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Simulation comparison of VAV and VRF air conditioning systems in an existing building for the cooling season

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ABSTRACT

Performance of two widely used air conditioning (AC) systems, variable air volume (VAV) and variable refrigerant flow (VRF), in an existing office building environment under the same indoor and outdoor conditions for an entire cooling season is simulated by using two validated respective models and compared. It was observed that the indoor temperatures could not be maintained properly at the set temperature by the VAV no-reheat boxes. However, it could be maintained by the VAV boxes with reheat with a significant energy consumption penalty. It was found that the secondary components (indoor and ventilation units) of the VRF AC system promised 38.0–83.4% energy-saving potential depending on the system configuration, indoor and outdoor conditions, when compared to the secondary components (heaters and the supply fan) of the VAV AC system. Overall, it was found that the VRF AC system promised 27.1–57.9% energy-saving potentials depending on the system configuration, indoor and outdoor conditions, when compared to the VAV AC system.

1. Introduction

A great amount of world energy demand is associated with the built environment [1]. It is estimated that air conditioning (AC) systems consume about 50% of the total electricity use in the office buildings [2,3]. Therefore, reducing energy use for space cooling in buildings is a key measure for the energy-savings. In addition, the interactions between the AC systems and the building envelope and the occupants are important.

For the building air conditioning, two AC systems, variable air volume (VAV) and variable refrigerant flow (VRF) are used. Basically, a VAV system is an air system that regulates the supply air volume flow rate with a damper located in the VAV box to match the variation of the space cooling load in order to maintain the zone air temperature at the set temperature. On the other hand, a VRF system is a refrigerant system that varies the refrigerant flow rate with the help of the variable speed compressor and the electronic expansion valves to match the space cooling load in order to maintain the zone air temperature at the set temperature.

The VAV system was first introduced in the 1960s [4], and the VRF system was first introduced more than 25 years ago [5]. Due to the long histories, both systems have been widely studied experimentally and numerically [1–4,6–24].

Three popular AC systems, VAV, fan-coil plus fresh air (FPFA) and VRF, used in China in a 10-storey office building were studied by using the EnergyPlus software [3]. From the simulation results, the VRF AC system was found to be the most efficient system compared to the other two AC systems. The energy-saving potentials of the VRF system were expected to achieve 22.2% and 11.7%, compared with the VAV system and the FPFA system, respectively. However, this study was a case study without having any experimental validation.

One comparison study performed in a government building was reported in Ref. [5]. A rooftop VAV AC system was used on one side of the building and a VRF AC system on the other side in the same building. The energy consumption of the VRF AC system was found to be 38% lower than that of the VAV AC system. However, it is worth noting that during the evaluation, the office space was mostly unoccupied during much of the day due to the installation.

Despite the previous numerous studies on the VAV and VRF AC systems, it is found that there are only limited comparison studies conducted for the VAV and VRF AC systems without having detailed information such as component and system capacities, internal load profile, etc.

This study addresses the simulation evaluation and comparison of VAV and VRF AC systems in an existing office building under the

Abbreviations: CR, combination ratio; AC, air conditioning; COP, coefficient of performance; DX, direct expansion; ERV, energy recovery ventilator; FPFA, fan-coil plus fresh air; HRV, heat recovery ventilation; IU, indoor unit; OA, outdoor air; OU, outdoor unit; PLR, part load ratio; RTU, rooftop unit; VAV, variable air volume; VRF, variable refrigerant flow.

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Nomenclature

$\dot{Q}_{IU}$ Standard cooling capacity of the indoor unit
$\dot{Q}_{OU}$ Standard cooling capacity of the outdoor unit
$\dot{Q}_{OU,T}$ Total cooling capacity of the outdoor unit

same indoor and outdoor conditions. The EnergyPlus building simulation package [25], which is an energy analysis and thermal load simulation program, was used for the simulation studies. Ref. [26] introduces the existing building and the VAV AC system, and describes the VAV model and the validation of the model with the experimental data. This paper introduces the VRF model and provides the simulation comparison of the VAV and VRF AC systems in terms of energy consumption and the indoor thermal comfort in the existing building.

2. VRF AC system

2.1. Existing building

The 3rd and 4th floors of the Chesapeake building, an administrative office building, constructed in 1991, located on the campus of University of Maryland, were used for the simulation comparison of VAV and VRF air conditioning systems. Details of the building structure and the internal load sources can be found in Ref. [26]. The zoning of the 3rd and 4th floors of with the zone numbers is provided in Fig. 1a and b, respectively.

2.2. VRF AC system

An available EnergyPlus VRF module, developed by Ref. [3,18] was used for the simulation evaluations of the VRF system. Basically, this module uses the existing air-cooled direct expansion (DX) coil in the EnergyPlus software, which determines the part load performance of the coil by using the total cooling capacity and the energy input ratio as a function of the part load fraction. The single DX coil is used for each indoor unit of the VRF system. The summation of each indoor unit's cooling capacity gives the total cooling capacity of the VRF system. The detailed formulation of the EnergyPlus VRF system module can be found in Ref. [19]. The developed model was validated experimentally in a steady-state chamber test [19,20] and in a field performance test [28].

The standard cooling capacities of the outdoor and indoor units; power input to the outdoor unit under varying outdoor and indoor conditions; and the airflow rates of each indoor unit are required by the EnergyPlus VRF system module as inputs. This required information can be found from the manufacturer's data [27].

The building model in the EnergyPlus software, described in Ref. [26] was run for a summer design day under the same internal load profile provided in Ref. [26]. For the summer design day, the maximum dry bulb temperature was selected as 34 °C, and the daily temperature range was selected as 10 °C [25]. The VRF indoor units were selected for 38 zones from the manufacturer's performance data to meet the cooling loads obtained from the EnergyPlus software [27]. Tables 1 and 2 show the information of the indoor units located in each zone on the 3rd and 4th floors, respectively.

For the outdoor unit selection, it was found that only one outdoor unit was available in the manufacturer's data, with a standard cooling capacity of 28.13 kW [27].

The developed EnergyPlus VRF module allows eight indoor units to be connected to one outdoor unit based on a combination ratio (CR), which is defined in Eq. (1).

$$CR = \frac{\sum \dot{Q}_{IU}}{\dot{Q}_{OU}} \quad (1)$$

The CR is the ratio of total standard cooling capacity of the indoor units connected to an outdoor unit to the standard cooling capacity of the corresponding outdoor unit. The manufacturer's data indicate that the several indoor units can be connected to one outdoor unit, as long as the CR is within 0.5 and 1.3 [27]. This is because, in terms of capacity, the outdoor unit is considered as "an oversized outdoor unit for the indoor units" when the CR is less than 0.5. On the other hand, for a CR higher than 1.3, the capacity of the outdoor unit is considered "not sufficient for the indoor units". The preferable CR value is 1.0. Based on this recommendation on the CR, the number of outdoor units, used for 38 indoor units was defined. Totally ten outdoor units were found to be sufficient for 38 indoor units. The outdoor and indoor units with the CR values can be found in Table 3.

On the other hand, the part load ratio of the outdoor unit is defined in Eq. (2) [3,28].

$$PLR = \frac{\dot{Q}_{OU,T}}{\dot{Q}_{OU}} \quad (2)$$

The coefficients of the performance curves used in the EnergyPlus software were obtained by curve fitting the manufacturer's data [27].

A typical VRF system structure (connection of indoor and outdoor units) can be found in Ref. [12].

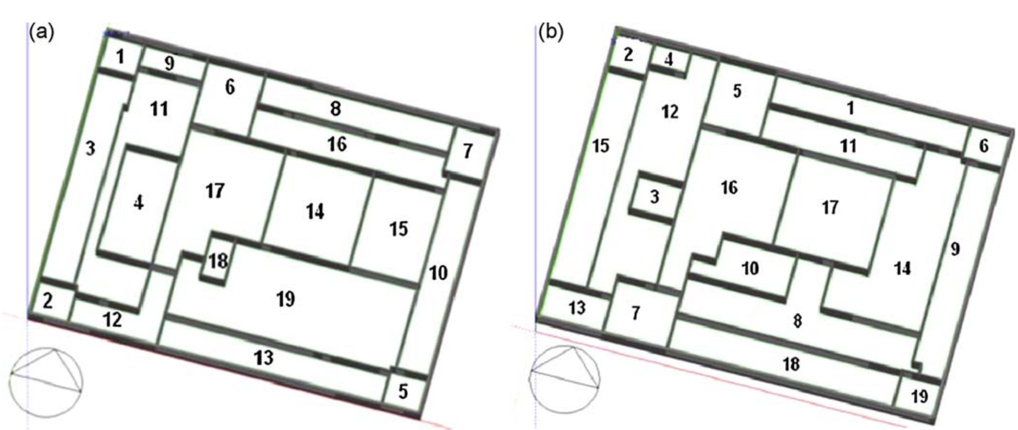

Fig. 1. Zoning of the 3rd and 4th floors, (a) 3rd floor (top view), (b) 4th floor (top view).

Table 1
Information for the VRF indoor units served on the 3rd floor.

Zones	Indoor unit	Indoor unit type	Cooling capacity W (BTU/h)	Airflow rate m^3/s (cfm)	
				Maximum	Minimum
1	IU31	Wall mounted	3,516 (12,000)	0.142 (300)	0.085 (180)
2	IU32	Wall mounted	3,516 (12,000)	0.142 (300)	0.085 (180)
3	IU33	Ceiling mounted built-in	28,128 (96,000)	1.36 (2600)	0.896 (1900)
4	IU34	Ceiling mounted	3,516 (12,000)	0.217 (460)	0.165 (350)
5	IU35	Wall mounted	3,516 (12,000)	0.142 (300)	0.085 (180)
6	IU36	Wall mounted	3,516 (12,000)	0.142 (300)	0.085 (180)
7	IU37	Wall mounted	3,516 (12,000)	0.142 (300)	0.085 (180)
8	IU38	Ceiling mounted	7,032 (24,000)	0.316 (670)	0.231 (490)
9	IU39	Wall mounted	3,516 (12,000)	0.142 (300)	0.085 (180)
10	IU310	Ceiling mounted	7,032 (24,000)	0.316 (670)	0.231 (490)
11	IU311	Ceiling mounted	5,274 (18,000)	0.236 (500)	0.189 (400)
12	IU312	Wall mounted	3,516 (12,000)	0.142 (300)	0.085 (180)
13	IU313	Ceiling mounted built-in	14,064 (48,000)	0.68 (1300)	0.448 (950)
14	IU314	Ceiling mounted	3,516 (12,000)	0.217 (460)	0.165 (350)
15	IU315	Ceiling mounted	3,516 (12,000)	0.217 (460)	0.165 (350)
16	IU316	Ceiling mounted	10,548 (36,000)	0.467 (990)	0.349 (740)
17	IU317	Ceiling mounted	3,516 (12,000)	0.217 (460)	0.165 (350)
18	IU318	Wall mounted	3,516 (12,000)	0.142 (300)	0.085 (180)
19	IU319	Ceiling mounted	10,548 (36,000)	0.467 (990)	0.349 (740)

Table 2
Information for the VRF indoor units served on the 4th floor.

Zones	Indoor unit	Indoor unit type	Cooling capacity W (BTU/h)	Airflow rate m^3/s (cfm)	
				Maximum	Minimum
1	IU41	Ceiling mounted built-in	21,096 (72,000)	0.996 (1970)	0.679 (1440)
2	IU42	Ceiling mounted	10,548 (36,000)	0.467 (990)	0.349 (740)
3	IU43	Wall mounted	3,516 (12,000)	0.142 (300)	0.085 (180)
4	IU44	Wall mounted	3,516 (12,000)	0.142 (300)	0.085 (180)
5	IU45	Wall mounted	3,516 (12,000)	0.142 (300)	0.085 (180)
6	IU46	Wall mounted	3,516 (12,000)	0.142 (300)	0.085 (180)
7	IU47	Wall mounted	3,516 (12,000)	0.142 (300)	0.085 (180)
8	IU48	Ceiling mounted	8,790 (30,000)	0.467 (990)	0.335 (710)
9	IU49	Ceiling mounted built-in	14,064 (48,000)	0.680 (1300)	0.448 (950)
10	IU410	Wall mounted	3,516 (12,000)	0.142 (300)	0.085 (180)
11	IU411	Ceiling mounted	5,274 (18,000)	0.269 (570)	0.184 (390)
12	IU412	Ceiling mounted built-in	14,064 (48,000)	0.680 (1300)	0.448 (950)
13	IU413	Wall mounted	5,274 (18,000)	0.269 (570)	0.184 (470)
14	IU414	Ceiling mounted	3,516 (12,000)	0.217 (460)	0.165 (350)
15	IU415	Ceiling mounted built-in	28,128 (96,000)	1.36 (2600)	0.896 (1900)
16	IU416	Ceiling mounted	3,516 (12,000)	0.217 (460)	0.165 (350)
17	IU417	Ceiling mounted	3,516 (12,000)	0.217 (460)	0.165 (350)
18	IU418	Ceiling mounted built-in	17,580 (60,000)	0.897 (1760)	0.613 (1300)
19	IU419	Wall mounted	3,516 (12,000)	0.217 (460)	0.165 (350)

2.3. HRV system

Since the VRF systems cannot provide any ventilation which is required by the ASHRAE standards, additional ventilation systems are necessary to be installed [12,13]. Heat recovery ventilation (HRV) system widely used in conjunction with the VRF system was considered as the ventilation system. The HRV system basically provides fresh air while recovering heat from the exhaust air stream in order to reduce the ventilation loads. A typical HRV unit used in conjunction with a VRF system can be found in Ref. [14].

The required ventilation rates of each zone were determined based on the ANSI/ASHRAE Standard 62.1 [29] for a maximum expected occupancy profile, and the area of the corresponding zone [12]. One HRV unit can be used for the ventilation of several zones, depending on the required ventilation rates of the zones and the airflow rate capacity of the HRV unit. Two available HRV units introduced in Ref. [12] were considered. Table 4 shows the HRV units with the manufacturer's airflow rate data, and the zones they provide ventilation.

The existing stand-alone energy recovery ventilator (ERV) module in the EnergyPlus software was used for the modeling of the HRV units. Stand-alone ERV consists of the supply and exhaust air fans and an air-to-air heat exchanger. The detail information for the ERV module can be found in Ref. [13].

Table 3
Outdoor and indoor units with the CR values.

Outdoor unit	Indoor units	CR
OU1	IU31 + IU32 + IU317 + IU320	1.00
OU2	IU33	1.00
OU3	IU34 + IU35 + IU36 + IU37 + IU38 + IU310	1.00
OU4	IU39 + IU313 + IU314 + IU318 + IU319	1.00
OU5	IU312 + IU315 + IU316 + IU44 + IU45 + IU46 + IU412	1.00
OU6	IU41 + IU47 + IU48	1.00
OU7	IU43 + IU49 + IU411 + IU414	1.00
OU8	IU410 + IU413	1.00
OU9	IU416	1.00
OU10	IU415 + IU418 + IU419 + IU420 + IU421	1.13

3. Comparison of the VAV and VRF AC systems

The VAV and VRF systems were compared under the same indoor and outdoor conditions for the summer period of June, July and August 2007. The actual outdoor condition of summer 2007

Table 4
HRV units and the zones.

HRV units	Manufacturer's airflow rate data (m^3/s)	Ventilation for the zones	
HRV-31	0.069	Zones on the 3rd Floor	1, 2, 3, 9, 12
HRV-32	0.069		6, 11
HRV-33	0.069		4, 17, 18
HRV-34	0.069		8, 17
HRV-35	0.069		5, 7, 14, 15
HRV-36	0.139		14, 19
HRV-41	0.069	Zones on the 4th Floor	2, 3, 4, 13, 15
HRV-42	0.069		5, 7, 12
HRV-43	0.069		1, 6, 11
HRV-44	0.069		16, 17
HRV-45	0.069		9, 14
HRV-46	0.139		8, 10, 18, 19

Table 5
Internal load profile.

	Hours	Lights	Electric Equipments	Occupants
Weekday	00:00–08:00	20%	20%	0%
	08:00–17:00	100%	100%	100%
	17:00–24:00	20%	20%	0%
Weekend	00:00–24:00	20%	20%	0%

obtained from Ref. [30] was used for the EnergyPlus weather file [25]. The thermostat set temperatures for each zone, provided in Ref. [26], were kept same for both VAV and VRF simulations. Table 5 shows the assumed internal load profile used for the comparisons. The internal load sources can be found in Ref. [26].

It was found that the coefficient of performance (COP) of the state-of-the art rooftop units (RTU) varied from 2.9 to 3.4 depending on the capacity of the RTU. The highest COP of 3.4 was found for a RTU with a capacity of 105.5 kW (30 t) [31]. In this simulation comparison of VAV and VRF AC systems, instead of using the existing 1991 model RTU with a rated COP of 2.0, described in Ref. [26], the state-of-the art RTU with a rated COP of 3.4 was considered for a fair comparison.

4. Results and discussion

4.1. Case I: Combined no-reheat and reheat boxes

The RTU based VAV system with 9 VAV no-reheat and 29 VAV reheat boxes, described in Ref. [26], and the VRF system described in Chapter 2 were compared.

Two different indoor unit fan operations, continuous and synchronized, were considered for the VRF indoor units. In the "continuous indoor unit fan" operation, the indoor unit fans were operated continuously throughout the ON time regardless of the indoor unit operation. On the other hand, in the "synchronized indoor unit fan" operation, the indoor unit fans were synchronized with the indoor unit operation, namely, they were only operated when the indoor units provided cooling, and stopped when the indoor units did not [13].

The economizer feature, which provides free-cooling, was also considered for the HRV units. The indoor set temperatures were used for the high temperature limit and for the low temperature limit, 15 °C (59 °F) was selected to prevent overcooling, which may cause an uncomfortable indoor environment. In addition, the exhaust air enthalpy was also used as a third parameter. Overall, when the outdoor temperature was within the high and low temperature limits and the enthalpy of the outdoor air was lower than the exhaust air enthalpy, the outdoor and exhaust airflows were fully bypassed around the heat exchanger in the HRV unit in order to provide free-cooling [13,25].

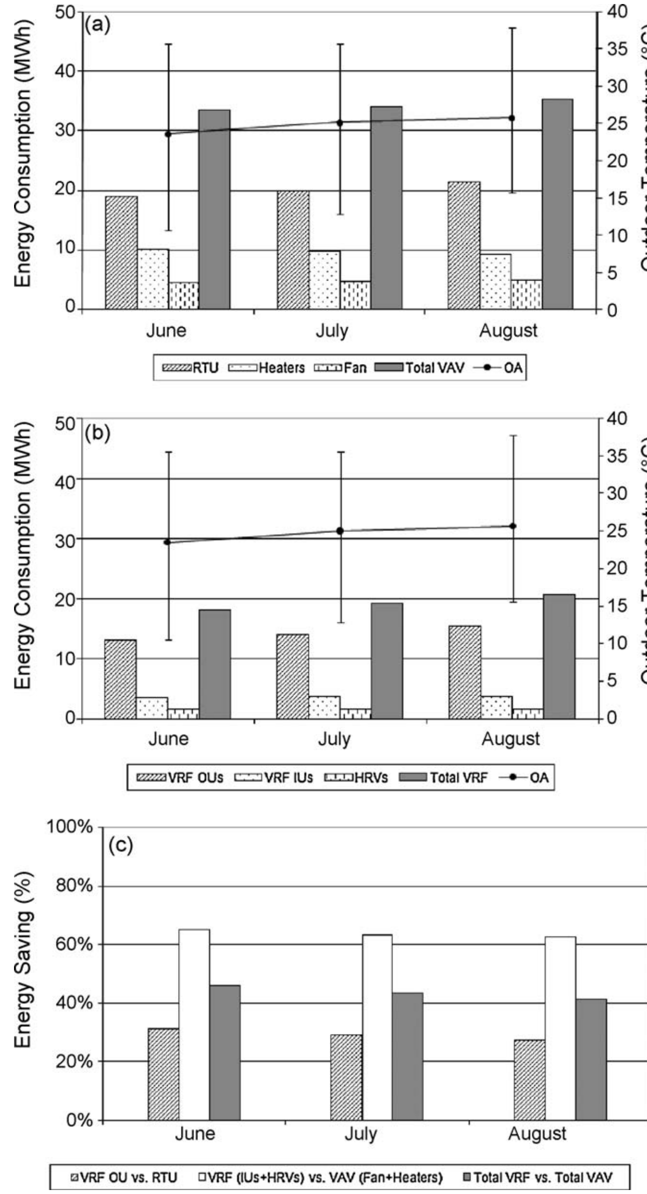

Fig. 2. Monthly energy consumption of the VAV and VRF systems and the energy-saving potential of the VRF system, (a) VAV system, (b) VRF system, (c) energy-saving potential of the VRF system.

4.1.1. Continuous indoor unit fan without economizer for the VRF system

Fig. 2a and b show the monthly energy consumption of the VAV and VRF systems, respectively with the monthly averaged outdoor temperature of the summer period of 2007. The monthly maximum and minimum outdoor temperatures are also provided in Fig. 2a and b with the bars. Fig. 2c shows the energy-saving potentials of the VAV as compared to the VRF systems.

As seen in Fig. 2a, when the monthly averaged outdoor temperature increases from 23.5 °C (June) to 25.0 °C (July), the monthly energy consumption of the VAV RTU increases from 19.0 MWh to 19.76 MWh; however, the monthly total energy consumption of the heaters of the VAV reheat boxes (i.e. the total energy consumption of the VAV reheat boxes) decreases from 10.11 MWh to 9.62 MWh. The reason for the reduction in the energy consumption of the heaters is due to the increase of the cooling demand. As described in Ref. [26], the heater of the VAV reheat box is only ON, when the damper of the VAV reheat box is closed to its minimum opening. Under the same conditions, when the outdoor temperature increases, the required cooling demand increases, and the VAV system needs to provide more airflow rate accordingly in order to keep the indoor temperature at the set temperature. That is why; the total ON period of the heaters decreases and results in a reduction in the energy consumption, when the outdoor temperature increases. Similar trend can be seen from Fig. 2a, when the monthly averaged outdoor temperature increases from 25.0 °C (July) to 25.7 °C (August).

It is observed that the heaters of the VAV reheat boxes share a significant portion (26.1–30.1%) of the total energy consumption of the VAV system.

As seen in Fig. 2b, when the monthly averaged outdoor temperature increases from 23.5 °C (June) to 25.0 °C (July), the monthly total energy consumption of the VRF outdoor units (i.e. the total energy consumption of 10 outdoor units) increases from 13.05 MWh to 14.00 MWh. For the "continuous indoor unit fan" operation, the power consumption of each indoor unit is constant throughout the day [13]. The monthly energy consumption of the VRF indoor unit fans is found to be 3.51 MWh in June and 3.63 MWh in July and August. Similarly, each fan power of the HRV units is constant throughout the day, and the monthly energy consumption of the HRV units is found to be 1.56 MWh in June and 1.61 MWh in July and August.

It is found that the VAV system provides 5.4–8.2% more cooling than the VRF system. This is due to the VAV reheat boxes. The VAV system requires more cooling to control the indoor temperatures.

As seen in Fig. 2c, it is observed that the energy-saving potential of the secondary system components (i.e. VRF indoor units and HRV units vs. VAV reheat boxes and VAV RTU fan) is higher than that of the primary system components (i.e. VRF outdoor units vs. VAV RTU). It is found that the primary and the secondary components of the VRF system promise 27.3–31.3%, and 62.4–65.3% energy-saving potentials, respectively when compared to the VAV system components. Overall, it is concluded that using the VRF system instead of the VAV system promises 41.2–46.1% energy-saving potentials.

Fig. 3a and b show the provided indoor condition of four zones by the VAV and VRF systems, respectively. Zones located on the 3rd and the 4th floors are "Zone 3rd 12", "Zone 3rd 18", and "Zone 4th 7" and "Zone 4th 4", respectively.

As seen in Fig. 3a, the VAV reheat boxes can maintain the indoor temperatures of "Zone 3rd 12", "Zone 4th 7" and "Zone 4th 4" at the set temperatures for a wide range of outdoor condition. However, it is observed that the VAV no-reheat box cannot keep the indoor temperature of "Zone 3rd 18" at the set temperature of 22.7 °C properly. This is because, depending on the internal load, even the minimum airflow rate supplied by the VAV no-reheat box provides too much cooling for the corresponding zone resulting in a lower indoor temperature than the set temperature.

As seen in Fig. 3b, the indoor temperatures of each zone can be maintained at the set temperature by the VRF system for a wide range of outdoor conditions. The indoor temperature data lower than the set temperature are due to the low outdoor temperature [13]. The HRV and VRF indoor units were independently operated. When the indoor temperature is lower than the set temperature, the VRF indoor unit does not provide cooling, however, the HRV unit still provides ventilation, which reduces the indoor temperature depending on the internal load.

Considering Fig. 3a and b, it can be said that the VRF system provides better thermal comfort compared to the VAV no-reheat boxes by eliminating over cooling.

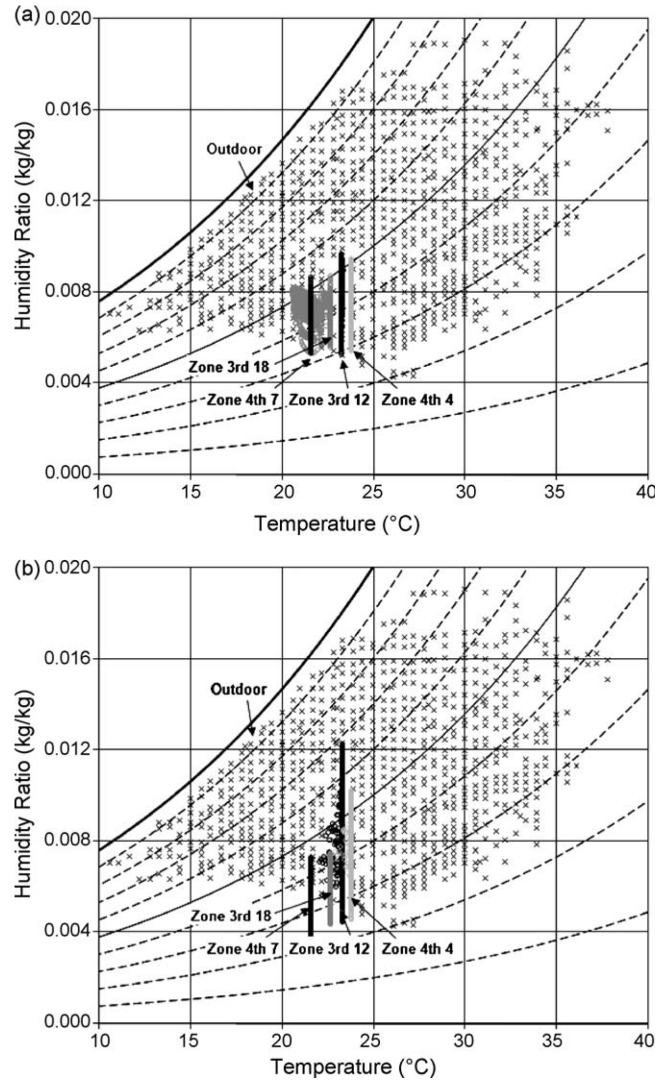

Fig. 3. Comparison of the indoor conditions for Case I, (a) VAV system, (b) VRF system.

4.1.2. Synchronized indoor unit fan operation with economizer for the VRF system

It is found that the energy-saving potential of the VRF AC system increases for the "synchronized indoor unit fan operation with the economizer" compared to the "continuous indoor unit fan operation without economizer" [13]. This is because, in addition to the free-cooling obtained by the economizer feature of the HRV units, the operation times of the indoor fans are reduced in the "synchronized indoor unit fan operation with economizer" case which decreases the energy consumption of the indoor unit fans and also decreases the internal load coming from the indoor units [13].

It is found that energy-saving potential for the secondary components of the VRF system increases from 62.4–65.3% to 79.2–81.5% for the "synchronized indoor unit fan operation with the economizer", when compared to the "continuous indoor unit fan operation without economizer".

In addition to the secondary components, it is also found that the energy-saving potentials of the VRF AC system increase from 41.2–46.1% to 49.3–54.8% for the "synchronized indoor unit fan operation with economizer", when compared to the "continuous indoor unit fan operation without economizer".

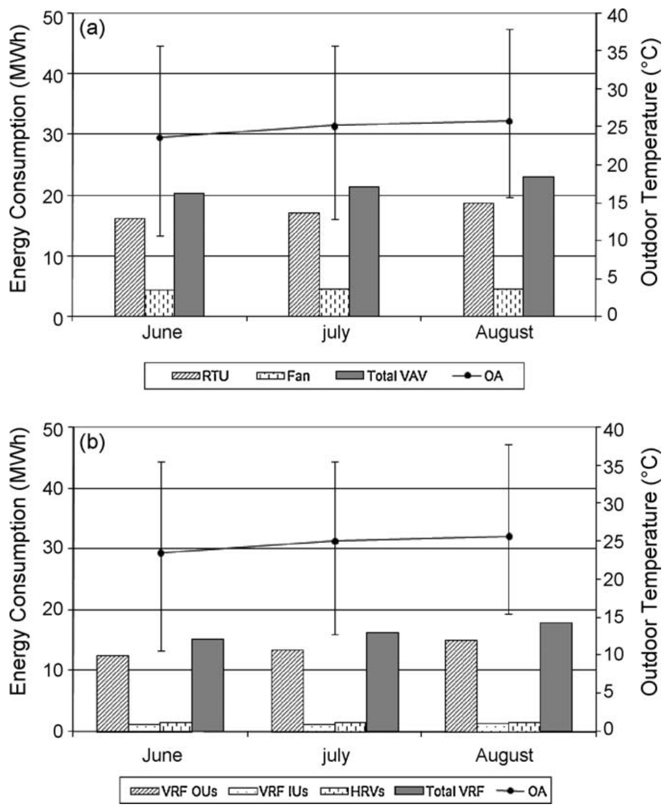

Fig. 4. Monthly energy consumption of the VAV and VRF systems for Case II, (a) VAV system, (b) VRF system.

4.2. Case II: VAV no-reheat boxes configuration

As described in Ref. [26], the existing VAV system is composed of 9 VAV no-reheat boxes and 29 VAV reheat boxes. In Case II, 29 VAV reheat boxes were replaced with 29 VAV no-reheat boxes in order to eliminate the parasitic energy consumption associated with the heaters of the VAV reheat boxes. The maximum and minimum airflow rates of the existing VAV reheat boxes were used as the maximum and minimum airflow rates of the new VAV no-reheat boxes. "Synchronized indoor unit fan operation with the economizer" case was applied to the VRV system.

Fig. 4a and b show the monthly energy consumption of the VAV and VRF systems, respectively with the monthly averaged outdoor temperature of the summer 2007.

As seen in Fig. 4a, since all the VAV boxes are no-reheat boxes, there is no energy consumption related to the heaters. It is found that the energy consumption of the VAV RTU increases from 17.36 MWh to 19.83 MWh, when the monthly averaged outdoor temperature increases from 23.5 °C (June) to 25.7 °C (August). Similarly, as seen in Fig. 4b, the energy consumption of the VRF outdoor units increases with the increasing outdoor temperature.

Since all the VAV boxes are no-reheat boxes, the provided cooling decreases. It is found that the VAV system provides 7.1–8.9% less cooling, than the VRF combined no-reheat and reheat boxes (Case I). For Case II, it is found that the VRF system provides 1.6–3.4% more cooling than the VAV system.

It is observed that since there is no energy consumption associated with the reheat heaters, the energy-saving potential of the VRF system compared to the VAV system decreases. It is found that the primary and the secondary components of the VRF system promise 24.5–28.0%, and 38.0–39.1% energy-saving potentials, respectively when compared to the VAV system. It is found that the VRF outdoor units were operating at low PLRs most of the operation time. The minimum, maximum and average percentages of PLR data points lower than 0.4 are found to be 65.2%, 73.1% and 70.6%, respectively. Since the VRF systems have higher part load efficiencies [3], VRF primary component promises energy-saving potentials compared to the VAV primary one.

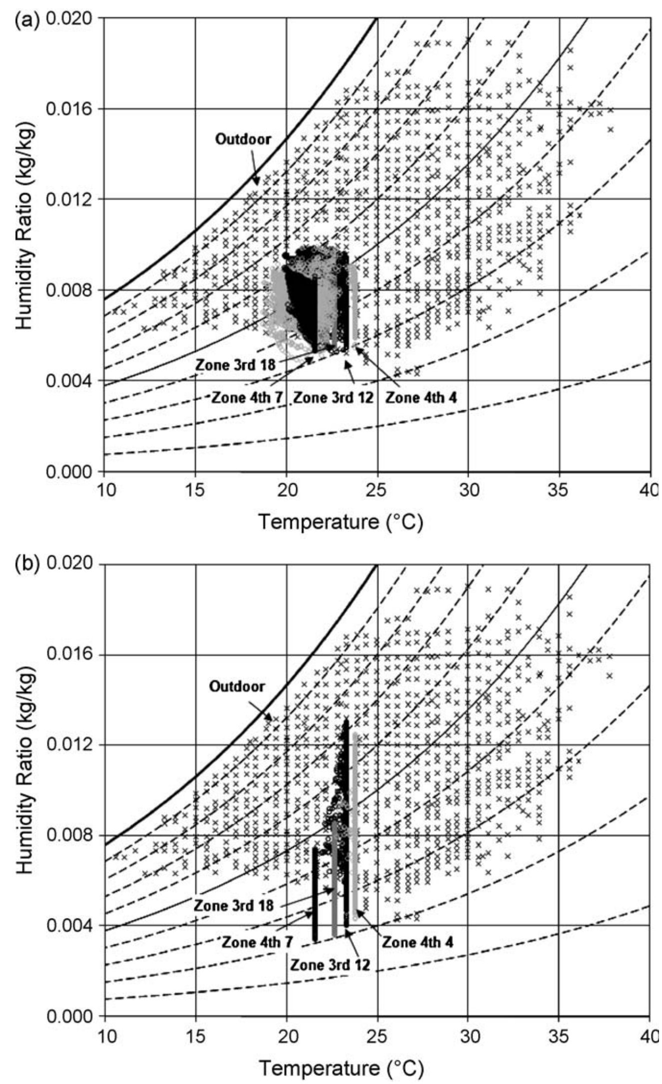

Fig. 5. Comparison of the indoor conditions for Case II, (a) VAV system, (b) VRF system.

Overall, it is found that using the VRF system instead of the VAV system with no-reheat boxes has an energy-saving potential ranging from 27.1% to 30.3%.

Fig. 5a and b show the provided indoor condition by the VAV and VRF systems, respectively. As seen in Fig. 5a, the indoor temperatures cannot be maintained properly at the set temperature by the VAV no-reheat boxes; however, as seen in Fig. 5b, the indoor temperatures can be kept at the set temperature by the VRF system.

It is observed that there is a trade-off between the energy consumption and the indoor temperature control for the VAV boxes. Using the VAV no-reheat boxes instead of the VAV reheat boxes reduces the total energy consumption of the VAV system; however, it scarifies the indoor temperature control resulting in worse thermal comfort.

4.3. Case III: VAV reheat boxes configuration

In Case III, the existing 9 VAV no-reheat boxes located on the 3rd floor were replaced with VAV reheat boxes. The maximum and

Table 6
Heater capacities for the new VAV reheat boxes.

Zone	Heater capacity (kW)
4	4.0
6	2.5
11	4.5
14	3.5
15	4.5
16	3.5
17	4.5
18	1.5
19	8.5

minimum airflow rates of the existing VAV no-reheat boxes were used as the maximum and minimum airflow rates of the new VAV reheat boxes. As for the assumption of the heater capacities, the maximum airflow rate and the corresponding heater capacity of the existing VAV reheat boxes provided in Table 2 in Ref. [26] were considered. Table 6 shows the assumed heater capacities for the new VAV reheat boxes. "Synchronized indoor unit fan operation with the economizer" case was applied to the VRF system.

Fig. 6a and b show the monthly energy consumption of the VAV and the VRF systems, respectively with the monthly averaged outdoor temperature of the summer 2007.

As seen in Fig. 6a, since all the VAV boxes are reheat boxes, the total energy consumption associated with the heaters is significant. It is found that the primary and secondary components of the VRF system promise 32.3–37.0%, and 81.4–83.4% energy-saving potentials, respectively, when compared to the VAV system. Overall, it is found that using the VRF system instead of the VAV system with VAV reheat boxes has an energy-saving potential varying from 52.7% to 57.9%.

Fig. 7a and b show the provided indoor condition by the VAV and VRF systems, respectively. As can be seen, VAV system with the

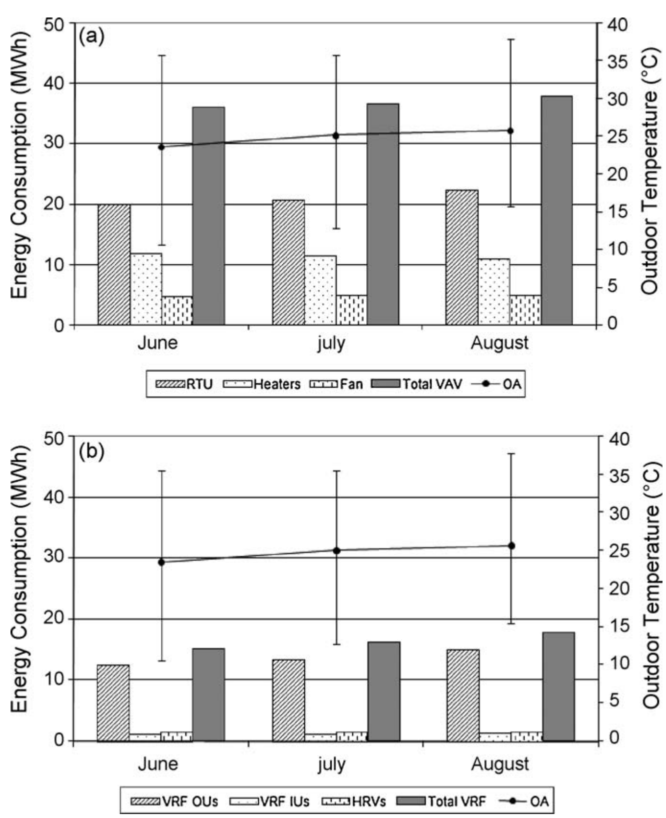

Fig. 6. Monthly energy consumption of the VAV and VRF systems for Case III, (a) VAV system, (b) VRF system.

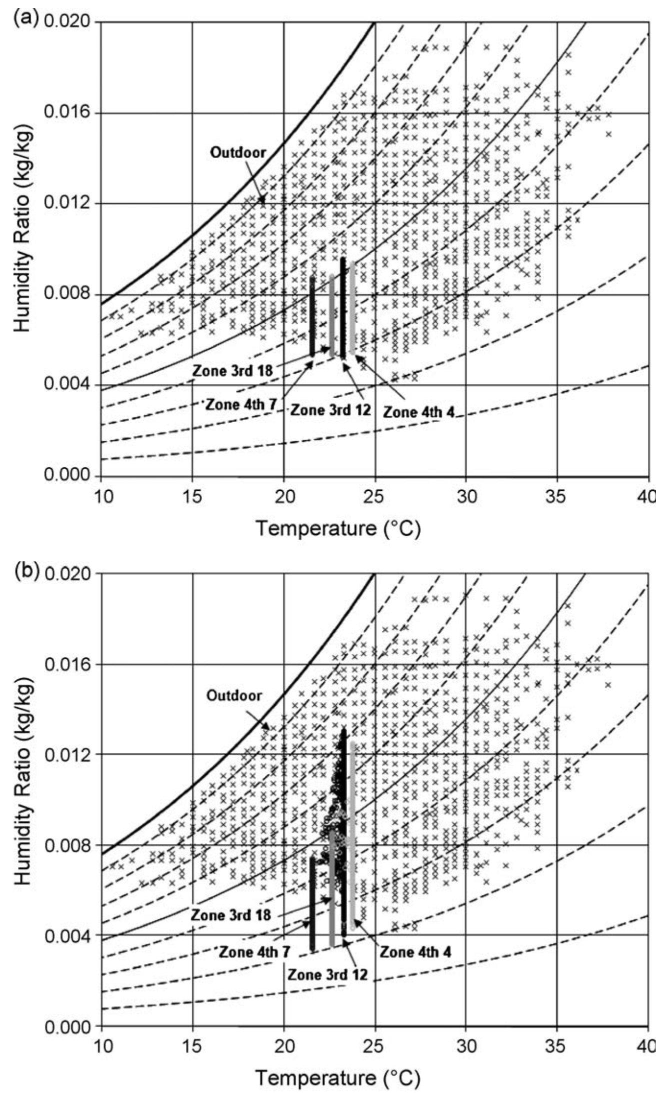

Fig. 7. Comparison of the indoor conditions for Case III, (a) VAV system, (b) VRF system.

reheat boxes and the VRF system can maintain the indoor temperatures at the set temperatures.

It is observed that using the VAV reheat boxes instead of the VAV no-reheat boxes increases the energy consumption of the VAV system significantly due to the energy consumption of the heaters; however, on the other hand, the indoor thermal comfort improves significantly because of the better indoor temperature control.

5. Conclusions

Two widely used air conditioning systems; variable air volume (VAV) and variable refrigerant flow (VRF) were compared numerically in an existing office building environment under the same outdoor conditions and internal load profiles for an entire cooling season. The following conclusions were deduced from the evaluations:

- There is a trade-off between the energy consumption and the indoor temperature control for the VAV system. It is observed that the indoor temperatures cannot be maintained properly at the set temperature without the VAV reheat boxes, but can be maintained with the VAV reheat boxes with an energy consumption penalty up to 65.8%.

- It is observed that the heaters of the VAV reheat boxes consume significant energy in order to control the indoor temperature. Due to the energy consumption penalty, it is found that the secondary components (indoor and ventilation units) of the VRF promises energy-saving potential when compared to the secondary components (heaters and the supply fan) of the VAV system. For Case I, the secondary components of the VRF system promises 79.2–81.5% energy-saving potentials, depending on the indoor and outdoor conditions, when the "synchronized indoor unit fan operation with economizer" is applied to the VRF system. Overall, it is found that the VRF system promises 49.3–54.8% energy-saving potentials, when compared to the VAV system.
- For Case II, VAV system with no-reheat boxes vs. VRF system, the primary and the secondary components of the VRF system promise 24.5–28.0% and 38.0–39.1% energy-saving potentials, respectively, when compared to the VAV system. It is found that the VRF outdoor units were operating at low PLRs most of the operation time. Since the VRF systems have higher part load efficiencies, VRF primary component promises energy-saving potential compared to the VAV primary one. Overall, it is found that using the VRF system instead of the VAV system which has only no-reheat boxes has an energy-saving potential varying from 27.1% to 30.3%. In addition, it is observed that the VRF system provides better indoor thermal comfort due to the better indoor temperature control, when compared to the VAV system.
- For Case III, VAV system with reheat boxes vs. VRF system, the primary and the secondary components of the VRF system promise 32.3–37.0% and 81.4–83.4% energy-saving potentials, respectively, when compared to the VAV system. Overall, it is found that using the VRF system instead of the VAV system which has only reheat boxes has an energy-saving potential varying from 52.7% to 57.9%. Since both systems can control the indoor temperature at the set temperature, it can be said that both systems provide similar indoor thermal comfort.

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