Performance of Chilled Water Storage Assisted Variable Refrigerant Flow System

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Abstract

In the US, more than 40% of the primary energy is consumed by buildings. In the building sector, more than 45% of the primary energy is used in space cooling, space heating and water heating. Variable refrigerant flow (VRF) system is a popular building air conditioning solution. Modern VRF systems such as multi-functional VRFs are also able to provide simultaneous space cooling, space heating and water heating to the building. Therefore, the performance improvement of VRF system becomes a key research topic. In this paper, a thermodynamic model of multi-functional VRF is proposed and implemented in simulation engine EnergyPlus. The model is validated in cooling season. The model agrees with the experimental data with an hourly cooling capacity deviation within ±10% and an hourly energy consumption deviation within ±5%. Due to low utilization rate of water heating operation when compared with space cooling and heating, an integrated VRF system with chilled water storage capability is thereafter proposed. The integrated system uses the water storage component in multi-functional VRF systems as a chilled water storage unit. The integrated system is able to switch between the air-cooled and water-cooled modes based on the ambient temperature. The integrated system is also modeled in EnergyPlus. The performance of the integrated system and the baseline VRF system is compared and the calculated seasonal cooling energy savings for a target building in Tampa, FL is 11.5%.

Keywords: variable refrigerant flow; thermal storage; energy saving

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1. Introduction

Variable refrigerant flow (VRF) system is an air conditioning solution that was introduced by Japanese manufacturers in 1980s. It has better systematic modularity and installation flexibility than conventional air conditioners. At this moment, most of the VRF systems available in the market could be categorized into two groups: heat pump type (HPVRF) and heat recovery type (HRVRF). The schematic diagrams of HPVRF and HRVRF are shown in Figure 1. In Figure 1, the HPVRF system works in a cooling mode. The system has four indoor units (IUs) and one outdoor unit (OU). In Figure 1, the discharged refrigerant from the compressor rejects heat to the ambient air in the OU heat exchanger. The subcooled refrigerant leaving the condenser bypasses the main electronic expansion valve (EEV) and directly flows into the IUs through the check valve. A typical IU is made up by one crossflow fan, direct expansion coils and one EEV. In the IU, the refrigerant from the OU expands and absorbs the heat from the room air. After that, the refrigerant is sent back to the compressor. In the heating season, the four-way valve is reversed and the flow direction is alternated so that the system is working in the heat pump mode where the room air is heated up. As compared to the HPVRF, the HRVRF includes an extra unit which is known as a heat recovery unit (HRU). Figure 1 also shows the cooling main operation of the HRVRF. The discharged refrigerant from the compressor is sent to the HRU instead of the OU. The HRU is in charge of refrigerant distribution based on the demand of the IUs. In HRVRF, high-pressure refrigerant vapor is delivered to the IUs that need heating. Later, in the HRU, the subcooled liquid from the IUs operated in heating mixes with the liquid refrigerant leaving the OU. When cooling is needed in some IUs, the HRU further delivers the subcooled liquid to these IUs. The refrigerant leaving the IUs operated in cooling flows back to the HRU. Finally, the HRU will send the superheated vapor back to the compressor. As shown in Figure 1, to deliver refrigerant of different states to different IUs, a typical HRU needs to have three pipes of refrigerant: low-pressure vapor, high-pressure vapor and high-pressure subcooled liquid.

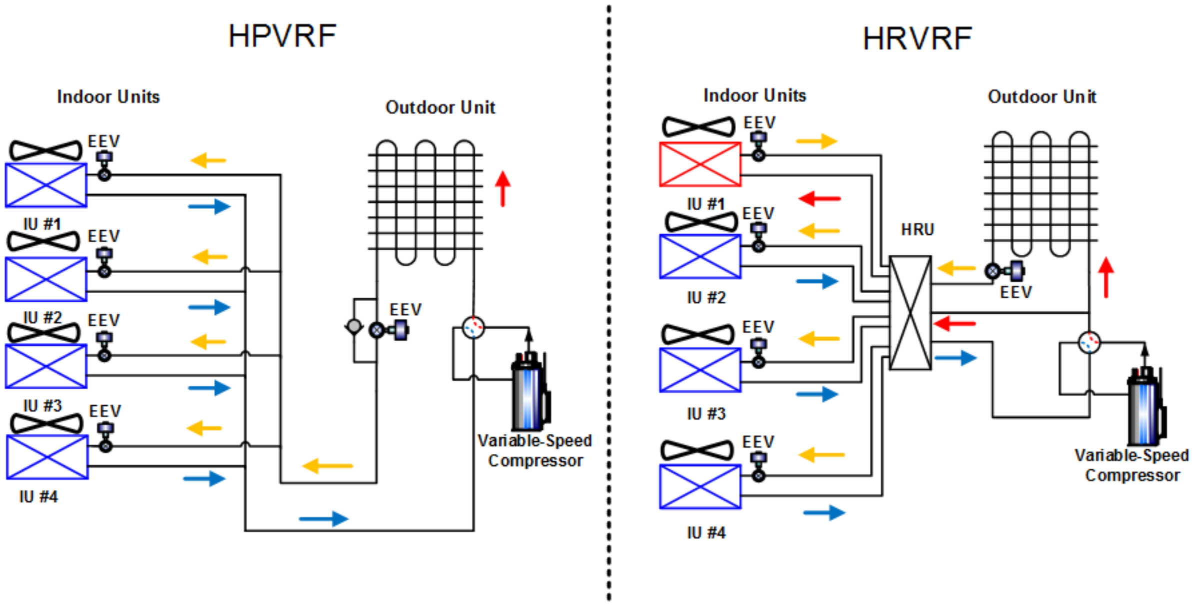


Figure 1 Schematic diagrams of HPVRF and HRVRF systems

In building application, the occupants could have demands other than space cooling and heating. For example, occupants also need ventilation and hot water. As a comprehensive and flexible building HVAC solution, VRF systems could also provide more functionality than air conditioning. For example, Zhu et al. [1–3] proposed a VRF system with an outdoor air processor. Simulation results showed that the proposed system could provide a better indoor thermal comfort with a COP 12.2% higher than HPVRF system in cooling season. Similarly, Aynur et al. [4–7] tested an integrated system made up of HPVRF system and a solid desiccant heat pump unit. It was found that the CO_2 concentration of the room could be kept within 450-500 ppm. To provide hot water to the building, a multi-functional VRF (MFVRF) was proposed by the researchers [8–10]. The MFVRF system in cooling main mode is shown in Figure 2. Compared to HRVRF, the MFVRF has a plate heat exchanger instead of IU. In the plate heat exchanger, the cold water is heated up by the high-pressure refrigerant delivered from the HRU. Similarly, by switching the refrigerant delivered from the HRU, it is also possible to generate chilled water via the same plate heat exchanger. Kwon et al. [11] tested a MFVRF system in heating and shoulder season. It was found that the hot water demand could improve the part load performance of the system. Lin et al. [10,12] also tested the MFVRF system in both heat recovery and water heating operation. It was found that the water heating operation could improve the daily performance of the system by 18% and 7% in cooling and heating season, respectively. The goal of MFVRF system is to provide space cooling, space heating and water heating to the building. The sizing of the system is based on cooling demand of the building. Therefore, the heating capacity of system is generally oversized. One advantage is that the system is able to provide hot water and space heating simultaneously. The disadvantage is the low utilization rate of the water heating component.

To evaluate building energy saving options, it is necessary to use building simulation tools. For example, eQuest and EnergyPlus are two of the most popular tools used by researchers. In the open literature, it could be found that most of the existing VRF models in building simulation tools are based on the performance mapping method. This method could only achieve accurate results with a carefully tuned model which includes detailed operation parameters and schedules. For example, the model developed by Zhou et al. [13–16] yielded weekly cooling energy and power consumption errors of 25.2% and 28.3%. Moreover, researchers also observed that the model could lead to a higher uncertainty when hourly performance is focused on, whereas Lin et al. [17] discussed the origin of inaccuracy of this method.

The objective of this study is to propose both a new VRF model with higher model accuracy and a new system with higher energy efficiency than conventional VRF systems.

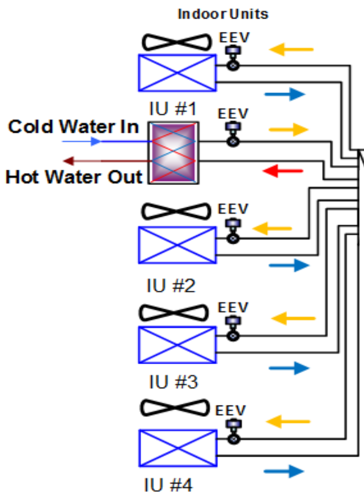
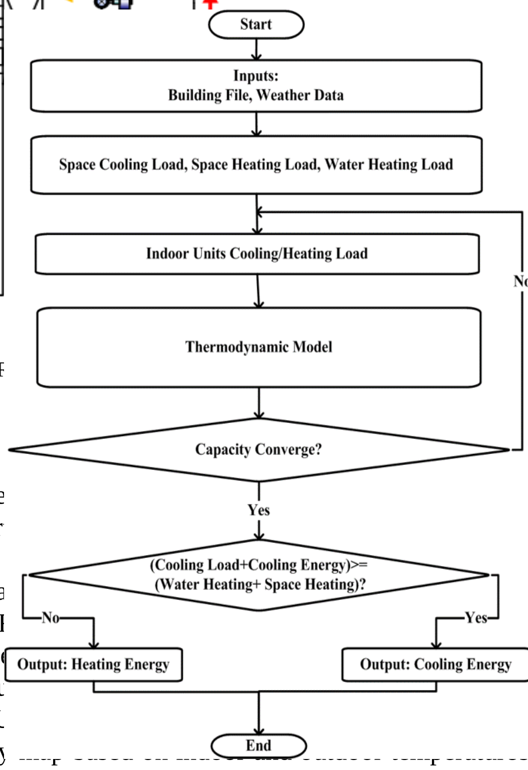
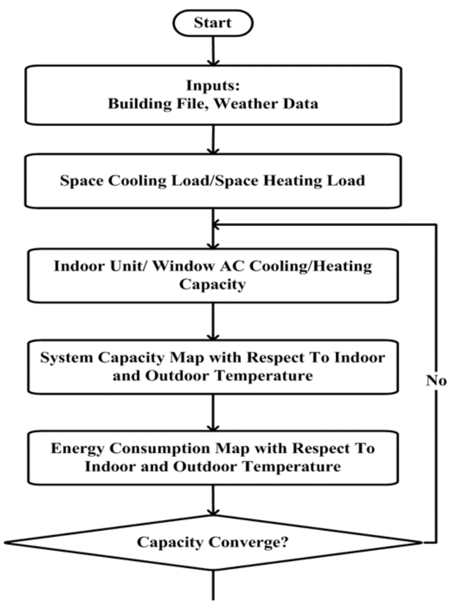


Figure 2 Schematic diagram of MFVF



2. New VRF Model

The performance mapping model was firstly develope milar concept was later incorporated into EnergyPlus 6.0 as par group [18–20]. The basic idea is illustrated in Figure 3 (a). The and weather data specified by the user. The model then calcula of the rooms. In the earlier versions of building simulation, the VI efore, some researchers would use the window AC module inst l, the required IU/window AC cooling or heating capacity is calcu ation from the IU and building side, it will continue with the OU two maps as lookup tables. The first one is the system capacity The second map is the energy consumption map. The OU module searches the operation point in the cooling capacity map. The ideal operation point should deliver the required IU load to the building. Once the operation point is found, the energy consumption of the system is calculated accordingly. Lin et al. [21] analyzed the uncertainty of the performance mapping method and concluded that a thermodynamic model could be a proper way to reduce the model uncertainty. The flow chart of the new model is shown in Figure 3 (b).



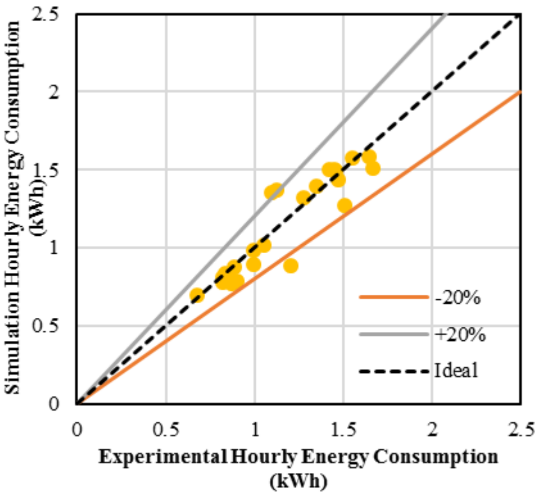
(a) Performance mapping method (b) New model

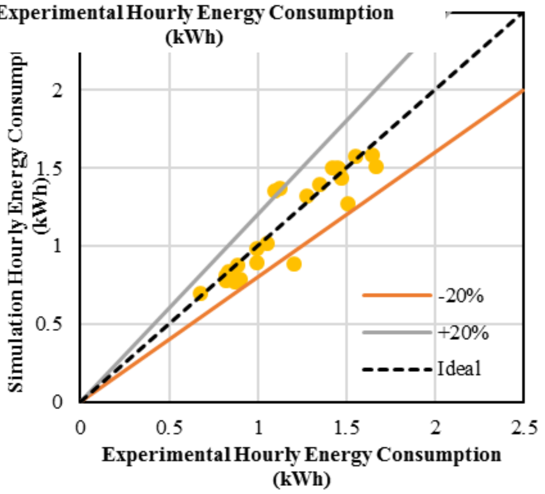
Figure 3 Flow charts of two models

As compared to Figure 3 (a), the model still starts with the estimation of room load and IU load. After that, the model calls the new OU module to calculate the energy consumption of the system. The required inputs for the OU module are the polynomial equations of compressor and user-specified control parameters such as superheat. In order to quantify the accuracy of the new model, the normalized mean bias error (NMBE) concept from ASHRAE guideline [22] shown in eq. (1) was used. The target NMBE value was less than 5%. The model was validated in cooling season. The hourly energy consumption validation is shown in Figure 4. The model could achieve a NMBE of 3.7%.

$$NMBE = 100 * \frac{\sqrt{\sum_{i=1}^{n}(y_i - \widehat{y_i})}}{(n-1)*\bar{y}} \quad (1)$$

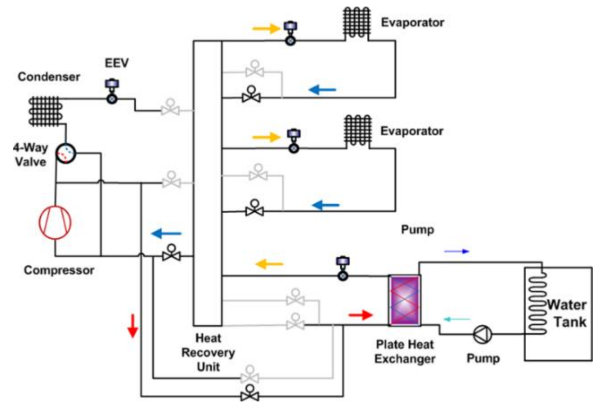
where y_i is the simulation result, $\widehat{y_i}$ is the experimental result, n is the amount of points, and $\bar{y}$ is the mean of experimental results.





3. Chilled Water Storage Syst

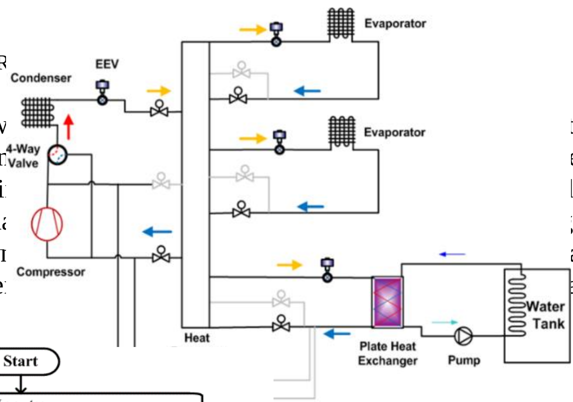
As mentioned in the introduc rate of water heating module. Therefore, inspired by MFVRF s proposed in this study. The schematic diagram of the syster 5 (a), the system has a plate heat exchanger. The discharged e ambient air. The subcooled refrigerant is sent to HRU and f . However, instead of heating up the water, the plate heat exc ng the subcooled refrigerant. Therefore, it works similarly to tank.



During the summer peak period, the VRF system is working under a higher condensing pressure than usual. With a high pressure ratio across the system, the performance of VRF system is highly deteriorated, as found in Kwon et al.'s study [8]. With the CWS operation, it is possible to switch the system to water-source operation during summer peak period. The discharging mode of the system is shown in Figure 5 (b). In Figure 5 (b), by manipulating the solenoid valves, the discharged refrigerant bypasses the OU heat exchanger and flows to the plate heat exchanger. In the plate heat exchanger, the refrigerant is cooled down to liquid state and delivered back to the HRU. The HRU further delivers liquid refrigerant to the IUs that need cooling. What needs to be pointed out is that such a system could not be easily simulated based on the performance mapping model. Therefore, in this study, this system is modeled based on the new model mentioned in section 2.

(a) Charging mode

Figure 5 VR



The overall modeling approach of this system is show tem has an additional logic loop which decides the operation e is higher than the setting temperature, the system works i lled water is used. When the ambient temperature is lower tha ing mode where the water in the storage tank is cooled dowr and the OU module until the condensing capacity requireme ater tank.

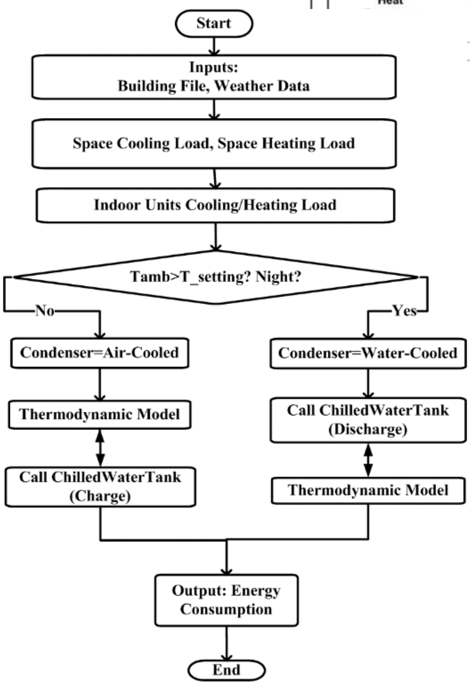


Figure 6 Flow chart of VRF system with CWS

4. Results and Discussion

The performance of the new system is simulated in an office building located in Tampa, Florida. In addition to the CWS part, the system also has seven IUs. The floor map of the building is shown in Figure 7. The specification of system is listed in Table 1. IU #1 was installed in Room A. IU #2 and #3 were installed in Room B. IU #3 and IU #4 were installed in Room C. IU #6 was installed in Room D. IU #7 was installed in Room E. The plate heat exchanger and the water tank are not shown in Figure 7. The storage tank had a total volume of 1 m^3 and the activation temperature of chilled water discharging operation was assumed to be 27°C. The target chilled water temperature was assumed to be 20°C. The set point of the rooms was 25°C.

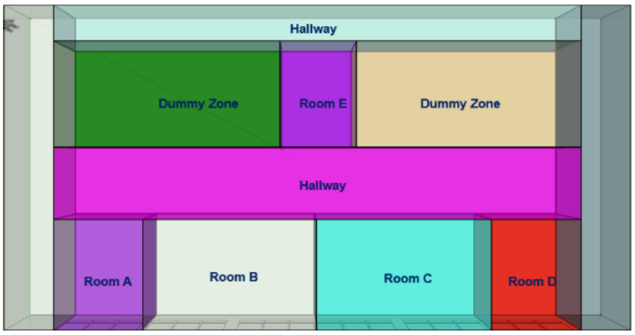


Figure 7 Floor layout

Table 1 VRF Specifications

Capacity	OU	IU #1 #6 #7	IU #2 #3	IU #4 #5
Cooling (kW)	28.1	2.2	3.6	5.6
Heating (kW)	31.6	2.5	4.0	6.3

The simulation was conducted from July 1st to September 1st. The TMY3 weather data of Tampa, Florida was used. The daily energy consumption of the new system and HPVRF system are shown in Figure 8. It could be found from Figure 8 that the new system consumes less energy than HPVRF systems. Overall, the energy consumption of HPVRF system is 2,828 kWh and that of the new system is 2,501 kWh. The overall energy savings is 11.5%.

Due to the nature of the vapor compression system, the seasonal energy saving depends on the climate of the location. The same system was simulated in Sterling, VA and Atlanta, GA. The energy savings are listed in Table 2. As can be seen from Table 2, the energy savings are reduced to 9.2% in Atlanta, GA. In Sterling, VA, the temperature in the cooling season is even lower than Atlanta, GA. Therefore, the seasonal energy saving is less, which is 6.2%. Because as the daily average temperature decreases from Tampa, FL. to Sterling, VA., the energy savings of the new system also decreases.

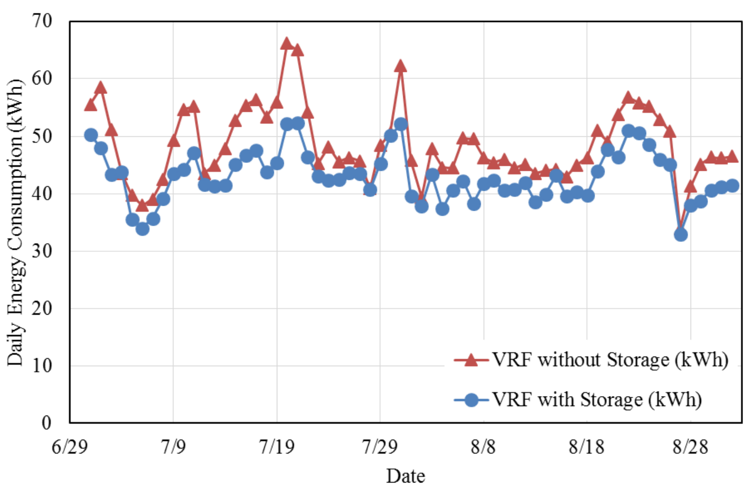


Figure 8 Energy consumption of VRF systems with and without CWS

Table 2 Energy savings in different cities

Location	Tampa, FL	Atlanta, GA	Sterling, VA
Energy Savings	11.5%	9.2%	6.2%

5. Conclusions

In this study, a thermodynamic model of VRF system was implemented in EnergyPlus and validated. The validation results show that the new model could achieve an uncertainty less than 5% in terms of hourly energy consumption. Based on the new model, a new VRF system with chilled water storage was discussed and modeled. The new system generates and stores chilled water during the cooling operation. During the summer peak period, the new system could use the chilled water as the heat sink instead of ambient air. Simulation results show that such a system is able to save 11.5% of seasonal energy as compared to a HPVRF system in Tampa, FL. The energy saving potential decreases when the climate of the location becomes milder.

6. References

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