AN INVESTIGATION ON OPERATIONAL PERFORMANCE OF THREE TYPICAL HVAC SYSTEMS IN WUHAN

Luhan Wang[1]，Guannan Li[2] ,Qing Yao[3]

[1]School of Urban Construction, Wuhan University of Science and Technology
(2 Huangjiahu West Road,Hongshan District,Wuhan 430065, China)
E-mail: 874598430@qq.com
[2]Associate professor, School of Urban Construction, Wuhan University of Science and Technology
(2 Huangjiahu West Road,Hongshan District,Wuhan 430065, China)
E-mail: guannanli@wust.edu.cn
[3]School of Urban Construction, Wuhan University of Science and Technology
(3 Huangjiahu West Road,Hongshan District,Wuhan 430065, China)
E-mail: 1053458858@qq.com

The importance of energy saving and the high requirements of indoor thermal environment provide opportunities and challenges for the development of the heating, ventilation and air-conditioning (HVAC) field. Among them, the chiller system, ground source heat pump (GSHP) system and variable refrigerant flow (VRF) system because of their own advantages have been widely promoted in the HVAC field and market. However, it's too expensive to compare the operational performance of three HVAC systems in actual projects or existing buildings at the same time. Therefore, the study carried out simulation modeling of chiller system, GSHP system and VRF system at the same time for a building in Wuhan area, which was realized through EnergyPlus environment. The operational performance of the three systems is quantitatively analyzed and compared from the three aspects of HVAC energy consumption, work performance and indoor thermal comfort. The results show that the total HVAC energy consumption of the GSHP system is smaller, and the air temperature adjustment ability and indoor personnel thermal comfort are better.

Key Words*：*HVAC; Chiller; EnergyPlus; Building performance

1. INTRODUCTION

Energy shortage has become an urgent problem in modern countries. According to statistics, building energy consumption accounts for nearly 40% of global energy consumption[1,2]. Among them, Heating, Ventilation and Air Conditioning (HVAC) systems account for 60% of building energy consumption and are the main building energy-consuming equipment[3,4]. The development of urbanization and the importance of energy saving have brought huge challenges and opportunities to the HVAC industry[5,6]. Many new HVAC technologies have been promoted with efficient energy efficiency and comfortable indoor thermal environment[5]. Among them, chiller system, ground source heat pump (GSHP) system and variable refrigerant flow (VRF) system have been widely promoted in the HVAC field and the market with their respective advantages.

Chiller system has always been one of the most important systems in the central air conditioning market. Under the trend of continuous expansion of the market size, chillers still maintain a relatively high market share[7]. According to the 2019 China Central Air Conditioning Market Report, the market share of all models of chillers reached 18.06%[8]. The GSHP air conditioning technology can utilize renewable soil heat (cold) energy resources[9]. In addition, GSHP system has the characteristics of significant energy saving, environmental protection and improvement of air conditioning quality[9]. VRF system meets the heating and cooling needs of the building according to the change of the flow rate of the control refrigerant, and it can also heat and cool different areas at the same time[10]. The three HVAC systems have their own advantages and disadvantages, but they cannot be compared in actual applications in existing buildings.

This study carried out simulation modeling of the Chiller system, GSHP system and VRF system by using EnergyPlus. Furthermore, the performance of three HVAC systems in Wuhan area, such as operating energy consumption, air temperature adjustment accuracy and indoor thermal comfort, is quantitatively compared and analyzed. It provides information and suggestions for the design of HVAC systems in engineering projects.

2. DESCRIPTION OF SIMULATION

2.1. Building overview

To ensure the accuracy and scalability of the study, a typical single-story building in the EnergyPlus case is selected, as shown in **Fig. 1**. The single-storey building has 5 hot zones, a core hot zone in the middle and four surrounding hot zones. The whole building is 30.5m long, 15.2m wide and 3.0m high, with a 0.6m air return chamber above it.

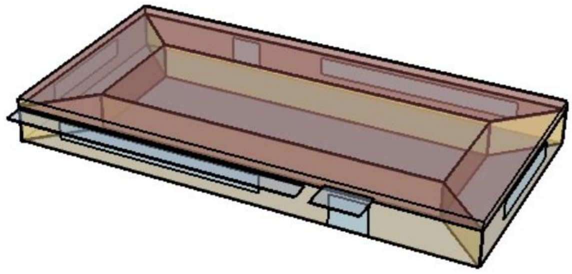

Fig. 1 3D view of the simulation small building.

Table 1 Building envelope and thermal properties.

Building envelope	Material	Thermal conductivity (W/m·K)
Roof	100mm Polyurethane extruded board	0.245
	150mm Reinforced concrete	1.95
Exterior wall	75mm Polyurethane extruded board	0.245
	150mm Reinforced concrete	1.95
Floor	30mm Polyurethane extruded board	0.245
	150mm Reinforced concrete	1.95
Internal wall	200mm Aerated concrete block	0.26
Windows	30mm LowE glass	0.9
	6.3mm Air gap	/
	30mm LowE glass	0.9
Door	100mm Grey glass	0.9

The simulation was carried out in Wuhan. In this study, the thermal properties of the building envelope and indoor load density were set with reference to the "Design Standards for Energy Efficiency of Public Buildings" (GB50189-2015). The specific settings are shown in **Table 1** and **Table 2**. The HVAC system in the building only operates during the cooling and heating seasons of the year. Summer (cooling season) operating hours are set from April 15th to September 30th, and winter (heating season) operating hours are from January 1st to March 15th and November 1st to December 31st. Among them, the indoor set temperature under cooling conditions is 26°C, and the indoor set temperature under heating conditions is 20°C.

Table 2 Internal loads density setting in Wuhan area.

Internal load	Unit
Occupant density	0.11peopel/m^2
Light power density	9W/m^2
Equipment density	15W/m^2

2.2. HVAC system model description

This study simulates the chiller system, GSHP system and VRF system in the same building model. As shown in Figs.2-4, the three systems are all primary return air systems. In the chiller system, the indoor load is borne by the independent fresh air system and the 5 air pan systems. The chiller and boiler determine the water flow according to the demand load and exchange heat in the cooling coil and heating coil to meet the indoor set temperature. In the GSHP system, the indoor load is borne by the central fan system and 5 indoor reheating coils. The heat pump unit switches the direction of the water loop through the reversing valve under different seasons, so that the heating coil or heat exchange in the refrigeration coil. In the VRF system, the indoor load is composed of 5 terminal air pan units, and the 5 terminal air pans are connected to a common outdoor unit. The refrigerant in the pipeline exchanges heat with the indoor air to meet the indoor setting temperature.

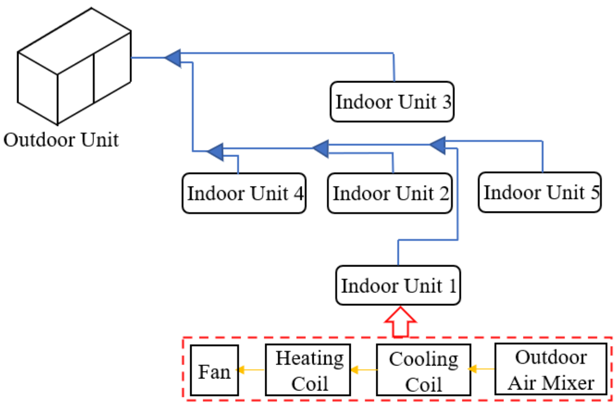

Fig. 2 Illustration of VRF system.

In order to make a reasonable comparative study, the fan efficiency (E_f) and motor efficiency (E_m) of the three systems were set to be 0.7 and 0.9 respectively under the dynamic pressure of 600Pa in the same running time. At the same time, the working pressure of all pumps in the GSHP and Chiller system is set at 5000Pa, the rated power (P_c) of the pump in the cold water loop is 250W, and the rated power (P_h) of the pump in the hot water loop is 350W.

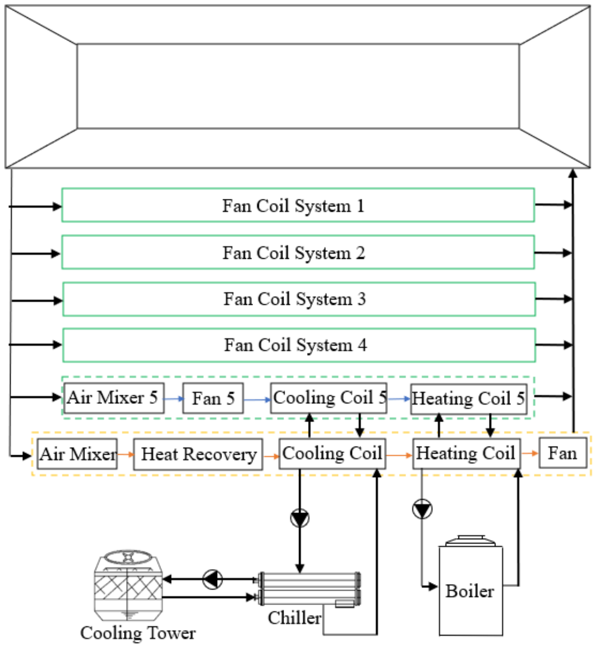

Fig. 3 Illustration of Chiller system.

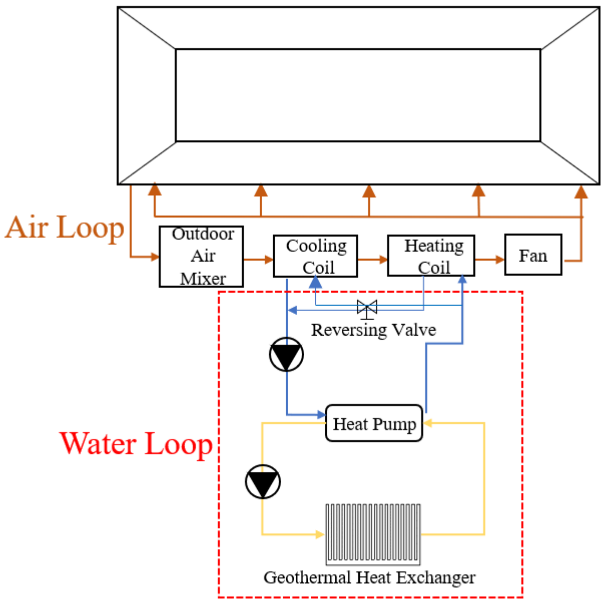

Fig. 4 Illustration of GSHP system.

3. RESULT AND DISCUSSION

This study mainly compares and analyzes the performance of the three HVAC systems from three aspects: system energy consumption, air temperature adjustment accuracy and indoor thermal comfort.

3.1. Energy comsumption of HVAC

Fig.5 shows the monthly total energy comsumption of HVAC and outdoor dry bulb temperature changes of three different systems. The total HVAC power consumption of the three systems is larger in January-February, May-September and November-December. In addition, power consumption peaks in January, July and August.While the time when the total power consumption of HVAC is lower appears in March-April and October. This is related to the operating conditions of the units in different months. For example, the total HVAC power consumption of the three systems in July to August (cooling conditions) and January (heating conditions) exceeds 4GJ. Comparing the total HVAC power consumption of the three systems, the total HVAC energy consumption of GSHP system is the smallest except March, October and November.

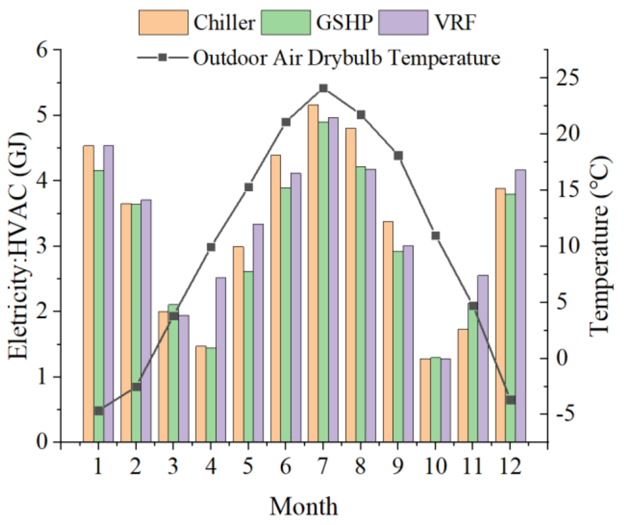

Fig. 5 Monthly HVAC power consumption and outdoor dry bulb temperature of the three systems.

The total energy consumption components of different systems are different. **Fig. 6** shows the energy consumption of each component of the three HVAC systems. The total energy consumption of the VRF System consists of three parts, namely cooling energy consumption, heating energy consumption and fan energy consumption. The total energy consumption of GSHP system is a more than that of VRF system, which is the energy consumption of pump.The total energy consumption of the chiller system is higher than that of the VRF system, and the higher part is the energy consumption of water pump and heat recovery. The total energy consumption of the GSHP system is the least, which is 37.13GJ, and the total energy consumption of the VRF system is the most, which is 40.34GJ.

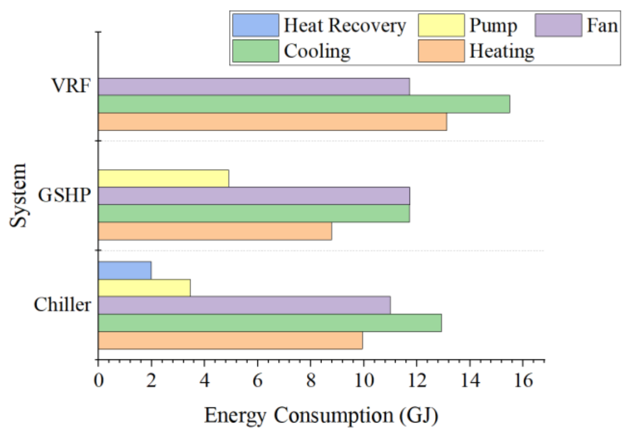

Fig. 6 Energy consumption of each part of the three HVAC systems.

3.2. Set-point unmet hours

The accuracy of air temperature regulation is analyzed by set-point unmet hours. Set-point unmet hours means that the air temperature of one or more hot zones during this hour does not meet the set temperature range. In short, the air temperature during this hour is higher than the cooling design temperature or lower than the heating design temperature. The temperature range is the set temperature tolerance[5], and the temperature tolerance in this study is set at ±0.2°C.

Table 3 shows set-point unmet hours of each HVAC system. The total set-point unmet hours of the GSHP system and the chiller system are both 0h, and the total set-point unmet hours of the VRF system is

chiller system have better air temperature regulation ability than and the VRF system. Consequently, these two systems can reach the set temperature of indoor cooling and heating more accurately during working hours.

Table 3 Set-point unmet hours of three HVAC systems.

	VRF	GSHP	Chiller
Set-point unmet hours during occupied heating period(h)	83	0	0
Set-point unmet hours during occupied cooling period(h)	70.5	0	0
Total set-point unmet hours(h)	153.5	0	0

3.3. Thermal comfort

Predicted Mean Vote (PMV) is an evaluation index to characterize the human body's heat and cold sensation, which represents the average heat and cold sensation of most people in a certain environment[11]. The PMV index divides human comfort into 7 levels. The closer the PMV index is to 0, the better the thermal comfort of the human body, as shown in **Table 4**.

Predicted Percentage of Dissatisfied (PPD) is an indicator that predicts the percentage of dissatisfaction that represents the percentage of people dissatisfied with the thermal environment. The quantitative relationship between PMV and PPD is:

$$PPD = 100 - 95\exp\left[-(0.03353PMV^4 + 0.2179PMV^2)\right] \quad (1)$$

The rooms in the building are selected for indoor thermal comfort analysis. Fig. 7 shows the average annual PMV and PPD of the three systems. The average value of PMV of the three systems is between -1 and 0, and indoor personnel feel comfortable and slightly cool. And the average PMV of VRF is the largest (closest to 0), and the average PMV of Chiller is the smallest (farthest from 0). However, the PMV value is positive or negative, so the mean PMV does not represent the thermal comfort of indoor personnel throughout the year to a certain extent. It can be seen from equation (1) that PPD is proportional to the square value of PMV and has nothing to do with the positive or negative value of PMV. Comparing the annual PPD average of the three systems, the average PPD of GSHP system is the smallest, and the indoor personnel have the best thermal comfort.

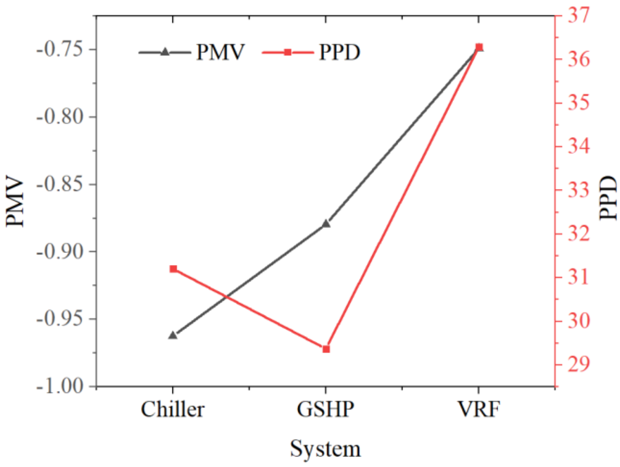

Fig. 7 Average annual PMV/PPD of three HVAC systems

Table 4 Thermal sensation corresponding to PMV value.

	+3	+2	+1	0	-1	-2	-3
Thermal Sensation	Hot	Warm	Slightly warm	Comfortable	Slightly cool	Cool	Cold

4. CONCLUSION

In this study, a building in Wuhan area was simulated and modeled with three HVAC systems, including a chiller system, a GSHP system and a VRF system. The energy consumption, air temperature adjustment accuracy and indoor thermal comfort of the three HVAC systems were quantitatively analyzed and compared. The conclusions are as follows:

1) The total HVAC energy consumption of the three systems in Wuhan in January, July, and August is relatively large, and the HVAC system has the largest energy-saving potential. Controlling and optimizing the HVAC system can save a lot of energy.
2) Among the three HVAC systems, the performance of the GSHP system is the best from three aspects of energy saving, air conditioning capacity and indoor thermal comfort. On the contrary, the performance of multiple online systems in these aspects is relatively poor.
3) In the HVAC system design of the actual engineering project, various aspects of the performance of the system can be analyzed and compared through the building energy consumption simulation software. This method can be used to select the most suitable system scheme.

ACKNOWLEDGMENTS: This study was financially supported by the National Natural Science Foundation of China (Grant No. 51906181) and the Excellent Young and Middle-aged Talent in Universities of Hubei, China (No. Q20181110).

REFERENCES

1) Zhang L, Ma X, Wang Y, et al. The increasing district heating energy consumption of the building sector in China: Decomposition and decoupling analysis[J]. Journal of Cleaner Production, 2020, 271: 122696.
2) Turner W J N , Staino A , Basu B . Residential HVAC fault detection using a system identification approach[J]. Energy and Buildings, 2017.
3) Han Qi, Wei Dong, Cao Yong. Study progress in fault detection and diagnosis technology of HVAC system[J]. HVAC, 2014, 44(03): 105-112. (Chinese Version)
4) Cheng Youliang, Liu Meng, Liu Zhidong, et al. Analysis and simulation study on the matching of residential energy consumption and solar absorption air conditioning systems in different regions[J]. Renewable Energy, 2020, 38(02): 179-186.(Chinese Version)
5) Wang S. Energy modeling of ground source heat pump vs. variable refrigerant flow systems in representative US climate zones[J]. Energy and Buildings, 2014, 72: 222-228.
6) Kiruthiga K, Thirumaran K. Effects of urbanization on historical heritage buildings in Kumbakonam, Tamilnadu, India[J]. Frontiers of Architectural Study, 2019, 8(1): 94-105.
7) Varvagiannis E, Charalampidis A, Zsembinszki G, et al. Energy assessment based on semi-dynamic modelling of a photovoltaic driven vapour compression chiller using phase change materials for cold energy storage[J]. Renewable Energy, 2021, 163: 198-212.
8) 2019 China Central Air Conditioning Market Summary Report Chapter 3 "Mainstream Model Market Analysis"[J]. Electromechanical Information, 2020(04): 29-48.
9) Xu C, Chen H. Abnormal energy consumption detection for GSHP system based on ensemble deep learning and statistical modeling method[J]. International Journal of Refrigeration, 2020, 114: 106-117.
10) Qian M, Yan D, Hong T, et al. Operation and performance of VRF systems: Mining a large-scale dataset[J]. Energy and Buildings, 2021, 230: 110519.
11) Fanger P O. Thermal comfort:analysis and applications in environmental engineering[R], Denmark: Copenhagen:Danish Technical Press. 1972.