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Comparative study of the cooling energy performance of variable refrigerant flow systems and variable air volume systems in office buildings

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HIGHLIGHTS

- We compared energy use of VRF and VAV systems for office buildings in China.
- We use field measurement, survey and simulation to analyze influencing factors.
- VRF consumed much less energy than VAV mainly due to different operation modes.
- VRF systems operate in part-time-part-space mode enabling flexible personal control.
- VAV systems operate in full-time-full-space mode leading to longer operation hours.

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ABSTRACT

Variable air volume (VAV) and variable refrigerant flow (VRF) systems are widely used in office buildings. This study investigated VAV and VRF systems in five typical office buildings in China, and compared their cooling energy use. Site survey and field measurements were conducted to collect the 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 indicated that the cooling energy consumed by VRF systems was up to 70% lower than that consumed by VAV systems. This was mainly because of the different operation modes of both system types that led to significantly fewer operating hours for the VRF systems. Building simulations were used to quantify the impact of operation modes of VRF and VAV systems on cooling loads. A prototype office building in China was used as the model. The simulation results showed that the VRF operation mode required much lower cooling load when compared to the VAV operation mode. For example, the cooling loads decreased by 42% in Hong Kong and 53% in Qingdao. The key findings include the following: the VRF systems operated in the part-time-part-space mode enabling occupants to turn on the air-conditioning only when needed and when the spaces were occupied. However, the VAV systems operated in the full-time-full-space mode limiting occupants' control of operation. These findings provide insights into VRF systems operation and controls as well as their energy performance, which could help guide HVAC designers on system selection and building operators or facility managers on system operations to achieve low- or zero-net energy buildings.

1. Introduction and background

The energy consumed by the building sector accounts for more than 30% of the total energy worldwide [1], and has exceeded the industrial and transportation sectors in developed countries [2–4]. In developed countries, heating, ventilation, and air-conditioning (HVAC) account for almost half of the total energy use in commercial buildings. The growing demand for improved thermal comfort in the building environment led to the wide spread implementation of HVAC systems, which caused a steady increase in building energy use [5,6]. Therefore, it is crucial to improve the energy performance of HVAC systems in order to reduce building energy and carbon emissions [7–11].

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Nomenclature

VAV	variable air volume	BMS	building management system
VRF	variable refrigerant flow	RH	relative humidity
DeST	designer's simulation toolkit	AHUs	air handling units
CDDs	cooling degree days	EEVs	electronic expansion valves
HDDs	heating degree days	ppm	parts per million
GSHP	ground source heat pump	HVAC	heating, ventilation, and air-conditioning
CFD	computational fluid dynamics		
SC	shading coefficient		

Variable air volume (VAV) systems are air systems that vary their supply air volume flow rate. This mechanism satisfies different space heating/cooling loads, maintains predetermined space air temperature and humidity for thermal comfort, and conserves fan power during part-load operations [12]. VAV systems satisfy indoor air quality (IAQ) requirements by supplying a minimum amount of outdoor air based on national regulations and standards [13]. There are two types of VAV systems, namely 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 a portion of the returned air [14]. The VAV systems usually rely on the reheating at zone terminal units to meet zone comfort requirements at part-load conditions. The VAV system is the most typical HVAC system in office buildings. According to the Advanced Variable Air Volume System Design Guide by the California Energy Commission (2003), approximately half of the newly constructed large office buildings will utilize VAV reheat systems between 2003 and 2012 [15].

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. There are two common VRF types, namely the heat pump type and the heat recovery type. The heat pump type VRF system only supplies cooling or heating at a time, but the heat recovery type VRF system supplies both cooling and heating simultaneously. Thus, VRF systems can be categorized into air-cooled and water-cooled groups depending on the cooling source for the outdoor condensers. The VRF system varies the refrigerant flow using variable speed compressors in the outdoor unit and electronic expansion valves (EEVs) located in each indoor unit. Advanced VRF systems can modulate the evaporating temperatures to meet the cooling loads of indoor units [16]. The ability of VRF systems to control the refrigerant mass flow rate according to cooling and/or heating loads has enabled the integration of as many as 60 indoor units with varied capacities using a single outdoor unit with one or multiple compressors. This unlocked the possibility of the zone level individual comfort control, with simultaneous heating and cooling in different zones, and heat recovery from one zone to another [17,18]. Given the extraordinary performances of individual and flexible zone level controls, the VRF systems have emerged as a great solution for applications requiring individualized comfort conditioning. Hence, VRF systems have gained much attention and are becoming more widely used with sales booming worldwide [19,20].

As an emerging HVAC technology, VRF systems were 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 the VRF systems saved 22.2% and 11.7% energy when compared with central VAV systems and fan coil systems, respectively [21]. The energy performance of a VRF system was compared with a ground source heat pump (GSHP) system based on the simulation of a small office building in EnergyPlus [22]. The results indicated that the GSHP system was more efficient than the VRF system especially in cold climates, but there were no observed significant differences in the 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, Georgia in the USA. Their energy performances were measured and compared. The field test results showed that the GSHP system consumed approximately 20% and 60% less energy than the VRF system in the summer and winter/shoulder seasons, respectively [23]. The two tested two floors had different thermal loads due to the different space types (the first floor contained conference rooms, while the second floor contained offices), such as window-to-wall ratios, and user behaviors. Hence, the comparison of the two systems was not valid. Subsequent studies included a one-to-one performance matching and comparison. For an existing office building in Maryland, USA, simulations showed the VRF systems energy savings to range from 27.1% to 57.9% when compared with central VAV systems depending on the system configurations and design conditions [24]. It was observed that the VRF systems consumed 35% less energy than the central chiller/boiler-based systems under humid subtropical climate conditions [18], and consumed 30% less energy than the chiller-based systems under tropical climate conditions [25]. The actual savings from the VRF systems varied depending on several factors including climate, operation conditions, and control strategies [26,27]. From the thermal comfort viewpoint, the individual control feature of the VRF system enabled adjustment of the thermostat settings according to the specific preferences of different users, and thus improved the thermal satisfaction [28,29]. This was illustrated by a field-performance test of two different control modes (individual and master modes) that were applied to the VRF system of the test building [29]. Therefore, the VRF system consumed less energy than common air conditioning systems, and provided better indoor thermal comfort due to its independent and flexible zoning controls.

In the current literature, numerical simulations are predominantly used to compare different HVAC systems [30,31]. In this case, the simulation inputs were primarily from HVAC specifications and assumptions. There was no research that identified key factors leading to energy consumption discrepancies based on detailed field investigations in real buildings. Additionally, there was no research that further quantified the influence of factors. This study investigated 11 buildings using VRF systems or chiller-based central VAV systems in five Chinese cities, namely Beijing, Qingdao, Hangzhou, Shanghai, and Hong Kong to address this gap in knowledge. As a result, the large discrepancies of cooling energy consumption between VRF systems and VAV systems were confirmed in this study. As indicated by Fig. 1, the VRF system consumed much less annual energy than the VAV system regardless of the climate zones. The impact of the VRF system will be further analyzed in Section 2. Among the 11 investigated