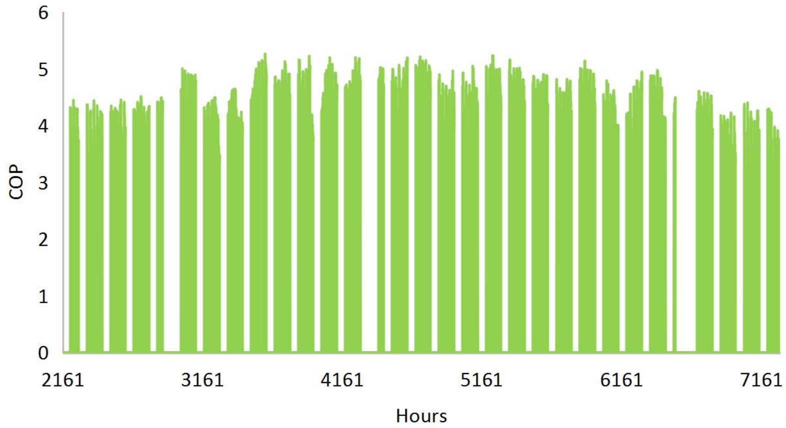

Fig. 11. COP of the VRF system under existing control

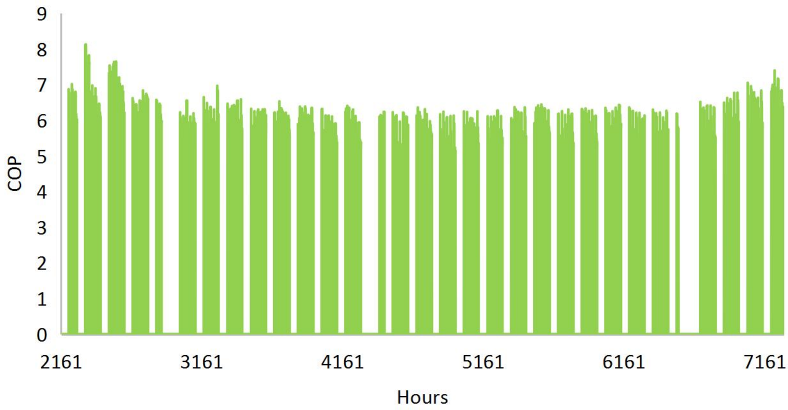

Fig. 12. COP of the VRF system under adaptive thermal comfort, variable evaporating and condensing temperature control

5 Conclusion

This paper presents a novel adaptive temperature control strategy for the VRF system. Through investigation, it was found that adaptive thermal comfort control leads to an energy savings of 4.61%. When adaptive thermal comfort, evaporating temperature and condensing temperature control was applied, the energy savings of the VRF system can be 34.66%. Therefore, this control strategy not only is applicable, but also can lead to significant amount of energy savings.

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