Evaluation of Variable Refrigerant Flow (VRF) System Performance Using an Occupancy Simulated Research Building: Introduction and Summer Data Analysis Compared with a Baseline RTU System

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ABSTRACT

Variable refrigerant flow (VRF) heat pumps are relatively new to the U.S. market although these systems have been used in many countries in Europe and Asia for more than 25 years. Although there are known benefits like easier modular installation and higher efficiency, several studies show that there are concerns regarding the application of VRF systems in the U.S, including 1) lack of awareness of energy efficiency advantages, and 2) higher first cost. VRF system performance has been measured mainly in laboratories, which are well controlled but cannot replicate how a unit performs in an actual installation. In real building installations, the performance measurement of this type of system would be a challenge due to the complexity of the system and number of sensors required to calculate the precise performance. In addition, without controlling the human behavior in the real building – which is difficult, there are too many uncertainties to evaluate the operational performance of the system. Oak Ridge National Laboratory's Flexible Research Platform (FRP) overcomes this hurdle by simulating occupancy through the use of controlled lighting, plug loads, internal sensible and latent heat generation, and HVAC operational schedules. To this end, a 12 ton VRF system was installed in the FRP in June of 2014 and was operated every other week alternately with a 12.5 ton conventional roof top unit. The hourly energy consumption of both systems was characterized based on outdoor air temperature, and energy savings for the cooling season are estimated to be 19.8% for the VRF system.

INTRODUCTION

Multi-split air conditioning systems or variable refrigerant flow (VRF) systems are relatively new systems in the U.S. market although the systems have been used in many countries in Europe and Asia for more than 25 years. The known benefits of the VRF systems include 1) easier modular installation (particularly beneficial for building retrofit), 2) space savings with multiple indoor units connected to one outdoor unit, 3) ability to respond to fluctuations in space load conditions, 4) easier and cost effective maintenance and commissioning, and 5) energy efficiency. Although VRF ststems are receiving increased attention in the U.S. marketplace due to these known benefits, several studies (Goetzler 2007, Amarnath and Blatt 2008, Aynur et al 2009) show that there are several main concerns for the

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application of VRF systems in the U.S., which include 1) lack of awareness and studies of energy efficiency advantages, 2) higher first cost - about 5% to 20% higher than the chilled water systems or 30% to 50% more than single packaged ducted system (Amarnath and Blatt, 2008), 3) lack of optimized /integrated VRF control in energy management control system (EMCS), 4) code compliance issues specific to the U.S., and 5) lack of training of the complicated VRF installation and/or differences in construction practices.

There have been numerous studies on the multi-split VRF systems since the systems were introduced in Japan about 30 years ago. Most studies include field and laboratory experiments and/or energy modeling analysis. In general, field experiments were performed with a set of VRF indoor units and outdoor unit, and their energy consumption and performance were analyzed in real buildings in several different scenarios (e.g., varying indoor loads, different control modes, ventilation impact, etc.). The field studies verified the measured cooling/heating performance of the VRF systems in these various conditions, while it was relatively hard to compare the VRF system performance with other HVAC systems in the same building. In other studies, energy modeling has been used to compare the VRF system performance with other HVAC systems in a building with the same conditions. Some modeling studies use generic building models to compare the performance and energy consumption of VRF and other HVAC systems, while others use calibrated models to do the same analysis. Although the latter case would provide better analysis results than the former, it still has limited accuracy when predicting the precise energy consumption of the alternative system in a real building due to uncertainties in the model algorithm itself and human behavior and operational schedules of the building. Therefore, it is desired to have a research building that is representative of real buildings with control of occupancy and other internal load profiles. The ability to operate multiple HVAC systems alternately under the same climate conditions would allow for a more direct comparison of the systems as they would be operating in the same building under similar outdoor weather conditions.

FLEXIBLE RESEARCH PLAFORMS

Recently, Oak Ridge National Laboratory (ORNL) constructed two light commercial building flexible research platforms (FRPs) on its campus: one single-story FRP and one two-story FRP (Figure 1). The two-story FRP exposes the "test buildings" to natural weather conditions for purposes of research and development (R&D) leading to system/building-level advanced energy efficiency solutions for new and retrofit applications. The buildings' occupancy is emulated with portable heaters and humidifiers so that variations in energy use between the two systems are attributable only to the system performance and weather. Variations from different weather conditions can be normalized using weather normalization or calibrated simulation modeling. The two-story FRP, having a footprint of 40'x40' (12 m x 12 m) (Figure 1), was used in this study and simulates light commercial buildings common in the nation's existing building stock.

RESEARCH PLAN

FRP with Baseline System

As a first step of the study, a baseline test building was designed, constructed on the permanent apparatus of the two story FRP, and monitored in series based on the literature review (EIA 2003, ASHRAE 1989, Huang et al., 1991) and communication with industry partners. The baseline building was designed to be representative of a typical existing low-rise office building in U.S, which is built in the 1990's. Building materials and equipment that were typically implemented in the 1990's were preferably applied to the permanent part of the FRP. The building has 10 conditioned zones including 2 core zones and 8 perimeter zones. The baseline 12.5 ton roof top unit (RTU) is rated at 9.7 EER, 10.3 IPLV, and 81% AFUE. Each room has a variable air volume (VAV) box with an electric resistant heating element. The central fan in the air handling unit (AHU) draws the return air from each room. An exhaust fan is located in each floor, and the exhaust fans are operating when the supply fan is running. The rooftop unit is programmed to maintain a constant discharge air temperature (set to 58°F (14.4°C)). The natural gas furnace portion

Figure 1 FRP permanent apparatus (above), single-story test FRP (lower left) and 2 story test FRP (lower right)

of the RTU would engage if the building return air temperature were to drop below 58°F. As long as the discharge air is at least 58°F, the zone electric heat in the VAV boxes will activate to provide the reheat. The building's setpoint temperature was set to 70°F (21.1°C) and 75°F (23.9°C) for heating and cooling, respectively. During unoccupied hours (6:00 pm to 6:00 am), the setback and setup temperatures are set to 60°F and 86°F, respectively. The baseline building characteristics are summarized in Table 1.

The baseline system's performance is monitored using multiple sensors in the building to measure RTU's capacities, electric power consumption and gas flow rate, and indoor condition. The performance of the system is being monitored by both refrigerant and air side measurements. Room temperature and relative humidity sensors as well as supply, return, mixed air temperature and relative humidity sensors are also being monitored. For the RTU power, compressor and fan power have been measured individually, and the individual room's reheat power was also monitored. All was collected and stored every 30 seconds.

Table 1. Baseline Test Building Characteristics

Building Component	Value
Location	Oak Ridge, TN
Building Width	40 feet (12.2 meter)
Building Length	40 feet (12.2 meter)
Story Height (floor to floor)	14 feet (4.3 meter)
Number of Floors	2
Number of thermal zones	10 (8 parameter & 2 core zones)
Wall Structure	Concrete Masonry Units (CMU) with face brick
Wall Insulation	Fiberglass R_{US}-11 (R_{SI}-1.9)
Floor	Slab-on-grade
Roof Structure	Metal deck with polyiso & ethylene proplylene diene monomer (EPDM)
Roof Insulation	Polyiso R_{US} -18(R_{SI}-3.17)
Windows	Double clear glazing
Window-to-Wall Ratio	28%
Lighting power density	0.85 W/sqft (9.18W/m^2)
Equipment power density	1.3 W/sqft (14.04W/ m^2)
Baseline RTU Capacity	12.5 ton
EER	9.7
Gas furnace efficiency	81% AFUE
Reheat	VAV box with elec. reheat

FRP with VRF System

The VRF system was designed based on the load calculation from Manual N (Rutkowski 2008), and the corresponding indoor units and outdoor unit were recommended by the manufacturer. Figure 2 shows the location the indoor units and the assigned rooms in the first and second floor of the FRP. The outdoor unit is a type of heat pump (i.e., no heat recovery operation) and equipped with two scroll compressors, and charged with R-410a. Total cooling and heating capacities of the outdoor unit are about 144 MBH (42.2 kW) and 162 MBH (47.5 kW), respectively, and 10 indoor units' (6 wall mounted and 4 ceiling mounted) cooling and heating capacities are ranged from 7.5 (2.2 kW) to 18 MBH (5.3 kW), and 8.5 (2.5 kW) to 20 MBH (5.9 kW), respectively. The rated EER and IEER for the outdoor condensing unit are 11.2 and 22.7, respectively. Since the VRF system did not have any feature for providing ventilation for current installation, a separate intake vent was installed for each floor to introduce the outdoor air in conjunction with the existing exhaust fan in order to provide adequate ventilation. For pair comparison between the RTU and VRF systems, the original outdoor air intake for RTU was completely closed, and the ventilation air from this separate intake vent was used for both systems. The OA requirements for the building was estimated according to the the ASHRAE Standard 62.1-2013 given the 225 sqft/person (20.9 m^2/person) of occupant density and 3,200 sqft (297 m^2) of floor area.

The heating and cooling setpoints for the VRF system were the same as that of the baseline RTU.

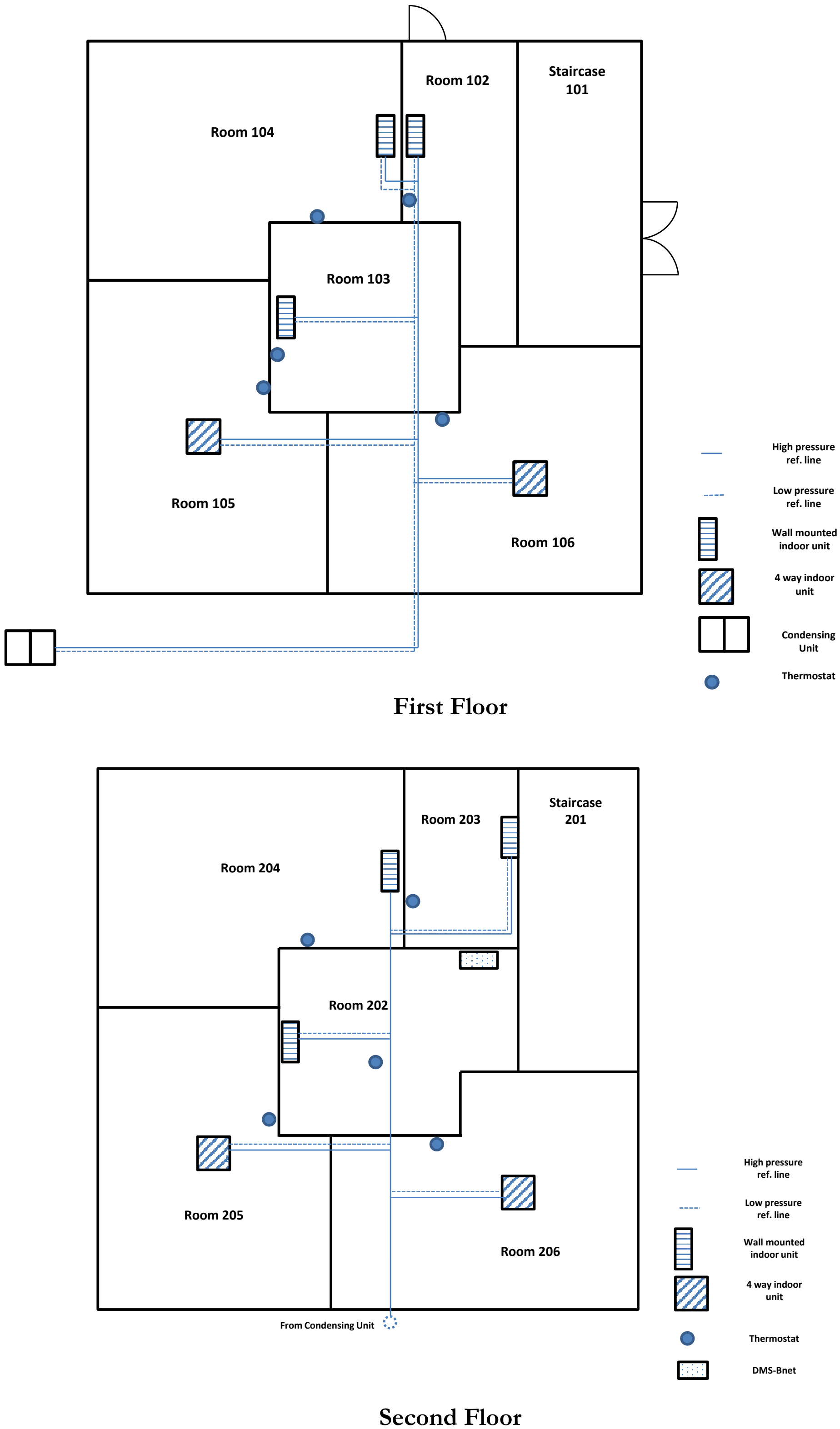

Figure 2 Layout of the VRF systems in the first and the second floors on the FRP

SUMMER DATA COMPARISON ANALYSIS

Data from the summer of 2014 was analyzed by plotting the hourly energy consumption of each system during occupied hours against the corresponding hourly average outdoor air temperature.

The results of this analysis are shown in Figure 3 and Figure 4. The VRF system has very high energy savings at mild outdoor conditions when the unit is operating at part load, which is expected of a unit with variable speed operation. In Figure 4, the increased energy use of the RTU between 50°F (10°C) and 68°F (20°C) is due to the VAV boxes using the electric resistance elements to reheat the air to maintain a proper supply temperature for each zone as seen. At high outdoor air temperatures, the energy use of the two systems converges. This is an expected trend since the EER ratings of the units are fairly similar. Using the curve fits from Figure 3, the energy use for the period of 7/7/2014 to 9/30/2014 for the hours between 8 am and 6 pm was calculated for both systems. This data showed a 12.1% savings for the VRF system, Table 2.

In addition to the savings during regular operation, there was significant energy savings during periods of standby operation, such as the unoccupied hours when the thermostat was setup. The RTU unit used, on average, 900 W with most of this being attributed to the fan for circulating the air. In contrast, the VRF unit only used 250 W on average. If this standby energy use is included for the unoccupied hours, the VRF energy savings increase to 19.8% for the same period, Table 3.

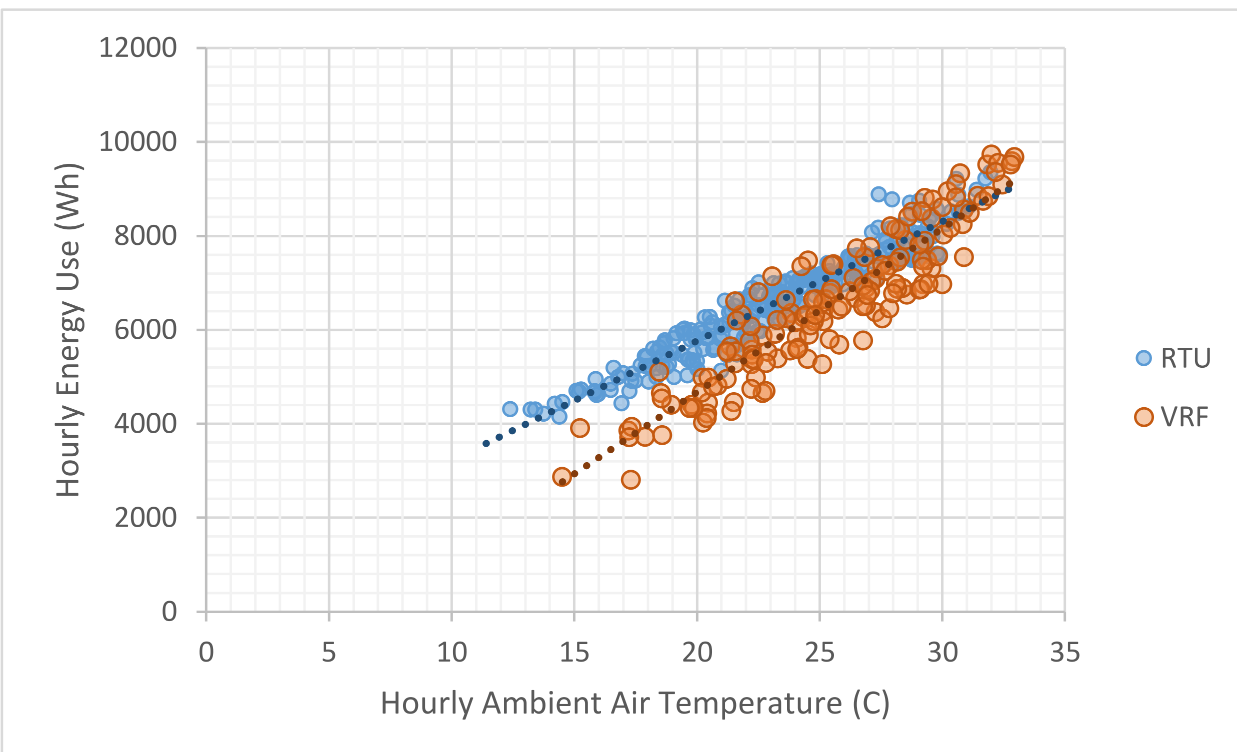

Figure 3 Hourly HVAC cooling energy use as a function of outdoor air temperature for the baseline roof top unit and the VRF system.

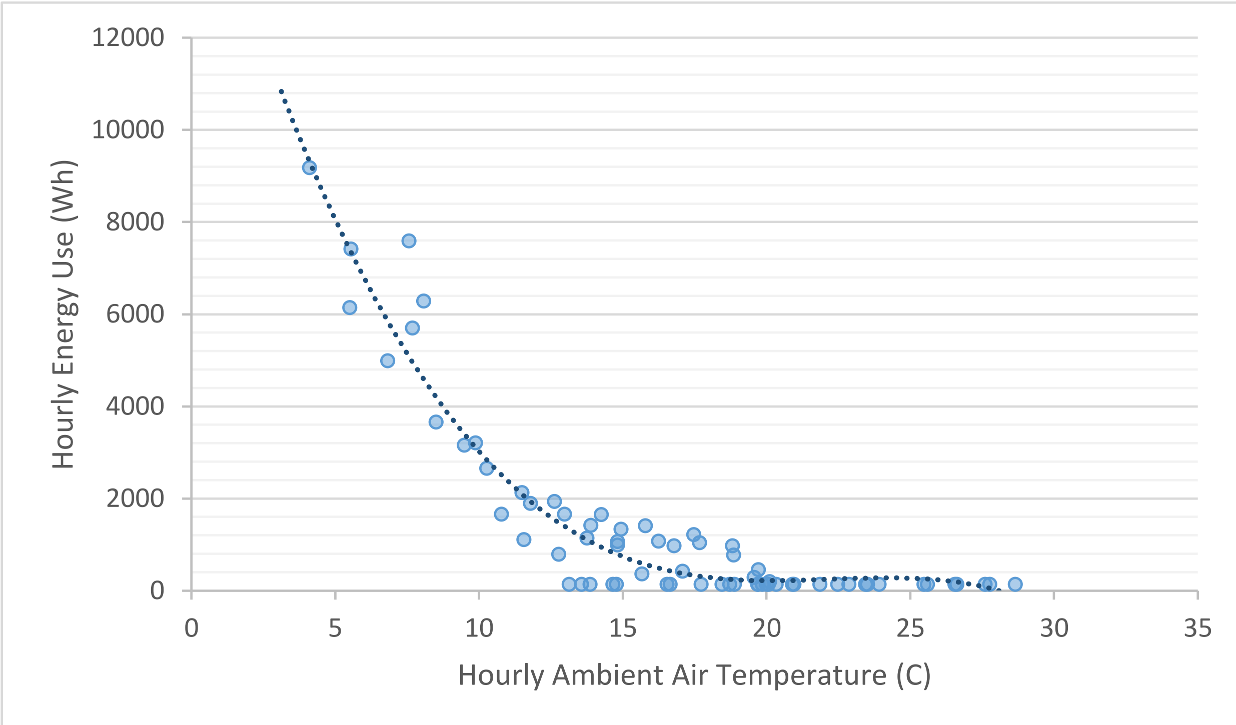

Figure 4 Hourly reheat energy use as a function of outdoor air temperature for the baseline roof top unit

Table 2. RTU and VRF Energy Use Estimates for the Period between 7/7/2014 and 9/30/2014 for the Hours of 8 am to 6 pm on Weekdays

	RTU	*VRF*
Total Energy Use (Wh)	4,909,974	4,315,795
% Difference (vs. RTU)	-	12.1%

Table 3. RTU and VRF Energy Use Estimates for the Period between 7/7/2014 and 9/30/2014 for the Hours of 8 am to 6 pm on Weekdays and including Standby Power Use for the Unoccupied Hours

	RTU	*VRF*
Total Energy Use (Wh)	5,635,374	4,517,295
% Difference (vs. RTU)	-	19.8%

SUMMARY

The study to investigate a multi-split VRF system's energy performance compared to typical RTU with VAV reheat was introduced in this paper. The systems were installed in ORNL's unique national user facility, aka FRP, which was operated with simulated occupancy and controlled internal loads in natural weather exposure. The baseline RTU and VRF system were operated and monitored every week alternately, and the system performances were compared. The VRF system showed a 19.8% energy savings over the baseline RTU for the period of July 7th to September 30th in 2014.

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