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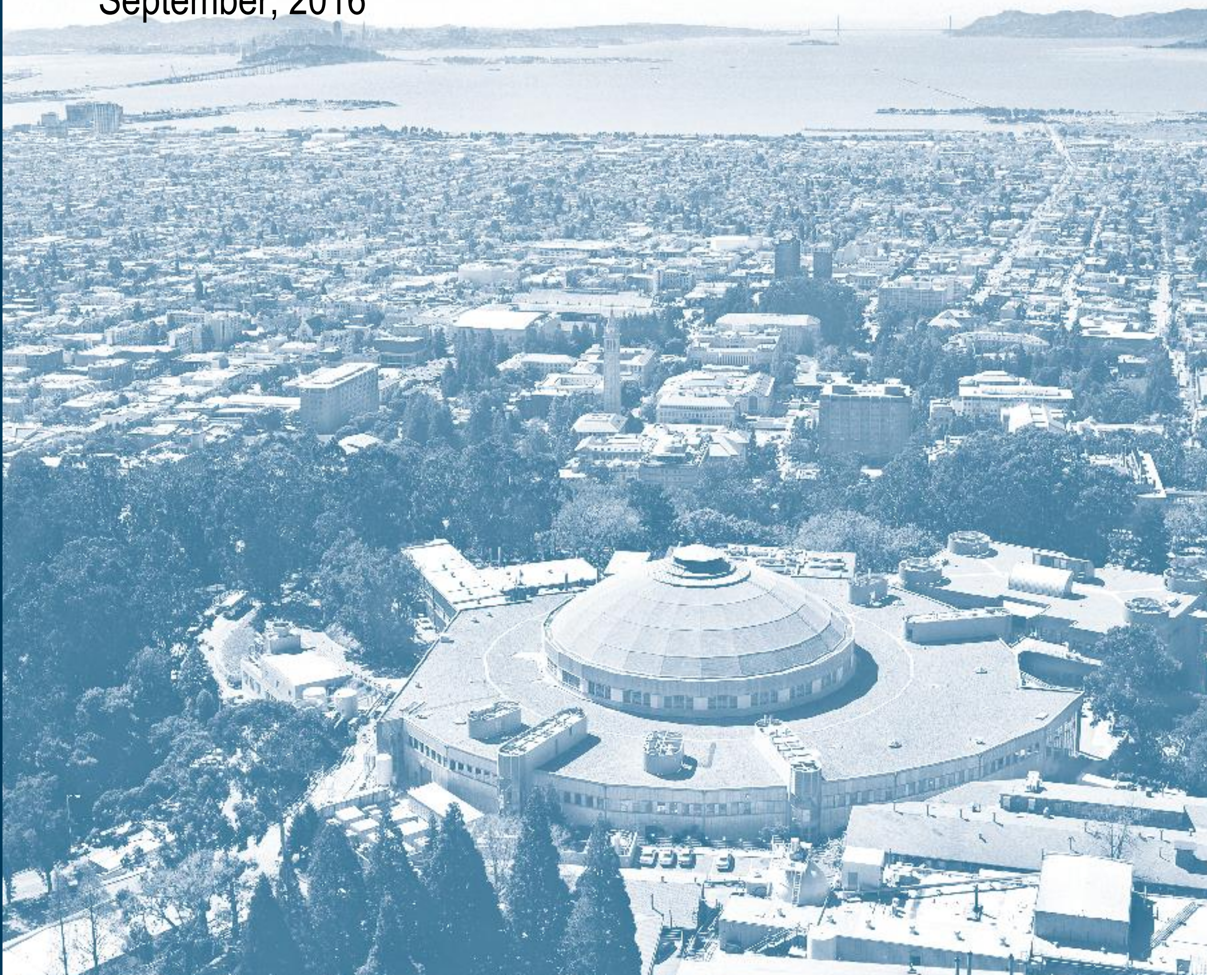

A Comparative Study on Energy Performance of Variable Refrigerant Flow Systems and Variable Air Volume Systems in Office Buildings

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Abstract:

Variable air volume (VAV) systems and variable refrigerant flow (VRF) systems are popularly used in office buildings. This study investigated VAV and VRF systems in five typical office buildings in China, and compared their air conditioning energy use. Site survey and field measurements were conducted to collect data of building characteristics and operation. Measured cooling electricity use was collected from sub-metering in the five buildings. The sub-metering data, normalized by climate and operating hours, show that VRF systems consumed much less air conditioning energy by up to 70% than VAV systems. This is mainly due to the different operation modes of both system types leading to much fewer operating hours of the VRF systems. Building simulation was used to quantify the impact of operation modes of VRF and VAV systems on cooling loads using a prototype office building in China. Simulated results show the VRF operation mode leads to much less cooling loads than the VAV operation mode, by 42% in Hong Kong and 53% in Qingdao. The VRF systems operated in the part-time-part-space mode enabling occupants to turn on air-conditioning only when needed and when spaces were occupied, while the VAV systems operated in the full-time-full-space mode limiting occupants' control of operation. The findings provide insights into VRF systems operation and controls as well as its energy performance, which can inform HVAC designers on system selection and building operators or facility managers on improving VRF system operations.

Key words: Variable Refrigerant Flow (VRF) Systems, Variable Air Volume (VAV) Systems, field measurement, building simulation, energy performance, comparative analysis

1. Introduction and Background

The energy consumed by the buildings sector accounts for more than 30% of the total energy worldwide [1], and has exceeded the industrial and transportation sectors in developed countries [2]. In developed countries, heating, ventilation and air-conditioning (HVAC) accounts for almost half of the total energy use in commercial buildings. The growing demand for better thermal comfort in the built environment leads to the wide spread of HVAC installation, which causes the steady increase in building energy use [3]. Therefore, it is crucial to improve the energy performance of HVAC systems to reduce building energy and carbon emissions [4][5][6][7].

Variable air volume (VAV) system is an air system that varies its supply air volume flow rate to satisfy different space heating/cooling loads, to maintain predetermined space air temperature and humidity for thermal comfort, and to conserve fan power during part-load operations [8]. A VAV system satisfies the occupants' indoor air quality (IAQ) requirement by supplying a minimum amount of outdoor air based on national regulations and standards [9]. There are two types of VAV systems: packaged VAV using direct-expansion cooling coils, and central VAV using chilled-water cooling coils. Many VAV systems supply air with a constant temperature and recirculate portion of the return air[10]. VAV system usually relies on reheat at zone terminal units to meet zone comfort requirements at part-load conditions. VAV system is the most typical HVAC system in office buildings. According to the Advanced Variable Air Volume System Design Guide by California Energy Commission (2003), about half of the newly constructed large office buildings will be served with VAV reheat systems between 2003 and 2012 [11].

Variable Refrigerant Flow (VRF) system is a refrigerant system, generally comprised of an outdoor unit serving multiple indoor units connected by a refrigerant piping network. There are two common VRF types: the heat pump type and the heat recovery type. The heat pump type VRF system supplies only cooling or only heating at a time, while the heat recovery type VRF system can supply cooling and heating simultaneously. Depending on cooling source for the outdoor condensers, VRF systems can be categorized into air-cooled and water-cooled. VRF system varies the refrigerant flow using variable speed compressors in the outdoor unit and the electronic expansion valves (EEVs) located in each indoor unit. Advanced VRF systems can modulate the evaporating temperatures to meet the cooling load of indoor units [12]. Its ability to control the refrigerant mass flow rate according to the cooling and/or heating load enables the integration of as many as 60 indoor units with varied capacities with one single outdoor unit with one or multiple compressors. This unlocks the possibility of zone level individual comfort control, simultaneous heating and cooling in different zones, and heat recovery from one zone to another [13][14]. Because of the extraordinary performance in individual and flexible zone level control, VRF systems are great fit for applications requiring individualized comfort conditioning. As a result, VRF systems have gained much attention and are becoming more widely used with sales booming worldwide [15][16].

As an emerging HVAC technology, VRF systems have been comprehensively compared with conventional HVAC systems, such as VAV systems, fan coil systems, and packaged ducted systems. A simulation study on a prototypical ten-story office building in Shanghai China showed that VRF systems saved 22.2% and 11.7% energy compared with central VAV systems and fan coil systems, respectively [17]. The energy performance of a VRF system was compared with a ground source heat pump (GSHP) system based on simulation of a small office building in EnergyPlus [18]. The results show that the GSHP system is more efficient than the VRF system especially in cold climate, but no significant difference in climates with modest heating loads. A VRF system serving the first floor and GSHP system serving the second floor were installed at ASHRAE Headquarter in Atlanta USA. Their energy performance was measured and compared. The field test results show that the GSHP system consumed about 20% and 60% less energy than the VRF system in the summer and winter/shoulder seasons, respectively [19]. However, as the tested two floors have different thermal loads due to the different space types (first floor has conference rooms … while office rooms at second floor), window-to-wall ratio, and user behaviors, the comparison is not as fair between the two systems. More work is needed to perform a completely apply-to-apple performance comparison. For an existing office building in Maryland, USA, VRF systems showed that the simulated energy savings are from 27.1 to 57.9% compared with central VAV systems depending on system configurations and design conditions [20]. It was found that VRF systems consumed 35% less energy than the central chiller/boiler-based systems under the humid subtropical climate condition [14], and 30% less than the chiller-based systems under the tropical climate conditions [21]. The actual savings from VRF systems would vary depending on several factors including climate, operation conditions, and control strategies [22][23]. From the perspective of thermal comfort, the individual control feature of the VRF system enables the adjustment of thermostat settings according to the specific requirements of different users, hence improves the thermal satisfaction [24][25]. This was proved by a field-performance test of two different control modes (individual and master) that were applied to the VRF system of the test building [25]. Therefore, the VRF system not only consumes less energy than the common air conditioning systems, but also provides better indoor thermal comfort due to its independent and flexible zoning controls.

In the current literature, simulation is the prevailing method used to compare different HVAC systems. In this case, the simulation inputs are basically from HVAC specifications and assumptions. There was no research that identifies the key factors leading to the energy consumption discrepancies based on detailed field investigation in real buildings, or even further quantifies the influence of the factors. To address this gap, the authors investigated 11 buildings using VRF systems or chiller-based central VAV systems in five Chinese cities: Beijing, Qingdao, Hangzhou, Shanghai and Hong Kong. As a result, the large discrepancies of air-conditioning energy consumption between VRF systems and VAV systems are confirmed in this study. As Annual HVAC energy consumption of the 11 investigated buildings**Error! Reference source not found.** shows, VRF system consumes much less annual energy than the VAV system regardless of climate zones, the impact of which will be further analyzed in Section 2. Among the 11 investigated buildings, five buildings (2 using VRF, 3 using VAV) have more detailed survey information and sub-metered energy data. They were chosen for further comparison and analysis to reveal the key influencing factors of energy use discrepancy, with their influence quantified using building simulation.

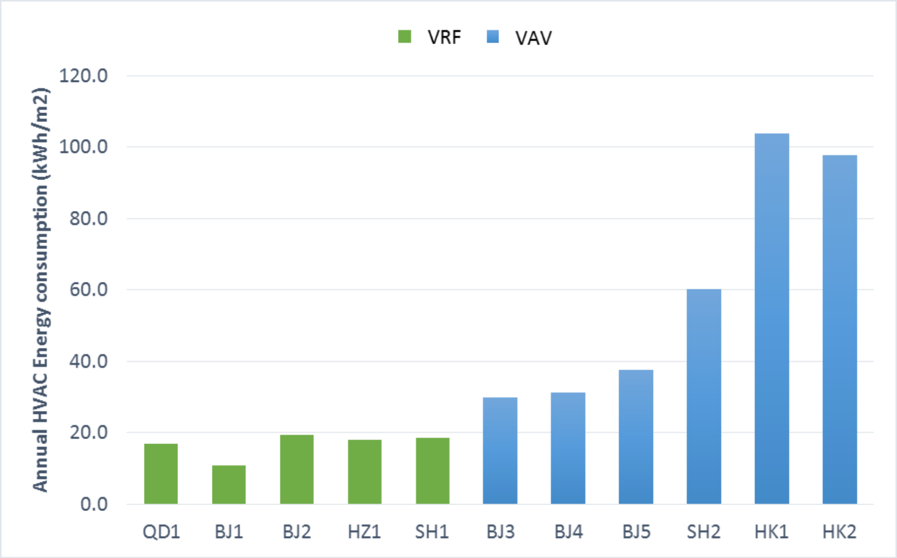

Fig 1. Annual HVAC energy consumption of the 11 investigated buildings

Notes: QD: Qingdao, BJ: Beijing, HZ: Hangzhou, SH: Shanghai, HK: Hong Kong.

In this study, heating system energy use was not included mainly due to different heating systems are used in the five selected buildings: the buildings in Beijing and Qingdao use district heating, buildings in Hangzhou use VRF for heating and no heating in Hong Kong. Therefore, it makes no sense to compare heating energy use of these buildings.

For building simulation, there are a limited number of simulation tools that are capable of modeling VRF systems, such as EnergyPlus and Trace 700. In previous research, a customized version of EnergyPlus was developed and used for a few simulation studies on VRF systems [17][20][26][27]. However, this special version is not available to the public and was not verified or adopted by the EnergyPlus development team. In 2015, a new VRF heat pump model was developed, validated and implemented in EnergyPlus by LBNL, and the new VRF model has been available in EnergyPlus version 8.4 [28]. The Designer’s Simulation Toolkit (DeST) [29][30][31], developed by Tsinghua University, also has the ability to simulate VRF system [32]. In our study, DeST was adopted as the simulation tool.

2. Methodology

The discrepancies in energy consumption of VRF and VAV systems are not only caused by the difference of HVAC system efficiencies, but also by other factors, such as climate, building envelope properties, operation schedules and occupant behaviors.

In our study, we used field investigation and simulation. Field investigation in the five selected buildings, including site survey, field measurement and sub-metering data, was used to identify main influencing factors. Simulation was used to analyze the sensitivity and quantify the impact of individual influencing factor on building energy performance. The overall methodology of this study is shown in Fig 2.

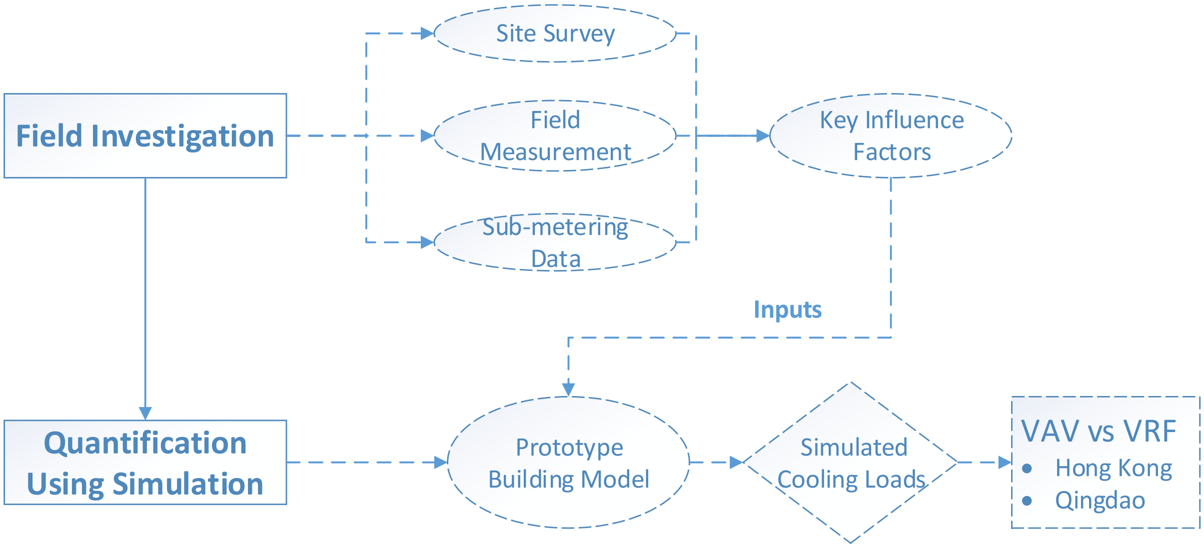

Fig 2. Overall Methodology

2.1. Building Selection

Five of the eleven investigated office buildings (**Error! Reference source not found.**) were selected for further comparison and analysis as they have detailed survey information and sub-metered energy use data. They are located in different climate zones in China, their façades are shown in **Error! Reference source not found.**. Three buildings (C, D and E) use chiller-based central VAV systems, while the other two (A and B) use air-cooled VRF systems.

Building A: HZ Building B: QD Building C: HK Building D: HK Building E: BJ

Figure 1 the five investigated buildings

Table 1 summarizes the characteristics of the five buildings. They are high-rise large office buildings. Except Building E in Beijing was built in 1990, the other four buildings were built in similar period between 2003 and 2008. Buildings C and D are located in Hong Kong where is much warmer than the other three locations.

Table 1 Summary of the five buildings

Buildings	**Location/ Climate Zones**	**ASHRAE Climate Zones**	**Cooling Degree Days (CDD)**	**Air-conditioned Floor Area (m^2)**	**Year Built**	**HVAC Systems**
A	Hangzhou /Hot Summer Cold Winter	3A	2978	29913	2006	VRF(heat pump type)
B	Qingdao / Cold Zones	4A	1991	44870	2006	VRF(heat pump type)
C	Hong Kong /Hot Summer Warm Winter	2	4782	118000	2008	Multiple VAVs
D	Hong Kong /Hot Summer Warm Winter	2	4782	26961	2003	Multiple VAVs
E	Beijing / Cold Zones	4A	2274	30300	1990	Multiple VAVs

2.2. Site Survey

To better understand the actual behavior of the building operators and occupants in the five buildings, two sets of survey questionnaires were developed and conducted on site. One set targeted the operators, using questions on characteristics of building envelope, air conditioning systems and operation strategy; while the other targeted the occupants, using questions on occupancy, lighting, equipment, ventilation, air conditioning temperature set point and operation. The survey was carried out in 2012 and a few offices of each the investigated buildings were selected for questionnaires survey of occupants. Another set of questionnaire survey was sent to operators. The survey results, together with the collected measurement data, will be used to analyze and understand the differences between the VRF and VAV systems.

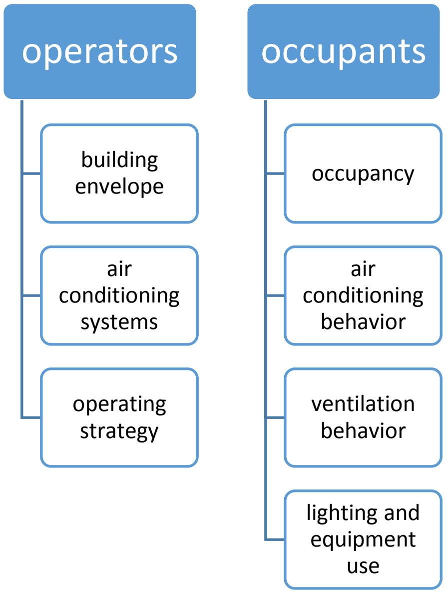

Figure 2 Site survey of building operators and occupants

2.3. Field measurement and sub-metered data

With the rapid development of automatic metering technology, sub-metering systems are widely installed in commercial buildings in China to track energy use. If better building management and controls are pursued, a BMS would be installed. The three investigated VAV buildings (C, D and E) are all equipped with the sub-metering system as well as the BMS system. The two VRF buildings (A and B) monitored and recorded the energy use by the VRF system's built-in energy monitoring system.

In this study, hourly energy consumption data of the air conditioning systems were collected from the sub-metering system and the BMS. Meanwhile, indoor environmental conditions (including indoor air temperature, humidity and CO2 concentration), internal heat gains (including lighting and equipment power density), and occupant behaviors (including turning on/off the HVAC, switching on/off lightings, and opening/closing windows) were all measured in a few offices of each of the five buildings.

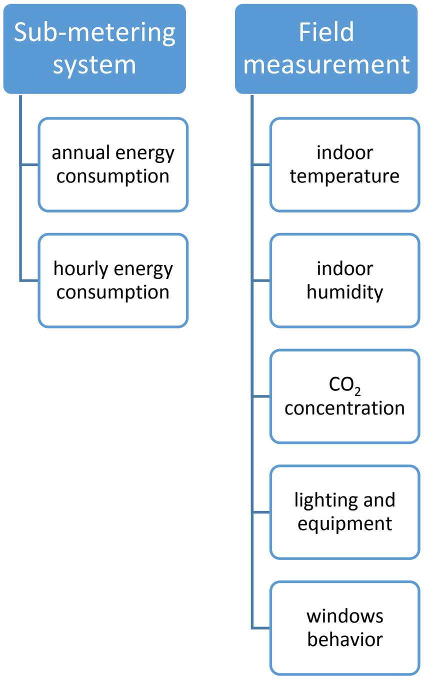

Figure 3 Data collection from field measurement and sub-metering system

2.4. Simulation

Based on the site survey and field measurement, main factors were identified that drive the energy use discrepancy between VRF and VAV systems. However to quantify the sensitivity and influence of each factor, building simulation is needed. The Designer's Simulation Toolkit (DeST) was developed by Tsinghua University, China since early 1990s for practical and research use of building simulation. DeST was designed to simulate and analyze both building energy consumption and HVAC system. It aims to improve the reliability of system design, ensure the quality of the system performance, and reduce building energy consumption. In our study, DeST was chosen as the simulation tool because it has built-in database of building materials, internal heat gains, HVAC systems, and operation controls for commercial buildings in China.

Figure 4 illustrates the simulation approach adopted in this study. A reference model with representative inputs for office buildings, including building envelope, internal heat gains and infiltration rate, was developed in DeST. The key impact factors, including operation strategy and control mode, were set differently for the VRF and VAV systems. Two representative climate zones of the five investigated buildings were selected so that the influence of the key factors can be analyzed under different weather conditions. Lastly, the simulated cooling loads of the VRF and VAV systems were compared. Cooling loads are directly from the demand side considering the impact of operation mode, but excluding the system side impact of efficiency of the VRF and VAV systems.

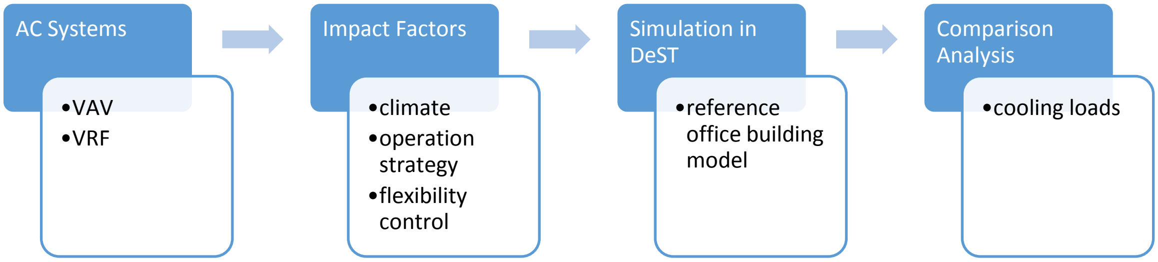

Figure 4 Simulation Approach

3. Results and Analysis

3.1. Energy Consumption

According to the field measurement of the five office buildings, the annual energy consumption of air conditioning systems are significantly different, shown in Figure 5. Buildings A and D with VRF systems, the left two bars in Figure 5, consumed significantly less cooling electricity than buildings B, C and E with VAV systems, the right three bars in Figure 5.

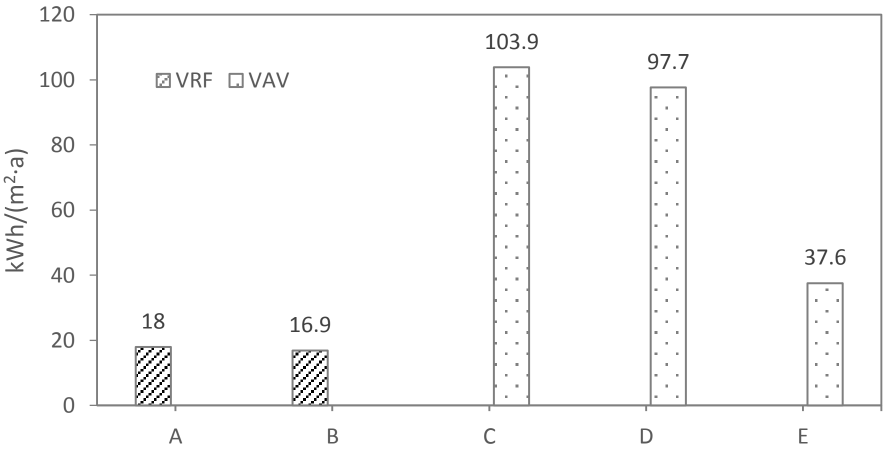

Figure 5 Annual air-conditioning energy consumption between VRF and VAV systems (kWh per m^2 of floor area)

These investigated buildings are located in four cities belonging to different climate zones in China. Figure 6 shows the annual outdoor temperature of these four cities. The cooling seasons of these four cities are quite different, especially that the average outdoor temperature in Hong Kong is much higher than those of the other three cities. This may have significant influence on the energy consumption of HVAC systems.

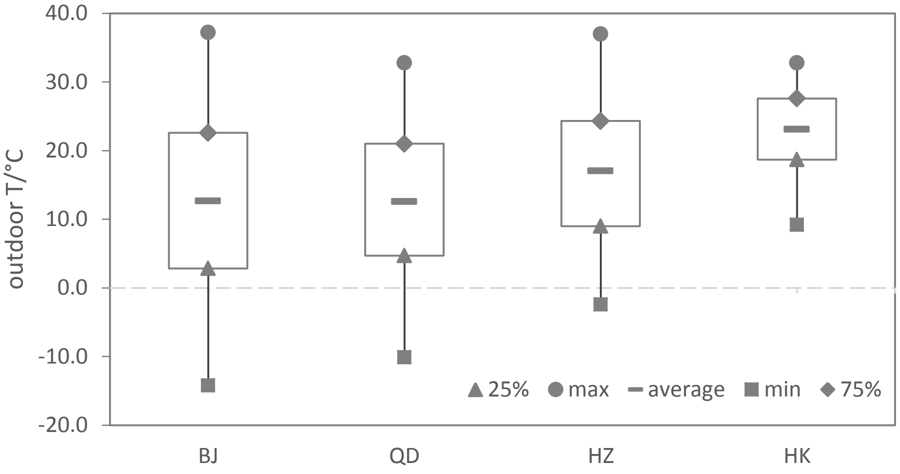

Figure 6 Statistics of the annual hourly outdoor air temperature

To normalize the impact of climate, the energy consumption values were normalized by dividing by the Cooling Degree Days (CDDs) of the specific climate. This is referring to the normalization method of climate in Energy Star [33], which uses the Cooling Degree Days (CDDs) and Heating Degree Days (HDDs) as the climate indices for normalization. The normalized air-conditioning energy consumption still shows, in Figure 7, significant discrepancies between the VRF and VAV systems.

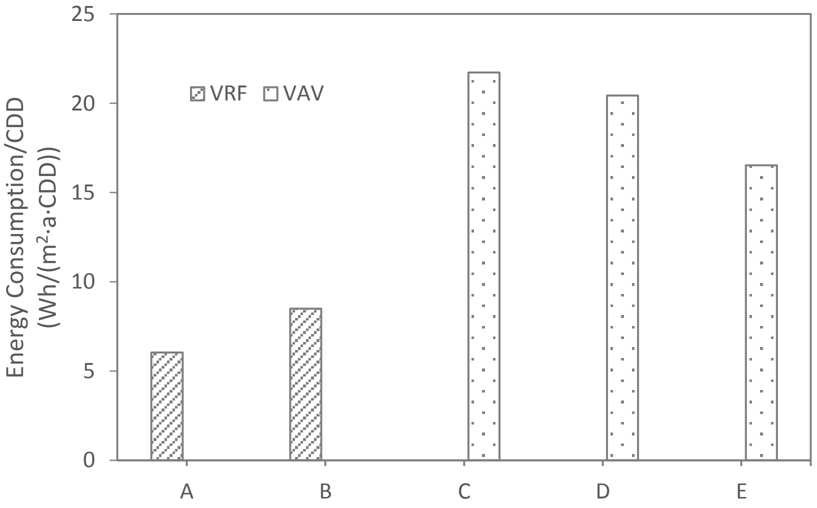

Figure 7 Normalized air-conditioning energy consumption by Cooling Degree Days

Similar to the climate diversity, the occupant schedules of these buildings were slightly different: the occupants generally work for five and a half days per week in Hong Kong while only five days in Beijing, Hangzhou and Qingdao. In this case, the CDD normalized energy consumption was further divided by the number of working days, five and a half days in Hong Kong and five days in other three cities. Such normalized energy consumption was still significantly diverse as shown in Figure 8.

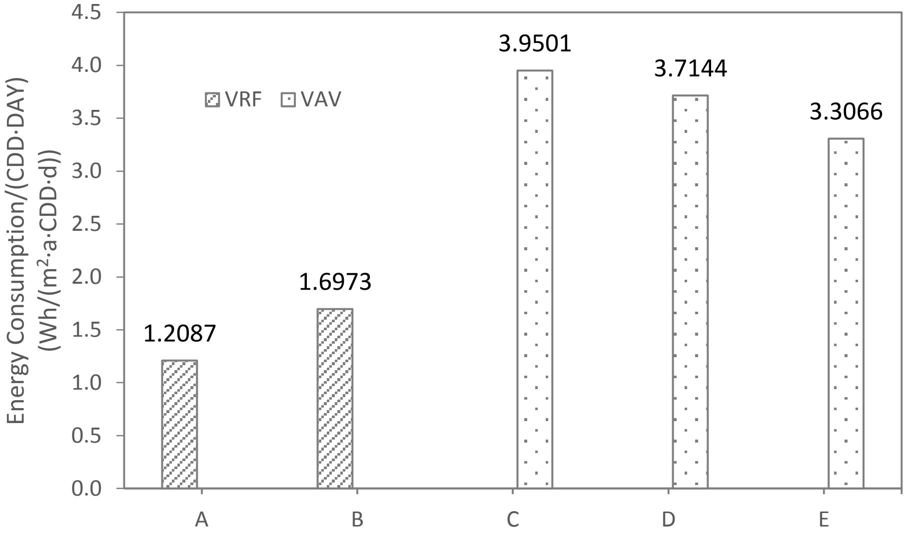

Figure 8 Occupant schedule normalized air-conditioning energy consumption

3.2. Influencing Factors

Based on Figure 8, the normalized energy use of the VAV systems is still more than twice of the energy use of the VRF systems in the investigated buildings. In other words, besides the climate and occupant schedule, there are other factors that lead to the energy use discrepancy. The results from site survey and field measurement were therefore analyzed to unveil the key influencing factors.

3.2.1. Internal heat gains

Internal heat gains greatly contribute to the air-conditioning loads and energy consumption, including occupant density, lighting power density as well as equipment power density. In this study, according to field-measured data, the average occupant density in the five office buildings was almost the same, about 0.09 person/m^2. As for lighting and equipment power density, the average lighting and equipment density was as high as 28 W/m^2 in Buildings C and D in Hong Kong, much larger than 15 to 18 W/m^2 in buildings in Hangzhou, Qingdao, and Beijing.

Compared to office buildings in mainland China, office buildings in Hong Kong tend to have higher lighting requirement and much more office equipment which lead to higher internal heat gains. Such differences in internal heat gains are not necessarily related to the use of different HVAC system types.

Comparing Building E (VAV system in Beijing) to Buildings A and B (VRF system in Hangzhou and Qingdao), the internal loads are similar but the air conditioning energy use differs by up to 175%

(Figure 8). Therefore, internal heat gains is not a key factor leading to the discrepancies of air conditioning energy use.

Table 2 Average occupant density, lighting and equipment power density in the five buildings

	Buildings	**Average**
Occupant density (persons/m^2)	A, HZ	0.09
	B, QD	0.08
	C, HK	0.08
	D, HK	0.11
	E, BJ	0.066
Lighting and equipment power density (W/m^2)	A, HZ	15.3
	B, QD	15.1
	C, HK	28.6
	D, HK	26.5
	E, BJ	17.7

3.2.2. Operation and controls

Besides internal heat gains, another important factor that has significant influence on energy consumption of the VAV and VRF systems is system operation and control strategy, which is directly related to building operators and occupants.

3.2.2.1.Starting temperature and operating temperature

Indoor environmental parameters, such as air temperature, humidity and CO_2 concentration, were measured in several offices of each investigated building. Figure 9 illustrates the measured indoor air temperature in two offices in Building B, and Figure 10 illustrates the measured return air temperature of four VAV boxes in Building E. According to the measured indoor air temperature, there were significant fluctuations with noticeable crests and troughs in the indoor air temperature of the VRF systems (0Figure 9), while the indoor air temperature of the VAV systems was relatively stable (Figure 10). It was concluded from the site survey that the crests happened when occupants switched on the VRF indoor units and the troughs were the traditional comfort temperature set point. In this study, we defined the average crest as the “starting temperature” and the average trough as the “operating temperature”. Occupants turned on VRF indoor units when they feel hot – indoor air temperature reaching the starting temperature. Once the VRF indoor units were on, they operated to maintain a comfort temperature, the operating temperature. When offices were not occupied, indoor units were turned off (e.g. for room5 in Figure 9, air conditioning was turned off around 11am). In the VRF systems, there are obvious patterns of starting temperatures and operating temperatures, while there are only patterns of operating temperatures found in the VAV systems. Based on the field measurement data of indoor air temperature, the starting temperature and operating temperature of the VRF systems were determined to be about 28°C and 26°C, respectively, while the operating temperature of the VAV systems was usually about 24°C.

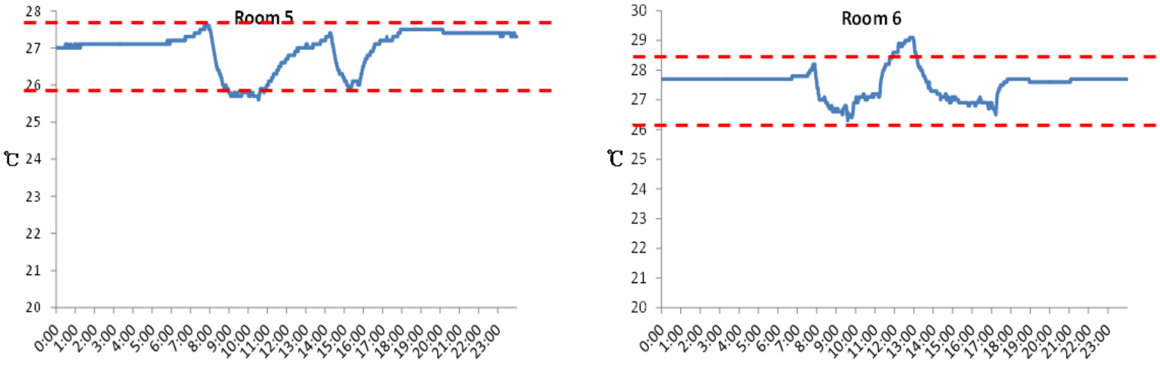

Figure 9 Measurement data of indoor air temperature in Building B with VRF systems

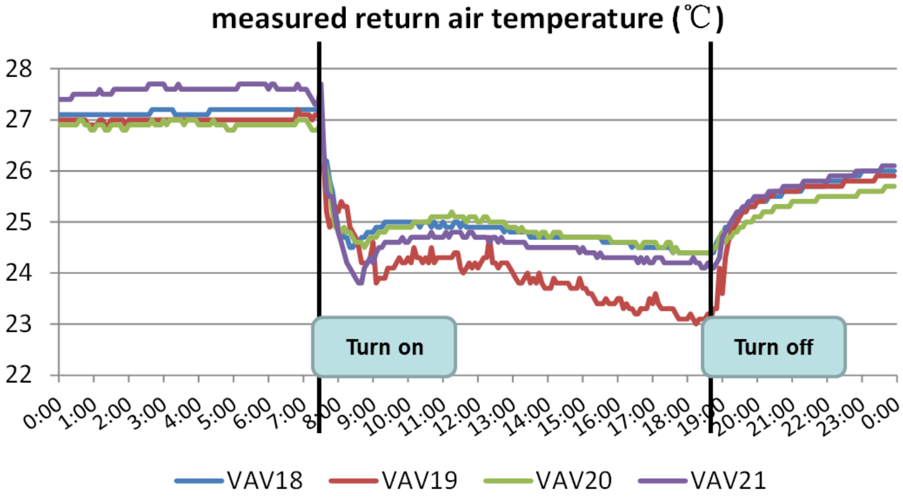

Figure 10 Measurement data of return air temperature of the selected VAV boxes in Building E with VAV systems

3.2.2.2.Flexibility of individual control

Moreover, according to the survey results of air conditioning operation modes, ventilation patterns and air-conditioning temperature setpoint in the VRF systems, shown in **Error! Reference source not found.**Table 3, the VRF indoor units were controlled by individual occupants, which is different from the VAV systems which are centralized controlled by the building operator. In other words, the VRF systems are more flexible and personalized.

Due to different internal heat gains and thermal comfort demand, three types of VRF operating modes were found in this study: (1) AC was operated by a fix schedule, with no window opening; (2) occupants preferred ventilation by opening windows, and only turned on the AC when feeling hot, indoor air temperature reaching the starting temperature; and (3) AC was rarely turned on, and occupants usually opened windows for ventilation. Outdoor air was provided in various ways in the VRF systems, including: dedicated centralized outdoor air handling units, dedicated indoor units, and infiltration.

As for the VAV systems, chillers were operated and maintained by specialized personnel, and the centralized VAV air handling units (AHUs) only worked during office hours, controlled by operators with fixed schedules. Usually centralized outdoor air was provided through the AHUs.

Table 3 Site survey of operation modes of the VRF systems

Tenant IDs	**VRF operation modes**			**Temperature setpoint (°C)**	**Ventilation when AC is on**
1	Turn on when feeling hot	1-3 hours per day	Ventilation when no AC	25-27	no
2	Turn on when feeling hot		Ventilation when no AC	25	no
3	All day			23-24	no
4	Turn on when feeling hot	usually turn on at noon, off after work	Ventilation when no AC	24	no
5	Turn on when feeling hot		Ventilation when no AC	25-26	no
6	All day			21-23	no
7	All day			25-26	Sometimes
8	Almost no AC		Always ventilation	25	no
9	Turn on when feeling hot	rarely	Ventilation when no AC	25	no
10	All day			19-23	occasionally

3.2.2.3. Summary of operation and control characteristics

According to the above analysis on site survey results and field measurement data, the key impact factors that lead to the energy use discrepancy between the VRF and VAV systems are the HVAC system operation characteristics and control strategy, including the starting temperature, operating temperature, operation modes, adjustable range, outdoor air units, as shown in 0.

Table 3 Key differences in operation and control between the VRF and VAV systems

	VRF Systems	VAV Systems
Staring temperature	Yes, about 28°C	No
Operating temperature	26°C	24°C
Operation Mode	Controlled by the occupants, indoor units are operated separately	Centralized control with fixed schedules
Outdoor Air Units	Usually use natural ventilation	Centralized fresh air

In summary, the VRF systems operated in part-time-part-space decentral mode where occupants turned on cooling only when feeling hot, while the VAV systems operated in full-time-full-space central mode for much longer operating period.

4. Simulation

4.1. Purpose of Simulation

According to the aforementioned analysis, the key factors causing the huge discrepancy of energy use between the VRF and VAV systems were concluded. However, to quantify the sensitivity and impact of individual factor, theoretically, we need to compare the VAV and VRF systems under same conditions of climate/location, building shape, building envelope, internal heat gains. In reality this is not feasible. Therefore, building simulation was adopted to quantify impact of operation mode on system performance.

A reference energy model with representative inputs for office buildings, such as building envelope, internal heat gains and infiltration rate, was developed using DeST. The key impact factors, included as the operation strategy and control mode, were set differently for the VRF and VAV systems. Two typical climates from the five investigated locations were also selected to help understand the influence of performance by climate. Lastly, the cooling loads of the VRF and VAV systems of the same reference office building were compared. Cooling loads are directly from the demand side considering the impact of operation mode, but excluding the system side impact of efficiency of the VRF and VAV systems. Therefore comparing the cooling loads can isolate impact of other factors but focus on the impact of the operation mode.

To exclude the impact of climate, building shape, envelope properties, room functions, internal heat gains, a reference office building model was built up with all parameters set to the same values, except using different operation modes of the VRF and VAV systems.

4.2. Simulation Model

4.2.1. The prototype office building model

The prototype office building model, shown in Figure 11, is a 22-floor tower building. The envelope properties were set according to the 2005 energy standards for public buildings in China, as shown in 0. The occupant schedule, lighting schedule and equipment schedule were set similar to the investigated office buildings, based on site survey, as shown in Figure 12 and Figure 13**Error! Reference source not found.**.

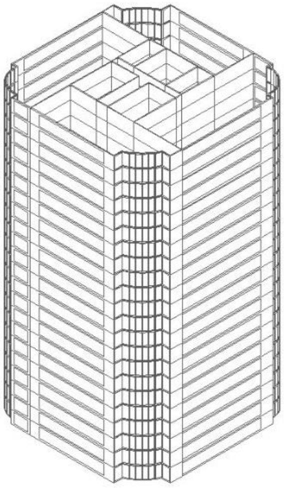

Figure 11 The reference office building model

Table 4 Key parameters of the reference office building model

	Item	Value
Wall	heat transfer coefficient (W/m^2.K)	0.564
Window	heat transfer coefficient (W/m^2.K)	1.8
	Shading coefficient	0.45
Window-wall-ratio		0.6
Occupant density (p/m^2)		0.089
Lighting power density (W/m^2)		10.66
Equipment power density (W/m^2)		16.85

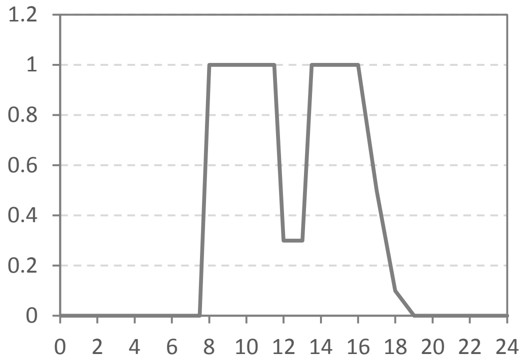

Figure 12 Occupant schedule in the reference model during weekdays

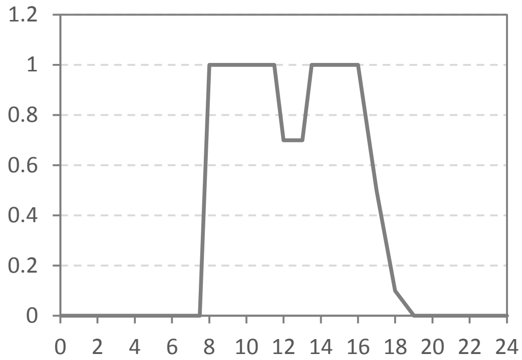

Figure 13 Lighting and equipment schedules in the reference model during weekdays

4.2.2. Operational parameters of the VRF and VAV systems

Operational parameters of the VAV and VRF systems are summarized in **Error! Reference source not found.** and **Error! Reference source not found.**, respectively, based on the site survey and measurements. The operating schedules of VAV systems were fixed contains both overtime work schedule and no overtime work schedule, while the operating schedules of VRF systems were more flexible, three types according to site survey results, related to indoor and outdoor condition. Moreover, the upper limit of thermostat set points in VAV systems was 24℃ while 26℃ in VRF systems.

These operation schedules and parameters were applied to the spaces in the prototype model according to their frequency from the site survey of space operation conditions.

Table 5 Operational parameters of the VAV systems

Item	Description
AC operating schedule	no overtime work: 8:00～19:00
	overtime work: 8:00～22:00
Thermostat setpoints	20 ~ 24℃
Humidity setpoints	35% ~ 70% RH
Outdoor air	30 m^3/h.person

Table 6 Operational parameters of the VRF systems

Room type	System operating schedule	Operating Temperature (°C)	Starting Temperature (°C)	Outdoor air flow rate
1	no overtime work: 8:00-19:00	26	No	30 m^3/h.person
	with overtime work: 8:00-22:00			
2	Ventilation only, no AC		No	≤ 5 ACH
3	Turn on VRF only when indoor air	26	28	30

	temperature exceeds the starting temperature, and natural ventilation can’t satisfy comfort need.			m^3/h.person
	If natural ventilation can satisfy comfort need, turn off VRF			≤ 5 ACH

4.3. Quantitative Analysis

Considering that the cooling loads under different climates may vary significantly, the quantitative analysis was performed in two cities representing two typical climates in China, Qingdao and Hong Kong.

According to the simulation results (Figure 14 and Figure 15), buildings with the VRF system operation mode have 53% and 42% less cooling loads than the buildings with the VAV system operation mode in Qingdao and Hong Kong, respectively.

Obviously, cooling loads of the VRF systems or the VAV systems in Hong Kong are significantly larger than those in Qingdao, mainly due to the characteristics of climates. Qingdao has a summer cooling season lasting for five months, while Hong Kong’s cooling season is year-round. The mild outdoor temperature in Qingdao enables more use of natural ventilation to replace mechanical cooling, which helps reduce cooling loads as well.

Operational parameters, including operation mode and indoor temperature setpoint, are the two key factors that the quantitative analysis tries to address. The results in Figure 14 and Figure 15 show the overall impact of the two factors. Their individual impacts are also simulated and analyzed, which show about equal influence by the operation mode and the indoor temperature setpoint.

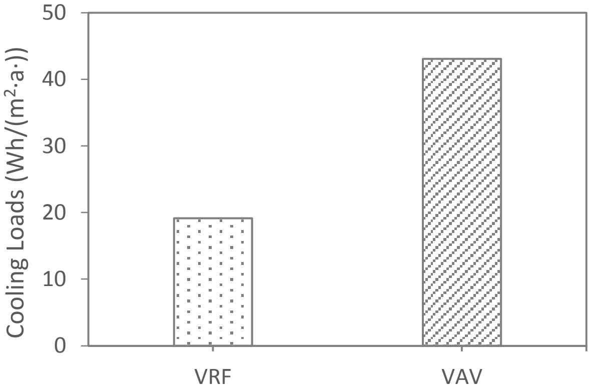

Figure 14 Simulated cooling loads of the VRF and VAV systems in Qingdao

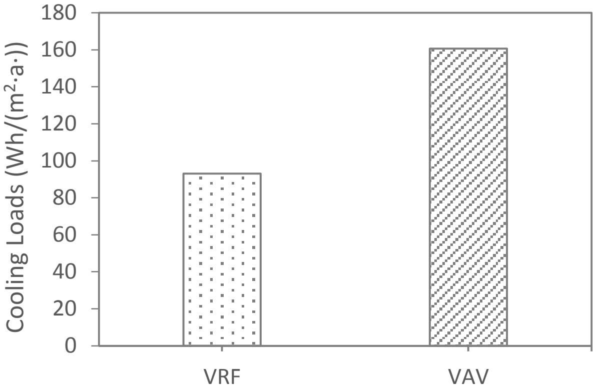

Figure 15 Simulated cooling loads of the VRF and VAV systems in Hong Kong

4.4. Summary

It can be concluded that the two key factors, operation mode and indoor temperature setpoint, result in the VRF systems having as much as 42% less cooling loads than the VAV systems in Hong Kong, and 53% in Qingdao.

5. Discussion

The VRF systems consumed much less energy than the VAV systems mainly due to the flexibility of operation and controls. The part-time-part-space operation mode of the VRF systems allows occupants to turn on the air conditioner only when needed and occupied, resulting in much less operation time, while the full-time-full-space operation mode of the VAV systems operated with a fixed schedule, which is less flexible (VAV boxes cannot be turned off even when a space does not need air-conditioning) and leads to much longer operation time. Moreover, the VRF systems have a wider range for capacity adjustment and occupants can turn off the air conditioner whenever they do not need it, beneficial to greater thermal comfort.

On the other hand, VAV systems have advantage in centralized installation and maintenance while the spidery nature of VRF pipework and specific installation requirements limit the application of VRF systems in some particular cases. Special tools and techniques are essential to tighten flare joints and minimize the risk of leakage during installation of VRF systems. Furthermore, VAV systems with air economizers are able to provide “free cooling” when the outdoor temperature is lower than the recirculation air temperature. While VRF systems usually recirculate indoor air and need separated outdoor air units to provide the code defined minimum ventilation, unable to make full use of “free cooling”. However, in China, occupants can open windows in most cases to ventilate and cool buildings with VRF systems, providing equivalent effect of “free cooling”.

Generally speaking, VRF and VAV systems have their pros and cons. The high flexibility of VRF systems make significant contribution to thermal comfort and energy savings. As a result, VRF systems are more suitable for buildings in part-time-part-space operation mode with high flexibility when the refrigerant pipework can be installed.

In the investigated VRF buildings, three operation modes were observed, as discussed in Section 3. The energy consumption of the VRF systems is the result of all three modes combined. What if the VRF systems are only controlled by one single operation mode? By assigning each single operation mode to the reference energy model, the differences among the three modes were estimated. The simulation results show that the operation mode with starting temperatures can reduce cooling loads by 18%, compared to the operation mode with the fixed schedule, while the operation mode with only natural ventilation does not consume cooling energy.

It should be noted that there are limitations in this study: (1) all five investigated buildings are located in China, so the findings are more applicable to buildings in China. However, the methodology of site survey, field measurement, analysis and simulation is generic and applicable to buildings in other countries; (2) the number of investigated buildings is limited (mainly due to requirement of detailed site survey, measurement, and sub-metering), more samples would provide richer data for the detailed comparisons; (3) ideally buildings in the same location/climate but with different VRF and VAV systems would help eliminate influence of weather on building energy use, simplifying the performance comparison.

6. Conclusion

VRF systems consumed much less energy than VAV systems in office buildings in China, mainly benefiting from their flexibility of operation and controls. VRF systems' part-time-part-space operation mode allows occupants to turn on cooling only when needed and when spaces are occupied; while VAV systems' full-time-full-space operation mode do not allow occupants to turn off cooling, resulting in much longer operation time and thus consuming much more energy.

In HVAC design, while there are many factors to consider in determining system type and operation strategy, enabling occupants' individual control in decentralized systems like VRF can improve comfort and save energy compared with centralized systems like VAV.

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