Performance of VRF systems based on large scale monitoring

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Abstract. Variable Refrigerant Flow (VRF) systems are refrigerant systems, which are generally comprised of an outdoor unit serving multiple indoor units connected by a refrigerant piping network. It is important to evaluate the performance of VRF systems, which can help the design and operate of VRF systems. Performance test done by manufactory can reveal the performance of VRF systems in designed conditions. However, it is hard to reveal effective performance in real buildings. The field test is complicated compared with the test in the laboratory and can only conduct on typical samples rather than large scale samples. However, typical samples are not enough for reflecting the performance of large scale VRF systems samples. A simple method of evaluating the performance of large scale VRF systems samples is necessary. This paper proposed and calculating model for electricity consumption and cooling demand of VRF systems based on measured operating data in the laboratory. The paper used the calculating model combined with 344 samples operating data from real residential buildings to calculate the performance of a large scale VRF. This paper analyzed the VRF systems’ performance with different influencing factors such as climate zones, cooling duration and outdoor temperature for the recommendation for VRF systems’ designing and operation.

1. Introduction

Space cooling demand in the world has increased dramatically in these years because of climate change, urbanization, and economy development [1]. Therefore, the performance of the HVAC system for space cooling is very important and necessary to be improved [2],[3]. Variable Refrigerant Flow (VRF) systems are HVAC systems, which are generally comprised of an outdoor unit serving multiple indoor units connected by a refrigerant piping network. VRF systems are widely used in residential buildings and office buildings in China. It is important to evaluate the performance of VRF systems, which can help the design and operate of VRF systems. The performance of VRF systems is influenced by many factors, such as operating mode and climate [4]. The methods of evaluating the performance of VRF systems are mainly performance test by manufactory in laboratory and field test on typical samples. The performance test by manufactory can reveal the performance of VRF systems in all the conditions [5]. However, it is hard to represent the main conditions of systems and cannot reveal the real performance in real buildings. In fact, the field test is complicated compared with the test in the laboratory and can only conduct on typical samples rather than large scale samples. The typical samples are not enough for reflecting the performance of large scale VRF systems samples. The main method of evaluating the performance of VRF systems are a physical model [6,7] and data-driven model [8,9]. The physical model required many detailed factors, which may not be able to test in real buildings. The data-driven model required much more data for model training [10]. A simple method of evaluating the performance of large scale VRF systems samples is necessary. Previous research has already proposed a hybrid model for evaluating VRF systems in office buildings [11]. The evaluation for VRF systems in residential buildings is also important. Therefore, this paper proposed a hybrid model for electricity consumption
and cooling demand for VRF systems based on measured operating data in the laboratory. In addition, this paper collected the operating data through monitoring sub-meters on VRF systems both from laboratory and residential buildings. The 344 samples of VRF systems in residential buildings are mainly from the south part of China and the number of samples from residential can reach a large scale level. The paper used the electricity consumption and cooling demand calculating a model of VRF systems combined with 344 samples operating data to calculate the large scale VRF systems’ performance. The paper analyzed the VRF systems’ performance with different influencing factors such as climate zones, cooling duration and outdoor temperature, which brings out the recommendation for VRF systems’ designing and operation.

2. Dataset and methods

2.1. Dataset introduction

The operating data through monitoring sub-meters on VRF systems both from laboratory and residential buildings were collected. The dataset from laboratory contained the measured data for electricity, cooling demand and other detailed parameters of outdoor unit for the same type VRF systems for cooling. The dataset from real residential buildings in this paper is the outdoor unit operating data of 344 VRF systems equipped with sub-meters, which are located in all climate zones in China. The distribution of VRF systems in all climate zones is shown in Figure 1. Most of the cases are located in the hot summer and cold winter climate zone. The research obtained the metered data of each indoor unit from June 2016 to Sept. 2016, and from Nov. 2016 to Feb. 2017. As the dataset covered the cooling season for VRF systems, this paper focused on cooling condition only.

![Figure 1. Distribution of VRF systems in climate zones of China.](image)

2.2. Overview of methodology

The methodology of the research is shown in Figure 2. Firstly, the paper established the hybrid performance model for VRF systems using the dataset from the laboratory. Then, the performance of VRF systems is calculated by combining the hybrid model with large scale dataset from real residential buildings. The paper analyzed the VRF systems’ performance with different influencing factors such as climate zones, cooling duration, and outdoor temperature. Finally, it proposed the recommendation for VRF systems’ designing and operation.

![Figure 2. The roadmap of methodology.](image)

3. Establishment of a hybrid performance model

The hybrid performance model of VRF systems was established according to Figure 2, the roadmap for the establishment of a hybrid performance model. Firstly, for electricity consumption, the paper proposed a multiple linear regression model. Then, a physical model was used for calculating the cooling
demand of VRF systems. Finally, the COP of VRF systems was calculated by combining electricity with cooling demand.

**3.1. Establishment of electricity consumption model**

For electricity consumption, the paper proposed a multiple linear regression model based on the dataset from a laboratory in all the operating conditions for the VRF system. The model equation is (1):

\[ E = \beta_0 + \beta_1 x_1 + \beta_2 x_2 + \cdots + \beta_n x_n \]  

(1)

where \( E \) is electricity consumption; \( \beta_i \) is parameter for multiple linear regression; \( x_i \) is parameter from outdoor unit of VRF system. Model validation is necessary for data-driven model. In order to validate the model, the paper used 70% dataset to train the model and 30% dataset to cross test the model (Figure 2). \( R^2 \) for both data training and data testing are all 0.99, which means that the model can predict the electricity of VRF systems.

**3.2. Establishment of the cooling demand model**

The paper established the physical model according to the field standard of air conditioner [12]. The cooling demand is calculated by equation (2).

\[ Q = \frac{P_{com} - Q_{loss}}{(h_2 - h_1)} \times (h_1 - h_3) \]  

(2)

where \( Q \) is cooling demand of VRF system; \( P_{com} \) is electricity of compressor; \( Q_{loss} \) is heat loss of compressor; \( h_1, h_2, h_3, h_4 \) are Enthalpy of state points in refrigeration cycle (Figure 3). For the physical model, \( Q_{loss} \) is calculated by the dataset from laboratory (Figure 3), where \( Q_{loss} = \alpha P_{com}, \alpha = 18\% \).

**3.3. Calculated COP of VRF systems**

Combined with electricity model and cooling demand model, the COP of VRF systems is calculated. For further analysis, COP for cooling season and COP for one day are calculated according to equations:

\[ \text{COP for cooling season} = \frac{\sum_{\text{Feb 2017 to Jun 2016}} Q_{cooling}}{\sum_{\text{Feb 2017 to Jun 2016}} E_{cooling}} \quad \text{and} \quad \text{COP for one day} = \frac{\sum_{24:00 \text{ to } 00:00} Q_{cooling}}{\sum_{24:00 \text{ to } 00:00} E_{cooling}} \]  

(3)
4. Results of performance for VRF systems

4.1. Distribution of cooling duration, electricity, cooling demand and COP for the cooling season

The calculated results of performance for VRF systems by the hybrid model are shown in Figure 4 and Figure 5. 90% of electricity consumption of cooling season were lower than 2801 kWh/household. The average electricity consumption of cooling season is 1454 kWh/household. For the cooling duration of VRF systems, 94% of samples cooling duration is lower than 2676 hours. The average cooling duration of the cooling season is 1370 hours. The main range of COP for the cooling season is from 2.9 to 4.4. 90% of cooling demand is lower than 9503 kWh/household. The average cooling demand for the cooling season is 5172 kWh/household.

![Figure 6. Distribution of electricity consumption and distribution of cooling duration](image)

![Figure 7. Distribution of COP for the cooling season and distribution of cooling demand](image)

4.2. Performance for VRF systems for different climate zones

In order to provide the recommendation for VRF systems designing and operation, performance for VRF systems for different climate zones is analyzed. The distribution of performance of VRF systems in different climate zones is shown in Figure 6-9. The amount of sample from Severe Cold region and Mild region is not enough, which cannot bring out the validated conclusion. For other three climate zones, it could find that median cooling electricity consumption in Hot Summer and Warm Winter Zone is mostly higher than other climate zones because of longer cooling duration and the median COP in Hot Summer and Cold Winter Zone is lower than other climate zones.

![Figure 8. The quartile map of cooling duration and cooling electricity consumption](image)
4.3. Performance for VRF systems for the different cooling duration

The cooling duration of VRF system can largely determine the performance. The cooling electricity for the cooling season with different cooling duration is shown in Figure 8. It showed that a longer cooling duration may bring out more electricity consumption. The COP for the cooling season with different cooling duration is shown in Figure 8. It revealed that the longer cooling duration may bring out a lower COP.

4.4. Performance for VRF systems for different outdoor temperature

In order to analyze COP for one day, the average outdoor temperature and average load ratio for one day were calculated. Figure 9 showed that COP reached a peak around 30 °C outdoor temperature and higher outdoor temperature may result in a lower COP for one day when the average outdoor temperature is higher than 30°C. It is because that load ratio of more than 50% of samples always appeared around 30 °C.

5. Discussion on a recommendation for VRF systems’ designing and operation

According to the calculated results of the VRF system performance model, it can provide a recommendation for VRF systems’ designing and operation. Firstly, the median cooling duration in Hot Summer and Warm Winter Zone is higher than other climate zones, which require more attention of designer for this climate zone. Secondly, the median COP in Hot Summer and Cold Winter Zone is lower than another climate zone. It revealed a high potential for improvement in this climate zone.
Thirdly, longer cooling duration may bring out more electricity consumption and longer cooling duration may bring out lower COP, which may result from the partial load for a long time. Finally, COP can be influenced both by outdoor temperature and load ratio. It may require a designer to know the real outdoor temperature and load ratio for designing and operation, which need further research on it.

6. Conclusions

The paper used the calculating model combined with 344 samples operating data from real residential buildings to calculate the large scale VRF systems’ performance. The paper analyzed the VRF systems’ performance with different influencing factors such as climate zones. There are four main outcomes of the study:

1. The average electricity consumption of cooling season is 1454 kWh/household. The main range of COP for the cooling season is from 2.9 to 4.4.
2. The median cooling duration in Hot Summer and Warm Winter Zone is higher than other climate zones. The median COP in Hot Summer and Cold Winter Zone is lower than another climate zone. It revealed a high potential for improvement in this climate zone.
3. The longer cooling duration may bring out more electricity consumption and longer cooling duration may bring out a lower COP. COP reached a peak around 30 °C outdoor temperature and higher outdoor temperature may result in lower COP for one day when the average outdoor temperature is higher than 30°C.

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References

[1] International Energy Agency, The Future of Cooling, 2018.

[2] W. Chung, Review of building energy-use performance benchmarking methodologies, Appl. Energy 88 (2011) 1470–1479, doi: 10.1016/j.apenergy.2010.11.022.

[3] K.J. Chua, S.K. Chou, W.M. Yang, J. Yan, Achieving better energy-efficient air conditioning - A review of technologies and strategies, Appl. Energy. 104 (2013) 87–104, doi: 10.1016/j.apenergy.2012.10.037.

[4] Yu X, Yan D, Sun K, et al. Comparative study of the cooling energy performance of variable refrigerant flow systems and variable air volume systems in office buildings[J]. Applied energy, 2016, 183: 725-736.

[5] Chou J S, Bui D K. Modeling heating and cooling loads by artificial intelligence for energy-efficient building design[J]. Energy and Buildings, 2014, 82: 437-446.

[6] Hong T, Sun K, Zhang R, et al. Development and validation of a new variable refrigerant flow system model in EnergyPlus[J]. Energy and Buildings, 2016, 117: 399-411.

[7] Zhang R, Sun K, Hong T, et al. A novel Variable Refrigerant Flow (VRF) heat recovery system model: Development and validation[J]. Energy and Buildings, 2018, 168: 399-412.

[8] Zhao D, Zhong M, Zhang X, et al. Energy consumption predicting model of VRV (Variable refrigerant volume) system in office buildings based on data mining. Energy, 2016, 102: 660-668.

[9] Liu J, Wang J, Li G, et al. Evaluation of the energy performance of variable refrigerant flow systems using dynamic energy benchmarks based on data mining techniques[J]. Applied Energy, 2017, 208: 522-539.

[10] Kusiak, A., & Li, M. (2010). Cooling output optimization of an air handling unit. Applied Energy, 87(3), 901-909.

[11] Zhang, G., Li, X., Shi, W., Wang, B., & Cao, Y. (2019). Influence of occupant behavior on the energy performance of variable refrigerant flow systems for office buildings: A case study. Journal of Building Engineering, 22, 327-334.