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Module Development and Simulation of the Variable Refrigerant Flow Air Conditioning System under Cooling Conditions in Energyplus

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Abstract: As a high-efficiency air conditioning scheme, the variable refrigerant flow (VRF) air-conditioning system is finding its way into medium-sized office buildings. Based on a generic dynamic building energy simulation environment, EnergyPlus, a new module is developed and the energy usage of the VRF system is investigated. This paper compares the energy consumption of the VRF system with that of two conventional air-conditioning systems, namely, the variable air volume (VAV) system and the fan-coil plus fresh air (FPFA) system. A generic office building is used to accommodate the different types of heating, ventilating, and air conditioning (HVAC) systems. Our objective is to examine the energy consumption of the VRF system applied to office buildings and make suggestions for evaluating and making decisions on HVAC systems in the early stages of building design. Simulation results show that the energy-saving potential of the VRF system is expected to achieve 22.2 percent and 11.7 percent, compared to the VAV system and the FPFA system, respectively. An energy-usage breakdown of electricity end-users in various systems is also presented.

Key words: Energy simulation, office buildings, HVAC systems, variable refrigerant flow air-conditioning system, energy usage

1. INTRODUCTION

As the world 's second largest energy consumer behind only the United States, China is now also one of the largest oil importers in the world[1]. Statistics on total energy consumption and building energy consumption shows that the proportion of building energy consumption to the total energy consumption in China's end-use sectors is expected to inevitably amount to 35% in the near future [2]. Furthermore, recent work on computer energy simulation studies and field surveys reveals that air conditioning represent 37~60% of total electricity use in office buildings, in accordance with buildings' functions[3, 4]. Consequently, studies on the effects of heating, ventilating and air conditioning (HVAC) system, along with building envelope，novel technologies about the utilization of natural energy and occupant behaviors, on energy efficiency by simulation is becoming concerns for professionals in this field[5-10]. This paper addresses the simulation of a variable refrigerant flow air-conditioning (VRF) system, which is earning popularity in commercial buildings such as small offices, shopping centers, hotels, and domestic occasions in China.

At present, researchers in the VRF field focus their interests mainly on features of the equipment itself, e.g. the simulation or experiment of the control logic of the variable speed compressor, refrigerant distribution, and the control method of electric expansion valve (EEV), or modeling of novel algorithm for various types of system part[11-14].

For decision-makers and practitioners in the HVAC industry concerned, especially for those who show some interest about high-efficiency systems like VRF, it becomes of interest to compare the VRF to other systems and evaluate VRF's performance early in the stage of building design.

So far, there is no well-known energy simulation software available yet which can be used for the energy analysis of VRF. The purpose of the investigation is to develop a new model in Energyplus, which is a new-generation building energy simulation program (BESP) [15, 16], in an attempt to predict and evaluate the energy-use level of the VRF air-conditioning system and hence to make comparisons with other HVAC systems. The energy examination of various air-conditioning strategies supports energy researchers and building owners in decision-making. The knowledge of how choices of the HVAC system affect the building performance can serve as a powerful tool for building designers and owners when they choose the system at last. This study aims to reveal the energy features and energy audit of VRF and provide insights in balancing various types of system plan and justifying the most appropriate system, and further, the differences can be quantified [17-19].

The module newly-developed has been testified[20] to be able to simulate the VRF system's energy characteristics at part load operating conditions by comparing simulation outcomes to experimental results in a literature. As covered in this study, the paper is concerned with application of Energyplus with the validated model. A generic commercial office building in Shanghai is used for the simulation study. Through graphical analysis, the energy consumptions of three popular systems, namely, the variable-air-volume (VAV) system, the VRF system, the Fan-coil Plus Fresh Air (FPFA) system, are presented and discussed.

2. MODELING AND PROGRAMMING OF VRF MODULE

2.1 Modelling of the VRF System in EnergyPlus

Hourly cooling loads for the building are calculated in this study by the building simulation program, Energyplus, which employs the heat balance engine with HVAC system integrated into the building simulation. More accurate than the weighting factor method used in its predecessors such as *DOE-2*, the heat balance method permits better simulation of a building's response to its heating and cooling system by allowing feedback between two main simulation components[21, 22]. The well-organized modular structure in the software allows users adding specific modules according to their own demands[23, 24]. The Energyplus program has been extensively validated through analytical, comparative, sensitivity, range, and empirical tests. The simulation results to date show good agreement with well-established simulation tools such as DOE-2.1E, BLAST, and ESP[25, 26].

Energyplus utilizes the performance-curve-oriented way to calculate the energy performance of HVAC systems. Detailed performance data and parameters, along with their applicability conditions usually shipped in the manufacture catalogue, therefore, are requirements.

First, the following relationship is established for the energy performance of the single DX cooling coil:

$$Q_{total} = Q_{total,rated}(TotCapTempModFac) \quad (1)$$

The single DX cooling coil acts here as the indoor unit of the VRF system, so the overall system performance is computed by the equation given as:

$$Power = \left[\sum_{k=1}^{n}(Q_{total} \times RTF \times MF)_k\right] \times (EIR) \quad (2)$$

$$EIR = \left(\frac{1}{COP_{rated}}\right)(EIRTempModFac) \quad (3)$$

Where:

Q_{total} = operating cooling capacity of the single DX coil at operation condition （W）;

$Q_{total,rated}$ = rated cooling capacity of the single DX coil （W）;

$TotCapTempModFac$ = total cooling capacity modifier with respect to temperatures. A function of two independent variables: wet-bulb temperature of the air entering the cooling coil, and dry-bulb temperature of the air entering the air-cooled condenser coil;

$EIRTempModFac$ = energy input ratio (EIR) modifier, also a function of two independent variables: wet-bulb temperature of the air entering the cooling coil, and dry-bulb temperature of the air entering the air-cooled condenser coil;

$Power$ = Power input of the VRF system;

k = index of indoor units;

n =total number of indoor units;

MF= modifier at part load ratio;

EIR=reverse of COP curve-fitted from catalogue data;

RTF = runtime fraction of the cooling coil. A ratio of part-load-ratio(PLR) to part load fraction (PLF, function of part load ratio);

COP_{rated} = rated coefficient of performance for the VRF system.

Then the energy features of VRF are determined through the above dominating mathematical equations.

Fig.1 shows the schematic process of modeling in the source codes of Energyplus. The new specific input parameters for the VRF are defined first in the InputProcessor module, which thereby gets the required information to simulate a VRF system. The energy consumption calculation of VRF is then embedded in the so-called ManageHVAC module. As the kernel program in the source codes of Energyplus, ManageHVAC conducts the whole HVAC system 's energy simulation , including air loops, zone equipments, plant supply and demand sides, and condenser supply and demand sides. After the simulation is finished successfully, electricity usage of the VRF system, as well as other abundant calculation results in CSV format, can be supplied to users for further research and analysis.

2.2 Description of the main VRF calculation program

Based on aforementioned modeling considerations, the coding work for calculation of the energy consumption of the VRF system is established at right place in the Energyplus source code and in the Energyplus coding style.

Fig.2 shows the schematic flowchart of the main energy computation program for the VRF system. Being consistent with the original open characteristics in Energyplus, the newly-developed module allows necessary expansibility. For example, in these codes, the number of indoor units is limited in eight currently. They are able to be extended to any desired amounts according to user needs.

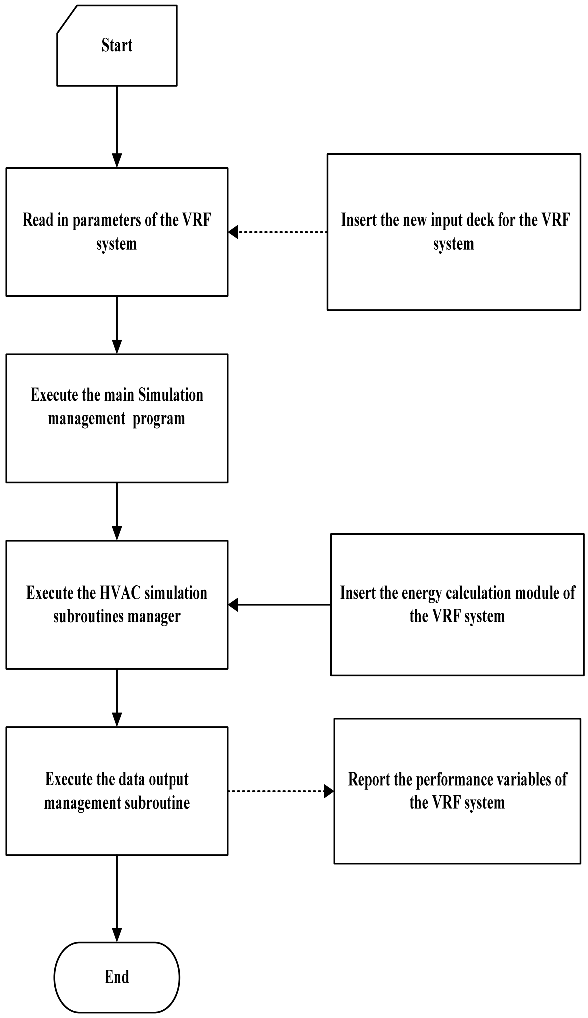


Fig. 1 Flowchart of the new VRF model embedded into EnergyPlus

3. CASE STUDIES: BUILDING AND SYSTEM DESCRIPTIONS

As an application of the VRF energy-calculation module in Energyplus, a comparative energy studies is conducted among three popular HVAC systems in China, namely, VAV, FPFA, and VRF. In this study, various systems are examined so that their applicability and features can be identified from the energy use's point view by simulation analysis.

A generic 10-storey office building is developed to serve as a platform which can accommodate different air-conditioning systems for the purpose of

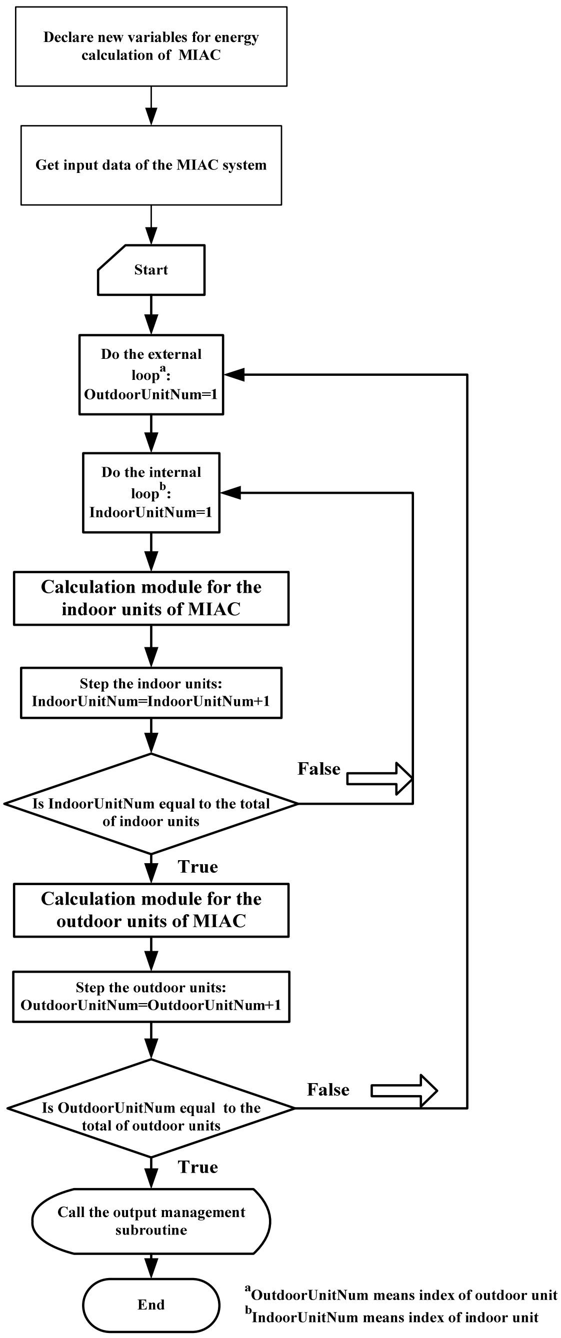


Fig.2 Flowchart of the main program for energy-use computation of the VRF system.

comparison research. The building type and materials selected for evaluation of different kinds of HVAC systems are based on the commercial building studied by D.H.W. Li[3], T.Miyazaki[27], and M.M.Ardehali[28]. However, in this study, some of the building envelope features are modified to meet the present research conditions.

Each floor of the building is divided into six conditioned thermal zones, corresponding to four outside exposures (north, east, south, and west), the interior zones, and the centre core. The typical floor in the simulation incorporates a floor-multiplier of 8 to account for the actual number of middle floors in the building. A summary of the key parameters of the building is given in Table 1, construction material properties is listed in Table 2, the typical floor plan and schematic diagram of three types of HVAC system are shown in Fig. 3. In this investigation, the following assumptions are made.

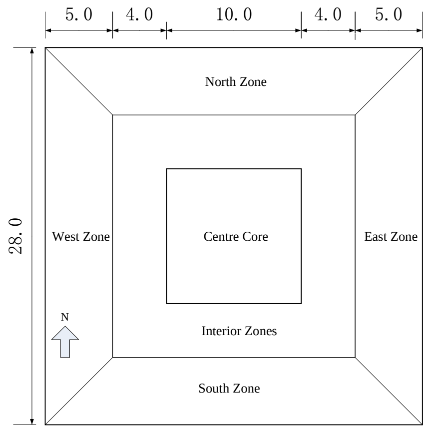
- All the floor plans in the sample building are the same. There are not basement spaces underneath the building.
- Only one type of HVAC system is installed to serve the building in each study.
- The indoor air set point is identical everywhere in the building.

The water-cooled type chiller and the VRF equipments from the same manufacturer are chosen to meet the cooling demand. There are not shading devices associated with the building envelope, nor are there any adjacent tall buildings that would bring on daytime shading. There is no roof glazing or skylights in the sample building. The geographical and weather file, infiltration, thermostat, and other parameters related to building load calculations are the same for all the HVAC systems simulated.

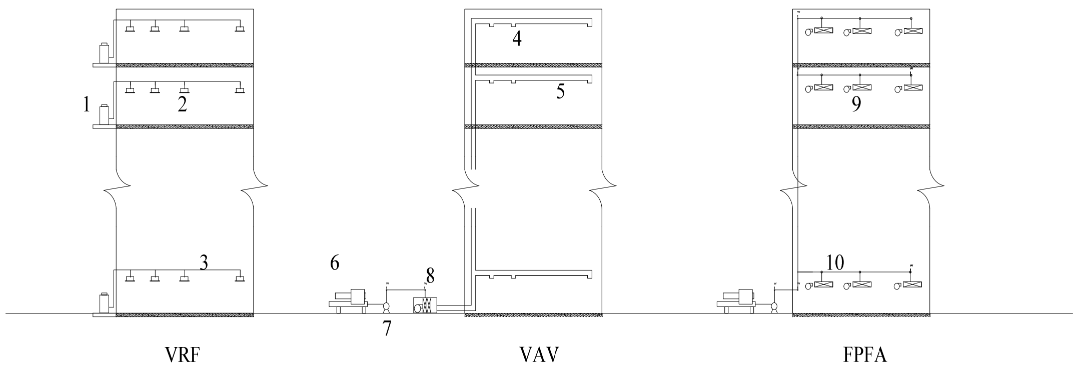
4. RESULTS AND DISCUSSION

A series of simulation are implemented for the performance comparison of the HVAC systems in this section. The results of the simulations for the purposes of evaluating systems are presented in categories that describe the energy consumption shares of the electricity end-users in systems such as VAV, FPFA, and VRF. Results show the differences among systems, as reported in Fig. 4. The breakdown of the total electrical energy consumption into various parts include system fans, chillers, pumps, space lighting, plug equipment, and VRF system. Energy usage of drink-water pumping, lifts and other non-HVAC-related power facilities is disregarded in electricity-usage breakdown of end users in the HVAC systems. In this figure," System

ESL-IC-06-11-80



(a)



Note: 1. VRF outdoor unit; 2.VRF Indoor unit; 3.Refrigerant loop; 4. Diffuser; 5. Duct; 6. Chiller; 7. Pump; 8. AHU; 9. Fan-coil Unit; 10. Water Pipe

(b)

Fig.3 (a) Typical floor plan of the sample building (Unit in meters); (b) Schematic diagram of three types of HVAC system

fans" means the central supply fan in VAV, or the aggregate of individual fans in FPFA, or the aggregate of indoor-unit fans in VRF; "Chillers" denotes energy consumption of chillers; "Pumps" refers to the chilled water and cooling water pumps; "VRF systems" stands for the energy input of VRF outdoor-units containing condenser fans, compressors, and control circuits; while "HeatRejection" is the tower fan electric consumption.

4.1 Breakdown of electricity end- users in HVAC systems

For the VAV system, lighting and plug load share a part of 46%, chillers 33%, system main supply fan 11%, water pumps 7%, and heat rejection keeps the left 3%; For the FPFA system, lighting and plug load share a part of 52% together, chillers 32%, indoor fans , system water pumps, and heat rejection hold 6%, 7% and 3%, respectively; For the VRF system, lighting and plug load own a part of 58%; the VRF system and indoor fans take the residual part 42%.

As the second largest energy consumer in the VAV system, the main air supply fan takes a remarkable larger part of electricity use than the indoor fans used in the FPFA and VRF systems. This share by the VAV supply fan is still much less than the survey data for a typical office building[4], whereas it agrees well with the simulation result of 14.1%~28.3% of the HVAC system consumption [29] comparatively. It can be explained that unreasonable choices and operation strategies of air transport facilities exist commonly in reality[30]. On-site measured data do not mean rational data. In a sense, thus, energy simulation of HVAC systems is able to put forward a gap as reference between the ideal consumption and the actual consumption of

Tab.1 Brief descriptions of the sample building and HVAC systems

Items	**Description**
General information	
Location	Shanghai, China
Building type and stories	Office building, 10 stories above ground
Floor areas	Total floor area=7,840 m^2
	Air-conditioned area=7,840 m^2
Floor area and height	28m ×28m; floor-to-floor height =3.5m
Windows and shading	Low-e double pane glazing. Window height=1.5 m; sill height= 0.80 m; WWR=30%. No shading device.
Operation hours	ON during weekdays: 7:00–17:00; OFF during all other days
Design values of internal heat gains, ventilation, and infiltration	
Occupancy density	5 m^2/person (perimeter and interior zones), 25 m^2/person (center core);
Lighting density	25 W/m^2 (perimeter and interior zones), 15 W/m^2 (center core);
Plug equipments load	20 W/m^2(perimeter and interior zones), 0 W/m^2 (center core);
Space design temperature	25.0°C
Infiltration	0.1 Air change per hour for each zone
Ventilation	4.0 m^3/(m^2.h) (perimeter and interior zones), 0.6 m^3/(m^2.h) (center core);
Night setup	37 °C;
Running period	June 1~ August 31, typical summer days in Shanghai (Ref. Weather file CTYW.STAT)
HVAC system and plant information	
HVAC systems	VAV No-reheat ; Fan-coil Plus Fresh Air(FPFA) ; VRF
Chiller types	Water-cooled screw chiller
Cooling source nominal COP (kW /kW)	Screw chillers for VAV and FPFA: 4.6 ; VRF units: 3.02
Fans and pumps	Variable speed drive(VSD) for the central fan and chilled water loop pumps in the VAV system ,and VSD for chilled water supply pumps in the FPFA system

Tab.2 Construction thermal properties

Layers (outer to inner)	**Thickness (mm)**	**Conductivity. (W/(m.K))**	**Density (kg/m^3)**	**Specific heat (J/(kg.K))**
Exterior wall				
Cast concrete	150	1.13	2000	1000
XPS Extruded Polystyrene	20	0.034	35	1400
Air gap	Thermal resistance R=0.18 m^2.K/m^2			
Plasterboard	15	0.25	2800	896
Interior wall				
Plaster(lightweight)	13	0.16	600	1000

Cast concrete	100	1.13	2000	1000
Plaster(lightweight)	13	0.16	600	1000
Ceiling/floor	(the order of floor materials is the reverse of that of ceiling materials)			
Cast concrete	150	1.13	2000	1000
Air gap	Thermal resistance R=0.18 $m^2.K/m^2$			
Plasterboard	10	0.16	950	840
Slate Tiles	10	2.00	2700	753

equipments. The indoor fan in the FPFA system uses 6% of energy, and its absolute magnitude locates in the middle of the fan energy in other two systems. It can be understood that there is a strong relationship between the fan energy and the type of cooling media. Specific enthalpy of refrigerant in the VRF system is much greater than water and air in other systems, and phase change takes place in the indoor evaporator, which are both believed to bring out less fan energy.

For the VRF system, the indoor fans' contribution to the whole VRF system's energy usage is 7%, according with the experimental result 9.8% [31] on the whole, considering diversity of application conditions and equipment series.

4.2 Summer electricity consumption for different systems

HVAC systems can be categorized to the all-air system, the water-air system, and the refrigerant system in accordance with the kinds of cooling media. Fig.4 depicts the electricity usage for HVAC systems. The VRF system is the most energy-efficient one among three sample cooling systems, followed by FPFA, while VAV ranks last, as shown in the figure. It denotes that an all-air system like VAV consumes more energy than either a water-air system (FPFA in this case) or a refrigerant system (VRF in this case), even though it is usually regarded as a high-efficiency system. The superiority of a VAV system is significant only if it is compared with a conventional constant air volume system[18,29].

The VRF system uses 11.7% less electrical energy than the FPFA system with a variable-speed-drive (VSD) loop water pump, 22.2% less electrical energy than the VAV system outfitted with a VSD fan in this case.

Owing to air-conditioning systems working usually off the rated condition, the par-load performance of the refrigeration equipments plays a significant role in final electricity usage of the building. The number of working hours of the three systems based on different part load ranges in this study is presented in Fig. 5. The profiles of part load show some differences, which are believed to be induced by diverse humidity levels during the simulation. Keeping the indoor air temperature at set point, the thermostat control makes the space humidity drift and results in various latent load and then the various total load. It can be seen from this figure that a notable majority of operation hours of all the VRF, FPFA and VAV systems occurs between 30% and 90% part-load operating conditions. The accumulative totals account for 79.3%, 83.7%, and 81.9% in the overall 660 operation hours for the VRF units, the chiller in the FPFA system and the chiller in the VAV system, respectively. It offers the VRF system an occasion to perform within its favorable energy-feature range in a significant part of working time. In other words, the VRF system is provided with a high efficiency at partial load condition and works at the condition in an essential part of operation time, which may be considered as one of reasons for its less energy usage. It may be established the more the VRF system works in the favorable part load range, the more energy savings can be achieved. As the cooling resources and the substantial energy consumers in other two HVAC systems, the screw chillers take similar efficiency at part load with that at full load[32] . Compared to the VRF system, this feature makes the chiller less sensitive to changes of the cooling load. Meanwhile, the refrigerant from nearby outdoor units in the VRF system goes directly to conditioned zones to exchange heat with air. By contrast, the chiller

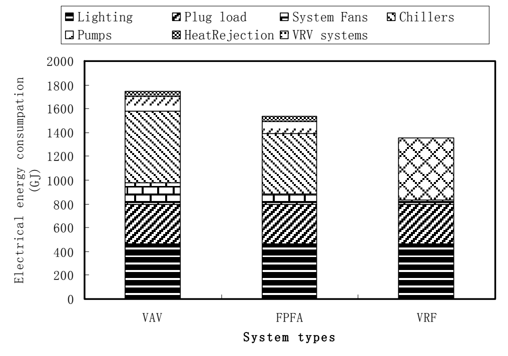


Fig. 4 Comparison of energy usage among three systems

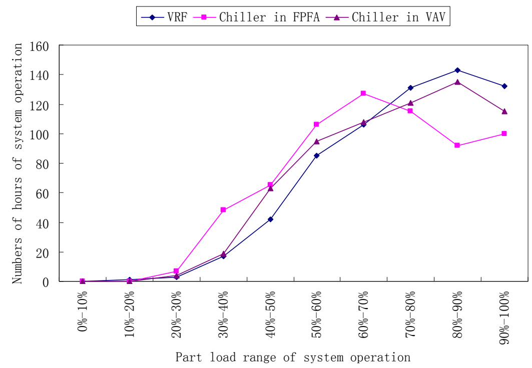


Fig. 5 Part load range of the three kinds of systems

needs one or two secondary heat-transfer process to pipe the low-specific-enthalpy cooling media, water or air, through a long way to cool the zones in the building. It tends to result in large heat exchange and transport loss and inevitably gives birth to added energy consumption.

5. CONCLUSIONS

Computer simulation is a convenient tool for assessing building energy performance, air-conditioning system features, and system operational strategies. It allows users to test their ideas and designs before a building is built to see what the impact of their decisions would be on energy consumption and other aspects. In this study, a new module is developed in the BESP program Energyplus, in order to evaluate the features of the VRF system under cooling condition in terms of energy usage. A case study is then made to demonstrate the application of the new module for the VRF air-conditioning system in a medium-sized office building.

Simulation results from the electricity-usage comparison among VAV, FPFA, and VRF systems implies that the VRF air-conditioning system is most energy efficient compared with other two conventional systems. The energy-saving potentials of the VRF system are expected to achieve 22.2% and 11.7%, compared to the VAV system and the FPFA system, respectively. With identical nominal cooling capacity, the VRF system and VAV (or FPFA) plus chillers system consume notably different electricity energy, due to various ways in transporting cooling media and diversity of part-load performance. This study provides architects and engineers a chance to analyses the energy features of the VRF system and to evaluate different systems from a point of view of energy characteristics, especially during the primary conceptual design stage.

It is pertinent to note that influencing factors of the energy consumption of air-conditioning system is fairly complicated in real buildings. Building designs, constructions, operation strategies, chillers configuration, maintenances, and other unpredictable ingredients can impact on the eventual facility bills for buildings. Simulations offer an ideal objective of energy usage for the integration of the building, air-conditioning systems and artificial interference under a certain condition, rather than a predetermined augur. But this investigation still owns its sense in suggesting the VRF system may be an attractive option and a more efficient operation for a new installation or a changeover form an inefficient old system, from an energy use perspective.

The future work is believed to include the economic evaluation and life-cycle cost analysis of various forms of HVAC systems. Also, a series of field test of the VRF system are underway, which will last for a whole year in the new Research Building of School of Mechanical Engineering in Shanghai Jiaotong University. As a part of the extension of this research, the module can be verified and adjusted. Further, the VRF system's performance in heating condition would be researched.

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