The New Variable Refrigerant Flow System Models in EnergyPlus: Development, Implementation and Validation

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Abstract

Variable Refrigerant Flow (VRF) systems provide more flexible controls and better thermal comfort while saving energy. There are two types of VRF systems: the Heat Pump (HP) and the Heat Recovery (HR). The VRF-HP system can provide either cooling or heating, but not simultaneous cooling and heating; while the VRF-HR system can deliver simultaneous heating and cooling to different zones by recovering heat from cooling zones to heating zones. For VRF models in a number of building simulation tools, a large number of system-level curves are used to describe the operational performance of the overall system. These models can generate satisfactory results for VRF-HP systems with simple controls (e.g., constant evaporative temperature), but for VRF-HP or VRF-HR systems with more complex controls under a wider range of operational conditions, there exist significant discrepancies between the simulated and measured energy use. This paper presents algorithms development and implementation of a new VRF-HP model and a new VRF-HR model in EnergyPlus. The two VRF models were successfully validated with measured performance data from real buildings and laboratory experiments.

Introduction

Variable refrigerant flow (VRF) system is a refrigerant system that varies the refrigerant flow rate using variable speed compressor(s) in the outdoor unit, and the electronic expansion valves (EEVs) located in each indoor unit (Aynur 2010). There are two types of VRF systems: heat pump (HP) and heat recovery (HR). The VRF-HP system is the most general type that can be used for either cooling or heating, but not simultaneously. The VRF-HR system can deliver simultaneous cooling and heating to different zones by transferring heat between the cooling and heating units (Goetzler and Ashrae 2007; Chua et al. 2013). VRF systems provide more flexible controls and better thermal comfort while saving energy, due to their multiple advantages: high efficiency during part-load conditions, minimal or no ductwork reducing heat losses, and smaller indoor fans consuming less energy as well as reducing indoor noise (Amarnath, Blatt, and Consultant 2008; Liu and Hong 2010; Yu et al. 2016).

VRF models have been developed and implemented in a number of building performance simulation (BPS) programs, including EnergyPlus (Version 7.2 and later) (Raustad 2013; Sharma and Raustad 2013; Li, Wu, and Shiochi 2009), eQUEST (a customized version only, which is not open to public), DOE-2.1E with user functions (Hong et al. 2005), Trace and IES-VE. These models use up to tens of system-level curves to describe the operational performance of the overall VRF system. The system-level curves work well for common VRF systems under normal conditions, but are usually limited when it comes to the evaluation of advanced VRF systems with more complex control logics to manipulate numerous operational parameters at various conditions. Furthermore, current system-level curves used to describe VRF systems are based on outdoor and indoor air temperatures, similar to those used by packaged DX systems. However, a VRF system is quite different, usually with one outdoor unit serving multiple indoor units with individual zone-level controls considering their potentially different thermostat settings and loads. Therefore, the VRF system performance should be better modeled using component level curves for indoor units, outdoor units, and their connecting piping network. Sharma et al. (Raustad 2013) compared the lab measured and simulated energy use of VRF systems, using the existing VRF model in EnergyPlus Version 7.2. They observed significant discrepancies in daily and monthly energy consumption, especially at low part-load operating conditions.

To address the limitations of existing VRF models and improve the simulation accuracy, a new VRF-HP model and a new VRF-HR model were developed in this study. They modeled component performance using component-level curves instead of the overall system curves. The models were implemented in EnergyPlus. Experimental measurements in a typical California house and a testbed in Japan were conducted for model testing and validation.

Model development and implementation

The VRF-HP system model

The new VRF-HP system model aims to simulate the energy performance of VRF systems in the heat pump operation model. Compared with the empirical VRF-HP model currently implemented in several BPS programs, the proposed model strictly adheres to a more physics-based development providing the ability to consider the dynamics of more operational parameters. This is essential for the description of more enhanced VRF control logics, including allowing: (1) variable

evaporating and condensing temperatures in the indoor and outdoor units, (2) variable fan speed based on the temperature and zone load in the indoor unit, and (3) further modifications of operational parameters (e.g., evaporating temperature, superheating degrees, and supply air flow rate) during low load conditions. The new VRF-HP model also provides a reliable approach to simulating the VRF system integrated with other energy saving technologies, e.g., dedicated outdoor air system. Furthermore, it enables the potential simulation of demand response of VRF systems by directly slowing down the speed of compressors in the outdoor units with inverter technology (Hong et al. 2015).

The new model implements separate curves for capacities and power inputs of indoor units and outdoor units, instead of overall curves for the entire system. For example, the new model implements a group of curves to describe the compressor consumption performance at various speed levels. This feature allows the user to provide fewer performance curves as the model inputs. Specifically, the proposed new model requires only seven types of curves to describe the performance of key components, while the current VRF models often require more than 20 curves to represent the system operation (DOE 2016). The definition of VRF performance data for simulation, being developed as part of ASHRAE Standard 205, will facilitate VRF manufacturers to provide adequate data to create the required performance curves. Finally, the new VRF-HP model includes an enhanced physics-based model to calculate thermal loss in the main refrigerant piping network, with an advantage over using a constant correction factor. The piping loss algorithm takes into account the influence of a number of dynamic factors (refrigerant flow rate, operational conditions, and refrigerant properties) and static factors (pipe length, pipe and insulation materials). These features significantly improve the accuracy of the simulated VRF system performance in both heating and cooling modes, especially during low part load operations (Hong et al. 2015).

The VRF-HR system model

Compared with the VRF-HP system, the VRF-HR is more complicated in terms of system configuration and operational controls. Figure 1 shows the schematic chart of a typical 3-pipe VRF-HR system. As can be seen in the figure, it has dedicated refrigerant pipes for suction gas, liquid and discharge gas. To enable simultaneous cooling and heating, complex refrigerant management loop and more system components are implemented, including one additional heat exchanger in the outdoor unit (OU) and multiple Branch Selector (BS) Units. The two heat exchangers in the outdoor unit can work at different evaporator/condenser combinations to enable specific operational modes to handle diverse and changing indoor heating/cooling load requirements. The Four-Way Directional Valves (FWV) and BS units enable the system to provide separate refrigerant piping connections for different operational modes. This leads to varying refrigerant flow directions and different control logics for

various operational modes, and therefore specific algorithms are needed for different major operational modes.

Depending on the indoor cooling/heating requirements and the outdoor unit operational states, the operations of the VRF-HR system can be categorized into six modes:

(1) Mode 1: Cooling load only. No heating load. Both OU heat exchangers operate as condensers.

(2) Mode 2: Simultaneous heating and cooling. The sum of the zone cooling loads and compressor heat is much larger than the sum of the zone heating loads. Both OU heat exchangers operate as condensers.

(3) Mode 3: Simultaneous heating and cooling. The sum of the zone cooling loads and compressor heat is slightly larger than the sum of the zone heating loads. One OU heat exchanger operates as a condenser while the other as an evaporator.

(4) Mode 4: Simultaneous heating and cooling. The sum of the zone cooling loads and compressor heat is slightly smaller than the sum of the zone heating loads. One OU heat exchanger operates as a condenser while the other as an evaporator.

(5) Mode 5: Simultaneous heating and cooling. The sum of the zone cooling loads and compressor heat is much smaller than the sum of the zone heating loads. Both OU heat exchangers operate as evaporators.

(6) Mode 6: Heating load only. No cooling load. Both OU heat exchangers operate as evaporators.

The system-level heat balance diagrams for all the six operational modes are shown in Figure 2. Note that the heat recovery loss (HR loss) only exists in Mode 3 and Mode 4, in which the OU evaporator and condenser run simultaneously. In these modes, the following two items are at similar levels: (a) the sum of IU heating loads and IU condenser side piping loss, and (b) the sum of IU cooling loads, IU evaporator side piping loss and heat released by the compressor. Take Mode 3 for example, item (b) is higher than item (a), and therefore the system requires the operation of OU condenser to release the extra heat to ensure the system-level heat balance. However, the extra heat is at a relatively low level so that the system needs to release more heat than required via OU condenser and meanwhile runs OU evaporator to ensure the heat balance as well as system reliability. This leads to the presence of HR loss.

A number of operational parameters are controlled to ensure system heat balance and stable operation, including evaporating temperature levels, condensing temperature levels, superheating and sub-cooling degrees, and the refrigerant flow rates at various components. The operational control logics for various modes are different and therefore particular algorithms were designed for different operational modes in the new VRF-HR model.

Compared with the empirical system curves based VRF-HR model currently implemented in several building simulation programs, the new VRF-HR model adheres to a physics-based development providing the ability to simulate the refrigerant loop performance and consider
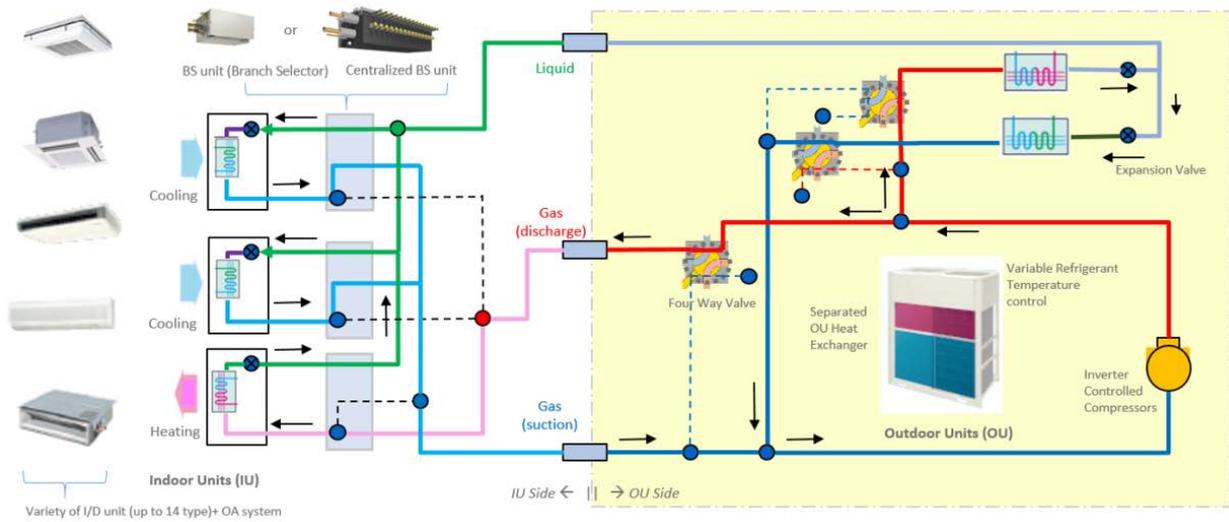
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Figure 1 Schematic chart of a 3-pipe VRF-HR system

Mode No.	Heat Balance Diagram	Note
1. IU_C Only, IU_H None		Cooling only
2. IU_C+Comp >> IU_H		Cooling Dominant w/o HR Loss
3. IU_C+Comp > IU_H		Cooling Dominant w/ HR Loss
4. IU_C+Comp < IU_H		Heating Dominant w/ HR Loss
5. IU_C+Comp << IU_H		Heating Dominant w/o HR Loss
6. IU_H Only, IU_C None		Heating only

Legend:
- OU Heating
- OU Cooling
- IU Heating
- IU Cooling
- Compressor
- Piping Loss_H
- Piping Loss_C

Figure 2 System-level Heat Balance Diagram for the Six VRF-HR Operational Modes

the dynamics of more operational parameters. This is essential for the representation of the complex control logics, e.g., the adjustment of superheating degrees during low load operations. Another feature of the new model is the implementation of component-level curves for indoor units and outdoor units, instead of overall curves for the entire system. Thus, it requires much fewer user specified performance curves as model inputs. These features considerably extend the modeling capabilities of the new VRF-HR model, including allowing:

(1) Implementation of various control logics for different VRF-HR operational modes.

(2) Variable evaporating and condensing temperatures in the indoor and outdoor units under a variety of operational conditions.

(3) Modeling of multiple OUs or a single OU with multiple compressors, by introducing compressor power/capacity curves under a range of Load Indices.

(4) More accurate estimation of HR loss, which is a critical parameter in the VRF-HR operations.

(5) Further modifications of operational parameters (e.g., evaporating temperature and superheating degrees) during low load conditions.

(6) Variable fan speed based on the temperature and zone load in the indoor units (IU).

(7) An enhanced physics-based model to calculate piping loss in the refrigerant piping network (varies with refrigerant flow rate, operational conditions, pipe length, and pipe and insulation materials) instead of a constant correction factor.

(8) Potential simulation of demand response of VRF systems by directly slowing down the speed of compressors in the outdoor units with inverter technology.

Model implementation in EnergyPlus

The new VRF-HP model and VRF-HR model were implemented in the 2015 and 2016 EnergyPlus releases. Detailed algorithms of the VRF models are presented in the EnergyPlus Engineering Reference Manual. EnergyPlus is an open source program that models heating, ventilation, cooling, lighting, water use, renew-able energy generation and other building energy flows (Crawley et al. 2001) and is the flagship building simulation engine supported by the United States Department of Energy. It includes many innovative simulation capabilities including sub-hourly time-steps, modular systems and plant integrated with heat balance-based zone simulation, multi-zone air flow, thermal comfort, water use, natural ventilation, renewable energy systems, and user customizable energy management system. Each release of EnergyPlus is continually tested extensively using more than four hundred example files and the test cases are defined in the ASHRAE Standard140 (ASHRAE 2014). It is a powerful tool that supports building professionals, scientists and engineers in optimizing building design and operations, and thus helps to reduce energy and water consumption. The

current VRF models stay in EnergyPlus for backward compatibility purpose.

Model validation

To validate the VRF algorithms and test the real performance of VRF systems, experimental measurements were performed on a real VRF-HP system in a typical California house and a real VRF-HR system in an experimental test facility in Japan.

The EnergyPlus release implemented with the new VRF models was used to simulate the energy performance of the tested VRF systems. The simulated and measured energy consumption data were then compared to determine the accuracy of the VRF model. Calibration criteria from ASHRAE Guideline 14 (ANSI/ASHRAE 2002) are adopted as the criteria of algorithm validation. When monthly data is compared, the model is considered calibrated if the absolute value of NMBE is less than 5% and CVRMSE is less than 15%. When hourly data is compared, the criteria of NMBE and CVRMSE are 10% and 30%, respectively.

Validation of the VRF-HP system model

A VRF-HP system was installed, commissioned and tested in an instrumented residential building, called the Caleb House, located in Stockton, California. The Caleb House is a two-story single family home with a total conditioned floor area of 205m^2 (88m^2 on the first floor and 117m^2 on the second floor). It was built in 2005, with four bedrooms, a living room, a dining room, a kitchen, a laundry room and three bathrooms. Figure 3 shows the facade of the Caleb house and the VRF-HP system schematic layout based on the floor plans. One outdoor unit and four indoor units serving the four zones in the VRF-HP system were installed. The two zones on the first floor are the living room and dining room. One zone on the second floor is the master bedroom, and the other is for the three guest bedrooms.

Figure 3 The facades and schematic layout of the Caleb House

The house was instrumented with a variety of sensors and meters, including temperature sensors, humidity sensors, and smart meters. They were used to monitor the temperature and humidity of each room and of supply and return air, the on/off status of the electric equipment, and the energy use of all the installed electric equipment. The

Caleb House was unoccupied to avoid uncontrollable impacts from occupants. However, additional equipment was deployed to create an artificial environment representing a real indoor environment with occupants, including electric heaters, humidifiers and fans. A weather station was installed outside the Caleb house, monitoring the ambient conditions, including dry-bulb air temperature, humidity, wind speed and solar radiation. All the measured data was collected per minute.

Validation of the VRF-HP algorithms was done using the hourly data on a daily basis, as the measured data from different monitoring systems were compiled and pre-processed per day. Seventeen typical cooling days were selected for validation of the cooling operation, and ten typical heating days were selected for validation of the heating operation.

Figure 4 and Figure 6 show good agreement between the measured and simulated hourly VRF-HP energy use in cooling mode and heating mode, respectively. The NMBE and CVRMSE for cooling mode are 2.8% and 14.6%, and -4.5% and 13.0% for heating mode, respectively. Figure 5 and Figure 7 show that the error associated with the simulated daily energy use is within the range of ±10 percentage for both cooling and heating modes. The results indicate that the simulated and measured VRF-HP energy use matched well for both the hourly and daily scale. Therefore, the new VRF-HP algorithms in both cooling mode and heating mode can be considered validated by the field test data.
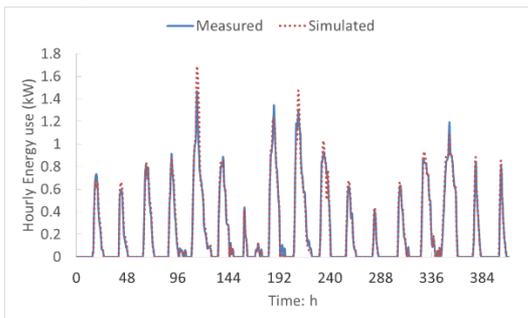

Figure 4 Hourly comparison between the measured and simulated VRF energy use in cooling mode: new VRF-HP model
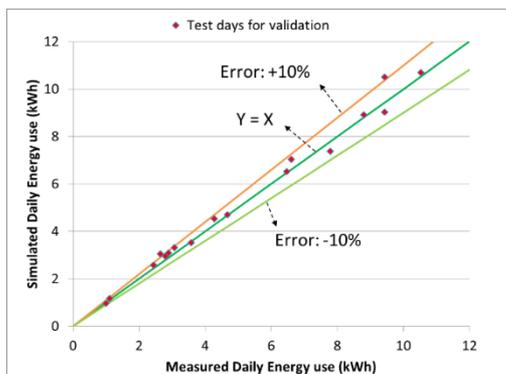

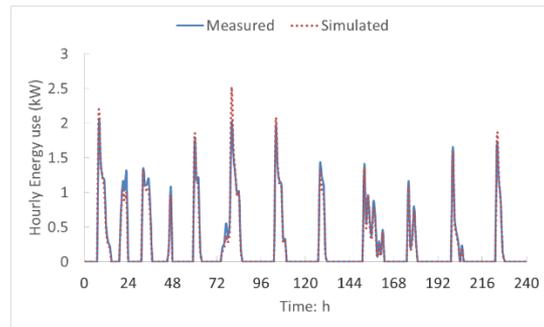*Figure 5 Errors of daily energy use in cooling mode: new VRF-HP model*

Figure 6 Hourly comparison between the measured and simulated VRF energy use in heating mode: new VRF-HP model
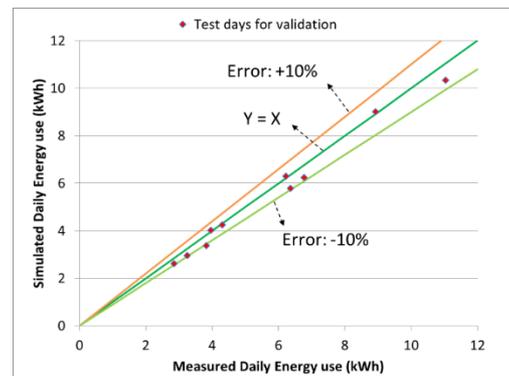

Figure 7 Errors of daily energy use in heating mode: new VRF-HP model

Validation of the VRF-HR system model

A typical 3-pipe VRF Heat Recovery Multi-Split System was installed in an experimental test facility in Japan to perform the measurement. The schematic layout of the testbeds is shown in Figure 8. Three testbeds are utilized in the test: two acting as the indoor side (one for the cooling zone and the other for the heating zone) and one acting as the outdoor side. Each indoor testbed has the capability to generate the constant cooling/Heating load by the embedded AC unit, and the outdoor testbed has the capability to keep the room temperature constant. The indoor unit terminals, located in the controlled thermal zone, supply conditioned air to the zone via a chamber where airflow rate is measured. Five terminal units are installed to create numerous heating/cooling load combinations: two on the cooling side and three on the heating side for instance. The cooling and heating capacities are 11.2 kW and 12.5 kW, respectively. The outdoor unit is installed in the outdoor testbed with an embedded extra AC unit controlling the testbed temperature. It has rated cooling and heating capacities of 56 kW and 63 kW, respectively.
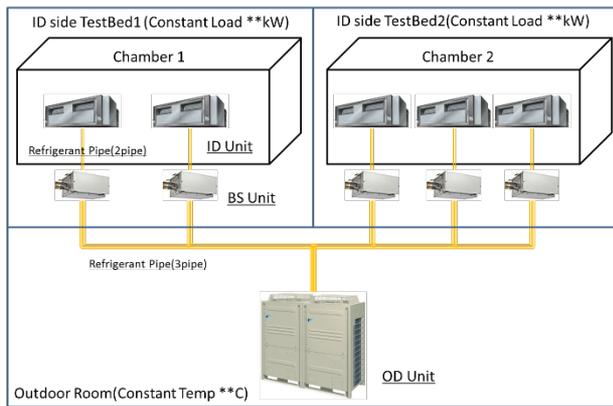
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Figure 8 Schematic layout of the VRF-HR experiment testbeds

Different indoor unit cooling and heating capacities are designed to represent various indoor load requirements, and outdoor air temperature is manipulated to represent various outdoor conditions to cover the various operation modes and to capture the operating characteristics. As summarized in Figure 9 below, comprehensive measurement data was collected for 15 static condition cases. They include different combinations of cooling and heading loads and ambient temperature, where the part load ratio range for simultaneous heating and cooling operation is about 5 to 45% and temperature range is 37 to 63°F, which is the dominant outdoor temperature in simultaneous heating and cooling operation. As aforementioned in Section 2, there are six operation modes for the VRF-HR system: Mode 1 (Cooling only), Mode 2 (Cooling dominant without HR loss), Mode 3&4 (Simultaneous Cooling and Heating with HR loss), Mode 5 (Heating dominant without HR loss), and Mode 6 (Heating only). The 15 experiment conditions cover all the operational modes except for Mode 2, which presents relatively small occurrence in actual system operations.
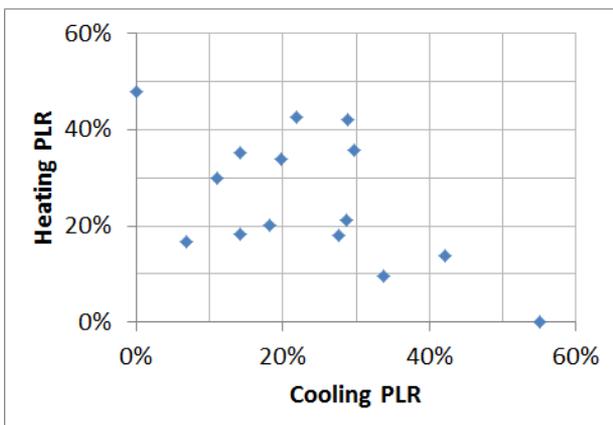

Figure 9 The experiment conditions of the VRF-HR system performance tests

A period of steady operation is selected from each experiment condition for the purpose of model validation. It is noted that the operating mode is not only determined by the simultaneous heating and cooling load but also hysteresis of the operating mode, so it varies in the real operation even the given load and temperature condition is same. The length of the periods could vary from a couple of minutes to half an hour with a measurement time interval of 10 seconds.

The testbeds are instrumented with sensors and meters, monitoring the environmental conditions (such as air temperature and relative humidity) as well as the system operations (such as compressor speed and the thermal properties of the refrigerant at different nodes, cooling and heating capacity by the air enthalpy method). The measured data was collected and used to calculate the heat transfer at each component, and then served as the true answer to validate the results from the EnergyPlus simulation.

To validate the VRF-HR algorithms, a model with two zones is developed to represent the two testbeds with indoor units. The environmental conditions in the testbed with the outdoor unit were monitored as the weather input for simulation. The sensible and latent loads in each indoor unit are calculated using the measurement data, and then inputted as the zone loads using the schedule object and equipment object. The model is then simulated using the new VRF-HR model in EnergyPlus and compared with the measured data to evaluate the accuracy of the algorithms.

The data was originally measured and collected with a time interval of ten seconds. Since the minimum simulation time step of EnergyPlus is one minute, the measured data was aggregated to 1-minute time interval for the validation purpose. Since sub-hourly data was used for comparison, it is more reasonable and rigorous to use the calibration criteria of hourly data for validation in this study.

According to the experimental data, the 15 experiment conditions covered five operation modes: Mode 1 (Cooling only), Mode 3&4 (Simultaneous Cooling and Heating with HR loss), Mode 5 (Heating dominant without HR loss) and Mode 6 (Heating only). The simulation results under each of the operation mode are validated using the corresponding measured data under the same operation mode. The Mode 2 (Cooling dominant without HR loss) didn't occur during the experiments. However, Mode 2 rarely happens in actual operation either, so it is not a problem that Mode 2 is not included in the validation. The compressor power is the main energy consuming component in the VRF-HR system, and is significantly affected by the compressor speed and operational conditions. So the measured and simulated compressor speed, compressor power consumption and the total system energy consumption are all compared. The comparison results are summarized in Figure 10, Figure 11, and Figure 12. The simulated results of all the five covered operation modes are basically showing satisfactory matches with the measured data. NMBE and CVRMSE are calculated based on the simulated results and measured data, with results shown in Table 1. The NMBE and CVRMSE are less than 10%, meeting the calibration criteria (<10%), indicating that the newly developed VRF-HR model in EnergyPlus can be considered validated for all the covered operation modes. It should be noted that the simulated results of Mode 1 and

Mode 6, which are the operation modes of the VRF Heat Pump model, are all within the ±10% range of measured data, reaffirming the accuracy of the new VRF-HP model.
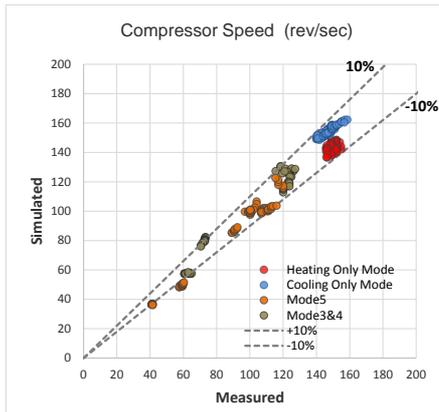

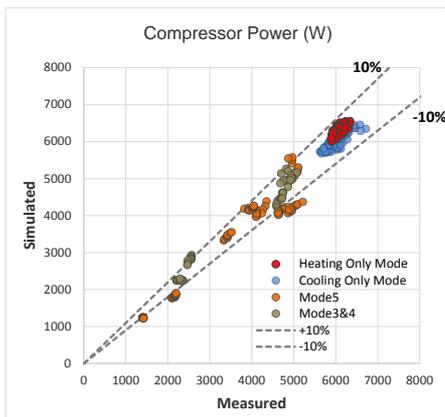*Figure 10 Comparison between the simulated and measured compressor speed*

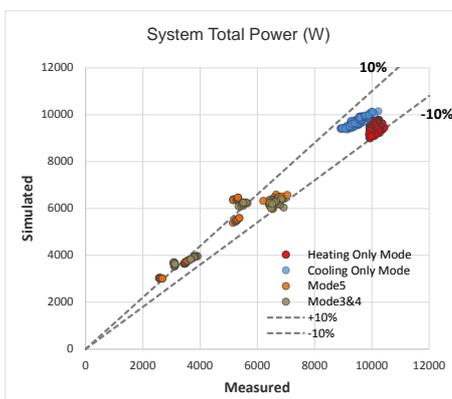*Figure 11 Comparison between the simulated and measured compressor power*

Figure 12 Comparison between the simulated and measured system total power consumption

Table 1 Validation results of different operation modes and the calibration criteria

%	Calibration criteria	Mode 1	Mode 3&4	Mode 5	Mode 6
NMBE	10	2.4	2.6	2.3	-6.6
CVRMSE	30	2.8	9.5	9.6	6.9

Conclusions

New VRF models for the heat pump mode and the heat recovery mode were developed and implemented in EnergyPlus. The VRF-HP model was validated using the field test data from a California house, and the VRF-HR model was validated using the experimental data from a testbed in Japan. The comparison between the simulated and measured VRF performance data shows great compliance based on the criteria of ASHRAE Guideline 14. Both the VRF-HP and VRF-HR models can represent the actual performance of the VRF systems accurately and are considered validated.

The new features of the VRF-HP model include: (1) introduction of the component-level curves instead of overall curves for the entire system, (2) variable evaporating and condensing temperatures in the indoor and outdoor units, (3) variable fan speed based on the temperature and zone load in the indoor unit, and (4) a physics model to calculate the thermal loss through the refrigerant piping network considering the variations of refrigerant flow rate and operational conditions.

Besides the new features of the VRF-HP model, extra new features of the VRF-HR model include: (1) implementation of various control logics for different VRF-HR operational modes, (2) modeling of multiple OUs or a single OU with multiple compressors, by introducing compressor power/capacity curves under a range of Load Indices, (3) more accurate estimation of HR loss, which is a critical parameter in the VRF-HR operations, and (4) further modifications of operational parameters (e.g., evaporating temperature and superheating degrees) during low load conditions.

Future work includes development and validation of two-pipe VRF models, implementing demand response control of VRF systems, as well as measurement and verification of VRF system performance in real commercial buildings.

Acknowledgment

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