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Numerical Analysis of the Building Energy Efficiency Using Two Different HVAC Systems: Variable Refrigerant Flow and Variable Air Volume Technologies

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Abstract

Variable refrigerant flow (VRF) and variable air volume (VAV) systems are considered among the best heating, ventilation, and air conditioning systems (HVAC) thanks to their ability to provide cooling and heating in different thermal zones of the same building. As well as their ability to recover the heat rejected from spaces requiring cooling and reuse it to heat another space. Nevertheless, at the same time, these systems are considered one of the most energy-consuming systems in the building. So, it is crucial to well size the system according to the building's cooling and heating needs and the indoor temperature fluctuations. This study aims to compare these two energy systems by conducting an energy model simulation of a real building under a semi-arid climate for cooling and heating periods. The developed building energy model (BEM) was validated and calibrated using measured and simulated indoor air temperature and energy consumption data. The study aims to evaluate the effect of these HVAC systems on energy consumption and the indoor thermal comfort of the building. The numerical model was based on the Energy Plus simulation engine. The approach used in this paper has allowed us to reach significant quantitative energy saving along with a high level of indoor thermal comfort by using the VRF system compared to the VAV system. The findings prove that the VRF system provides 46.18% of the annual total heating energy savings and 6.14% of the annual cooling and ventilation energy savings compared to the VAV system.

Keywords

HVAC systems, Variable refrigerant flow, Variable air volume, Energy consumption, Building simulation, Thermal comfort

Introduction

The building sector is responsible for more than a third of the world's energy consumption, with the associated 39% of CO_2 emissions [1-4]. The movement toward net-zero energy buildings and the need for green energy in the energy consumption of buildings is becoming increasingly demanding nowadays. This is from the integration of passive systems and bioclimatic designs adapted to each climate and following the requirements of the Moroccan Thermal Regulation of Construction [5], as well as active systems of high efficiency to reduce the negative impact of these buildings on natural energy sources and achieve sustainable development. One of the objectives of net-zero energy buildings is to optimize the use of heating and cooling energy systems that impact the electrical load of the building. As a result, a lot of studies have studied the energy efficiency of buildings by improving the building parameters such as construction, glazing, and people's behavior schedules [6-11]. Thus, many HVAC technologies are being promoted with an emphasis on their superior energy efficiency [12, 13]. The implementation of an effective HVAC system is essential for energy conservation. Among these, the VRF and the VAV systems are probably the most competitive technologies. Particularly, the VRF heat pump energy systems have several benefits, including high performance along with great energy efficiency, as well as its ability to manage the system's operation for partial loads and regulate the refrigerant flow rate in accordance with the heating and cooling demands [14, 15]. Moreover, the major drawback of a VRF system is related to its high initial investment costs as opposed to a traditional air-conditioning system [16, 17]. Whereas the VAV systems are advantageous compared to conventional energy systems, including lower fan capacity, greater adaptability with regard to adjusting loads, and improved indoor air quality and indoor thermal comfort [18, 19]. Furthermore, the most known limitations of the VAV system include the inadequate relative humidity control, the temperature-dependent ventilation rate and air quality, as well as the frequent need for re-heating or radiator heating [20]. Therefore, several experimental, analytical, and numerical studies on VRF and VAV systems in different climates are reported in the literature [21, 22]. Many of these simulation studies are conducted using the Energy Plus simulation engine. Park et al. studied the performance of a VRF system based on the energy simulation on Energy Plus, the simulated measurements are compared with the experimental measurements. The difference between simulation and measured data was minimal [23]. In addition, a VRF system model was developed to provide more accurate results than the current Energy Plus model. The new model was validated and compared with the operating system, which represents an office building in different locations. Furthermore, using the TRNSYS modeling tool, Yau et al. investigated and evaluated the energy consumption of an existing VAV system in a building and compared it with a VRF system [24]. According to the simulation's results, the VRF system can be more energy-efficient than the existing VAV system. The VRF system also has an investment payback period of about 6.6 years, which is promising because the investment cost of the VRF system covers its cost before the end of its lifetime, which is approximately 15 years. Zhou et al. used Energy Plus to compare the performance of three different HVAC systems: the fan coil plus fresh air (FPFA), the VRF, and the VAV. In comparison to the other two conventional systems, the VRF system appears to be the most energy-efficient, according to simulation findings of the comparison of power consumption between the VAV, FPFA, and VRF systems with the same capacity. Comparing the VRF system to the VAV and FPFA systems results in energy savings of 22.2% and 11.7% [25].

Nevertheless, the incorporation of nano-compounds into HVAC systems, as well as VRF systems, is an attractive option for enhancing energy efficiency, indoor air quality, and overall system performance. Enhanced heat transfer with nanoparticles [26, 27], enhanced nanostructured filtration [28, 29], and surface nano-coating [30, 31] are just few methods that nano-compounds made of nanoparticles or nanomaterials can be used to improve several aspects of HVAC systems. However, nano-compounds in VRF systems can improve filtering by lowering contaminants and pollutant levels, maintain constant temperature management, and enable more effective heating and cooling operations, resulting in lower energy consumption as well as low expenses [32].

The main aim of this paper is to study and compare the energy performance of two well-used and commercialized HVAC systems including VRF and VAV technologies. The comparison was based on thermal comfort assessment as well as the cooling and heating energy consumption reduction for a real existing building located in the semi-arid climate of Morocco.

Methodology

This study focuses on the comparison of the thermal indoor comfort along with heating and cooling energy consumption of a residential building using two different technologies of HVAC systems including the VRF and the VAV systems. Thus, the main aim of this paper is to choose the best and optimal HVAC system among the ones studied based on providing a high level of indoor thermal comfort as well as decreasing building energy consumption in a semi-arid climate. The indoor fresh air was not taken into consideration in this study. Figure 1 summarizes the main steps of the methodology developed in this study. The BEM was created using the Energy Plus simulation engine.

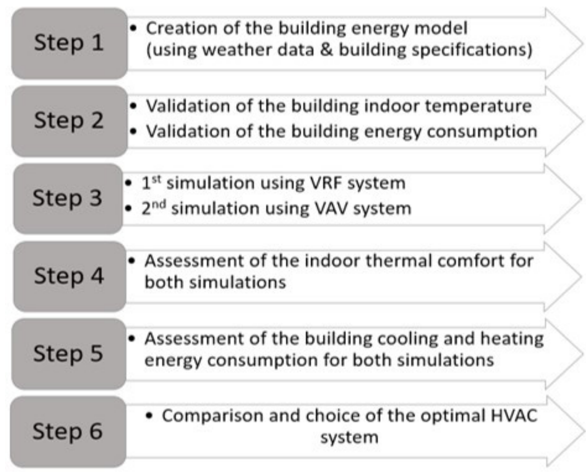

Figure 1: Methodology.

Building description

The building used in this study, as shown in figure 2, is dispatched on two stories with a light construction mainly built from wood. The building is located in the semi-arid climate of Benguerir City in Morocco. Table 1 summarizes the thermal transmittance of all main building components. The building contains five thermal zones equipped with a VRF heat pump system. This VRF heat pump system is composed of one single outdoor unit containing the condenser and one compressor. The outdoor unit is connected to 5 indoor units containing the evaporator and the expansion valve.

Figure 2: Case study building.

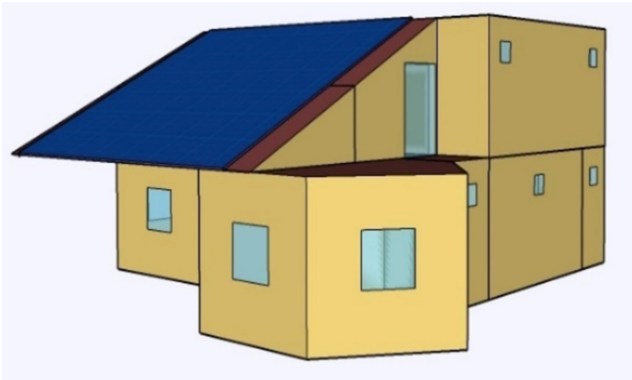

Figure 3: The developed 3D model of the studied building.

Table 1: Thermal transmittance of building contraction layers.

Component	Thermal transmittance (W/m².K)
Roof	0.28
Ceiling	0.33
Exterior and interior walls	0.34
Ground floor	0.68
Double clear low E glazing with an air gap	2.89

Building energy simulation

The developed 3D model of the real studied building is presented in figure 3. Two building energy model simulations were carried out for each of the VRF and the VAV systems, in order to conduct an appropriate energy performance comparison of both systems. The two simulations were undertaken under the same indoor and outdoor conditions without taking into consideration the indoor air quality. The comparison was made for heating and cooling periods on the hottest and the coldest days of the year. The VRF system used in this study is an air-source VRF heat pump system with no heat recovery. The VAV used is the type of packaged rooftop VAV system with parallel fan power boxes. Table 2 presents the properties of the main component of these two HVAC systems. The BEM was developed using the Energy Plus simulation engine. The occupancy schedule used was based on conventional residential occupancy. Moreover, the weather data were extracted from a local weather station in Benguerir city. More specifications on this meteorological weather station are stated in previous studies [33, 34].

Results and Discussion

Building validation

The building's indoor temperature was measured and collected from temperature and humidity sensors located inside the studied building. The sensors are connected to a SCADA system for building monitoring. Thus, after the creation of the first building energy model which includes the VRF system existing in the building, the simulated indoor temperature, and energy consumption was compared to real measured ones. According to ASHRAE guideline 14 [35], the acceptable statistical indices for the building calibration for hourly data should be as follows; CVRMSE < 30% and NMBE < 10%. Therefore, an empirical validation was conducted for the building's indoor temperature and the VRF heating and cooling energy use and the statistical indices were within the range of ASHRAE's recommendations. Figure 4 and figure 5 show the validation of the building's indoor temperature inside two thermal zones and the VRF cooling and heating consumption, respectively.

Indoor thermal comfort assessment

The building's indoor temperature was compared using both systems the VRF and the VAV as follows. The indoor temperature of the five building thermal zones was collected for both simulations using VRF and VAV systems for heating and cooling periods. In the heating period, we have chosen to work on the coldest day of the year, correspondent to the 1st of January. And in the cooling period, we have worked with

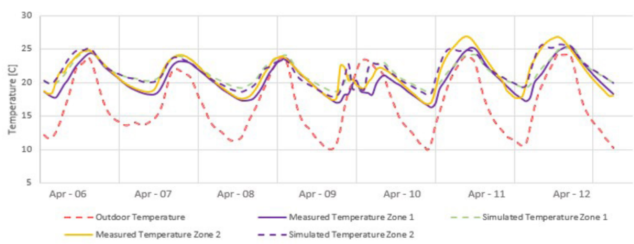

Figure 4: Measured VS simulated building indoor temperature.

Table 2: Properties of the VRF and the VAV systems.

HVAC system component	Air source VRF-HP system	PRU-VAV system with parallel fan power boxes
Heating	VRF heating DX coil	Electrical heating coil
Cooling	VRF cooling DX coil	VAV cooling DX coil
Terminal units	VRF-DX heating and cooling	Packaged Rooftop VAV with PFP Boxes and Reheat
COP	4.18	3
EER	3.9	3.8
Setpoint temperatures	Heating: 20 °C < T < 22 °C Cooling: 24 °C < T < 26 °C	Heating: 20 °C < T < 22 °C Cooling: 24 °C < T < 26 °C

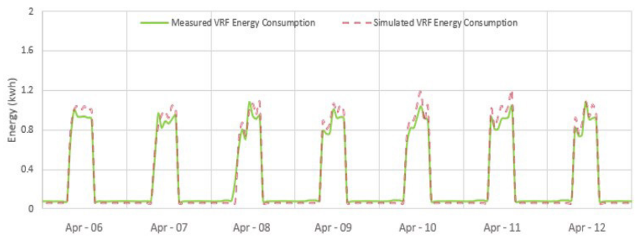

Figure 5: VRF cooling and heating energy consumption validation.

the hottest day of the year, the 14th of August. According to figure 6 and figure 7, we clearly notice that the VRF system provides the building with a level of temperature within the range of the setpoint temperature. While the VAV system is not able to respect the heating and cooling thermostat and did not maintain the indoor temperature at the ranges of the setpoint temperature. Moreover, the maximum temperature reached on the coldest day of the year is approximately 28 °C for both systems. Whereas the minimum temperature reached using the VRF system is 20 °C correspondent to the setpoint temperature. Controversy, when using the VAV system, the indoor air temperature drops until 14 °C. Furthermore, on the hottest day of the year, both the maximum and minimum air temperatures are within the range of the HVAC setpoint between 24 - 26 °C. In contrast, the maximum temperature reached when using the VAV system is above 35 °C.

Based on figure 8 and figure 9, the indoor relative humidity is out of the comfort zone which is generally between 30% to 60% according to ASHRAE Standard 55-2017 [36]. Nevertheless, the VAV system provides high fluctuations of relative humidity out of the comfort range compared with the VRF system for both heating and cooling periods. Thus, the VRF system offers a high level of thermal comfort for both indoor temperature and indoor relative humidity compared with the VAV system.

Energy consumption assessment

The energy consumption of both VRF and VAV systems was assessed in order to find out the most energy-efficient technology among these two HVAC systems. According to figure 10, the VRF system consumes less energy than the VAV system either for heating loads or cooling loads, or even fan

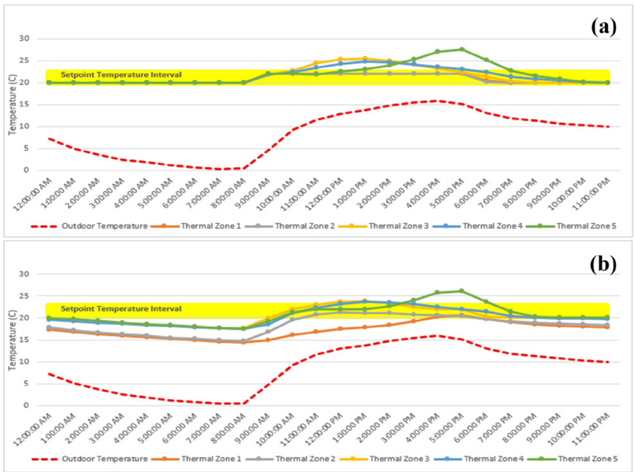

Figure 6: Variation of the building's indoor temperature on the coldest day of the year using **(a)** the VRF system and **(b)** the VAV system.

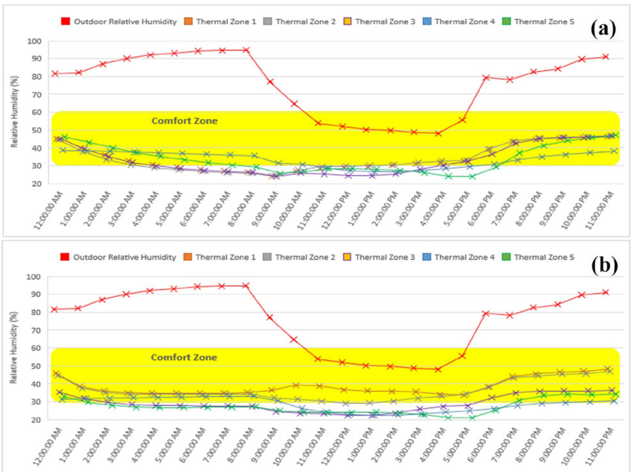

Figure 8: Variation of the building's indoor relative humidity on the coldest day of the year using **(a)** the VRF system and **(b)** the VAV system.

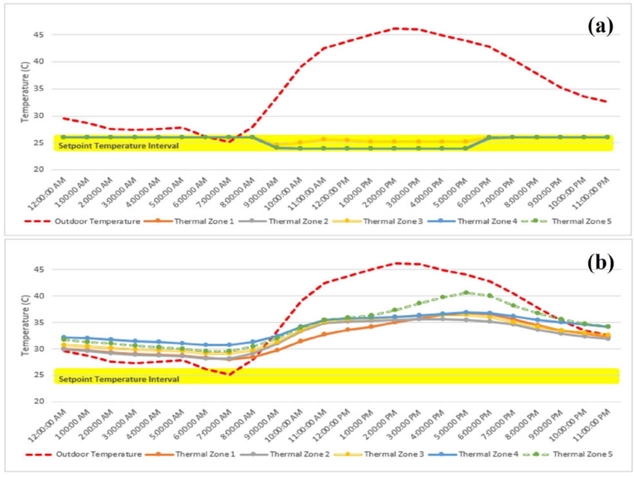

Figure 7: Variation of the building's indoor temperature on the hottest day of the year using **(a)** the VRF system and **(b)** the VAV system.

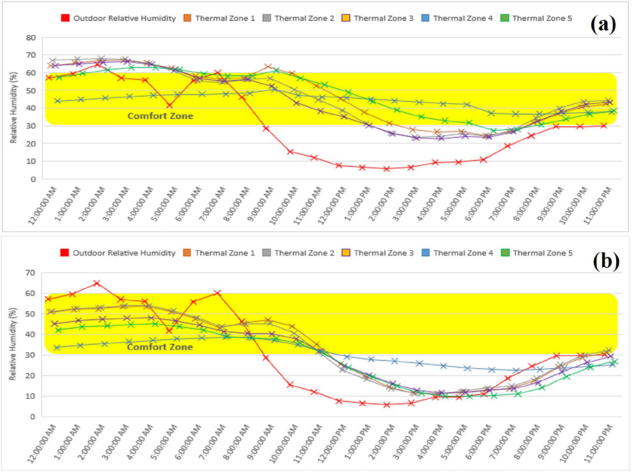

Figure 9: Variation of the building's indoor relative humidity on the coldest day of the year using **(a)** the VRF system and **(b)** the VAV system.

Table 3: Comparison of similar studies conducted in literature.

Ref.	Comparison	Evaluation	Savings
[30]	VRF heat pump and RTU-VAV systems	Cooling and heating energy use	17% for cooling 74% for heating
[19]	VRF heat pump and VAV systems	Energy use	18 - 33%
[31]	VRF heat pump and VAV systems	Cooling energy use	30%
[32]	VRF heat pump and RTU-VAV systems	Cooling energy use	20%
[25]	VRF heat pump, VAV and FCU systems	Energy use	11 - 22%

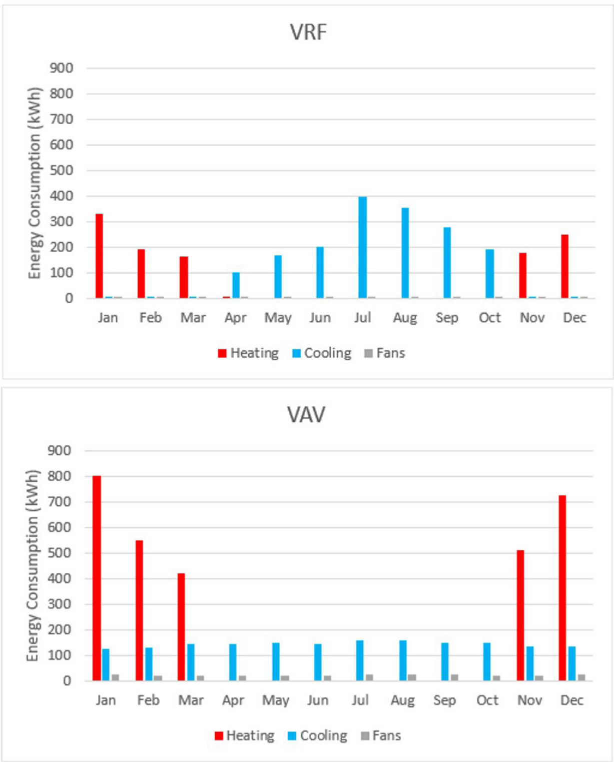

Figure 10: Monthly cooling and heating energy consumption comparison between VRF and VAV system.

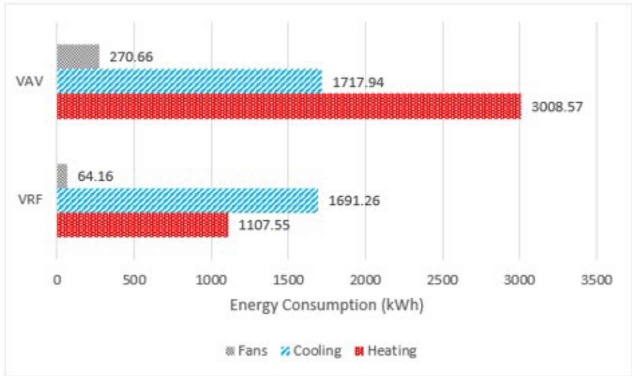

Figure 11: Comparison of the annual cooling and heating energy consumption for the VRF and the VAV systems.

loads. The VRF system consumes less heating energy than the VAV system in heating periods, while in cooling periods the VRF is the most energy consuming. Nevertheless, since the VAV system consumes energy for cooling all through the year for temperature regulation, the VRF system consumes cooling energy just in the summer period. Figure 11 presents the annual energy use for both systems. Thus, the VAV system is the most energy consuming system for heating and ventilation needs. The VAV system consumes approximately 3008 kWh for the annual heating energy and approximately 2000 kWh for the annual cooling and ventilation energy. Whereas the VRF system consumes only 1107 kWh for heating and 1700 kWh for cooling and ventilation.

Based on the findings obtained in the context of this paper, the VRF heat pump system provides 46% for heating energy savings and 6% for cooling energy savings compared to the VAV system. Therefore, based on table 3, these findings are matching with results already obtained in other studies present in the literature.

Conclusion

In this study, a building energy model was created based on a real existing building containing an air source VRF heat pump system located in a semi-arid climate. The building energy model was validated and calibrated based on empirical validation by minimizing the discrepancies between measured and simulated indoor temperature and energy consumption. Then a numerical comparison of the indoor thermal comfort and the energy consumption was conducted for both the VRF and the VAV systems. Based on the findings of this paper, the VRF system can provide a high level of thermal comfort inside the building, by being able of maintaining the setpoint temperatures in both cooling and heating seasons, as well as providing an acceptable level of indoor relative humidity within the range of comfort zone. Whereas the VAV system was unable to respect the setpoint temperatures of both cooling and heating thermostats. Otherwise, the range of relative humidity provided by the VAV and the VRF systems was approximately similar and with acceptable ranges between 30% to 60%. Moreover, according to the annual cooling and heating energy consumption of these two HVAC systems, we have reached significant energy saving while using the VRF system compared with the VAV system. The VRF system provides 46.18% of the annual total heating energy savings and 6.14% of the annual cooling and ventilation energy savings. These energy savings are achieved due to the ability of the VRF system to control and monitor temperatures inside the building. Therefore, according to the findings of this paper, the main benefits of the VRF system over the VAV system are related to its low energy consumption, its high energy efficiency as well as its ability to provide high level of indoor thermal comfort regarding air temperature and relative humidity. In future studies, it is recommended to study the life cycle cost analysis and the environmental impact of these both systems from economic and environmental perspectives. Since the VRF system is having higher initial investment costs compared to the VAV system. Therefore, the investigation of the payback period and the life cycle cost assessment would be beneficial to quantify the gains of using such an energy system. Moreover, indoor fresh air and air quality is highly recommended to be studied in further research.

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Conflict of Interest

None.

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