Modeling and Calibration of a Variable Refrigerant Flow (VRF) System with a Dedicated Outdoor Air System (DOAS)

Dongsu Kim[1], Heejin Cho[1], Piljae Im[2] and Sam Cox[1]

[1] Mississippi State University, Mississippi State, MS, USA
[2] Oak Ridge National Laboratory, Oak Ridge, TN, USA

Abstract

With increased use of variable refrigerant flow (VRF) systems in the U.S. building sector, there have been gaining interests in capability and rationality of various building energy modeling tools to simulate VRF systems. This paper presents modeling and calibration of a VRF system with a dedicated outdoor air system (DOAS) by comparing to the measured data from a real building and system. Modeling and calibration of a VRF-DOAS model were performed using the whole-building simulation, U.S. DOE's EnergyPlus version 8.1, with the measured data collected from an occupancy emulated research building, Flexible Research Platform (FRP), at Oak Ridge National Laboratory (ORNL). The initial building model was built, and the original EnergyPlus code was modified to model a specific DOAS installed in the FRP. The VRF-DOAS model can reasonably predict the performance of the actual VRF-DOAS system based on the criteria from ASHRAE Guideline 14-2014. The calibration results show that hourly CV-RMSE and NMBE would be 15.7% and 3.8%, respectively, which is deemed to be calibrated.

Introduction

The building sector accounts for about 40% of the entire energy consumption in the U.S. The energy used for HVAC systems represents approximately 50% of the total energy usage of a building sector (Chua et al. 2013).

Variable refrigerant flow (VRF) systems have been widely used in many Asian and European countries with several key benefits, including: energy efficiency, ease of installation, design flexibility, and easy maintenance (Goetzler 2007). As the VRF system is a still new HVAC technology in the U.S. marketplace, numerous studies have been performed for the VRF systems to evaluate the energy performance and to compare the energy efficiency with conventional HVAC systems. Most studies include field or laboratory empirical tests as well as simulation modeling analysis of the system performance or VRF control strategies (Im and Munk 2015)(Zhou et al. 2008)(Raustad 2013)(Meng et al. 2015).

Ventilation is one of the main issues with the VRF systems since the VRF system only circulates indoor air without any - outdoor air (OA) intake to satisfy indoor air quality (IAQ) in commercial buildings (Kim et al. 2016). Due to the main drawback with OA supplies, additional ventilation systems, such as DOAS combined with the heat recovery ventilation (HRV) or additional HVAC systems, are essential to be included with the VRF systems (Aynur et al. 2010). Many recent studies have shown the effects of DOASs with the VRF systems using experimental facilities or the simulation environment (Kim et al. 2016)(Aynur et al. 2008)(Zhu et al. 2014). Analysis results turned out that VRF systems combined with DOASs tended to consume higher energy when compared to the non-ventilation systems and the DOAS could affect indoor thermal comforts and IAQ depending on DOAS operation modes. As numerous previous studies have mentioned apparently, the VRF systems not just serve building energy savings due to the higher energy efficiency when compared to other conventional HVAC systems, but also provide better indoor environmental qualities with DOASs and its operation modes (Hong et al. 2016). However, there have been still several concerns for the application and analysis of the VRF-DOASs, such as higher initial cost, lack of familiarity with the technology, and safety issues with refrigerant leakage in the U.S. (Aynur 2010).

Therefore, the objective of this paper is to present modeling and calibration of a VRF-DOAS model using an experimental facility and the whole-building energy simulation, EnergyPlus. The original EnergyPlus code was modified to correctly model the installed VRF-DOAS and then calibrated based on the measured data from an occupancy emulated research building, Flexible Research Platform (FRP), at Oak Ridge National Laboratory (ORNL), under cooling and heating period.

Target Building Description

A test facility: two-story flexible research platform (FRP)

The two story flexible research platform (FRP) facility is a two-story, 3,200 ft^2 (297.3 m^2) multi-zone. The FRP is an occupancy emulated research building that represents a typical existing low-rise, small office building common in the US (Figure 1 (a)). For this study, the occupancy in the FRP was simulated by process control of lighting and other internal loads, such as portable heaters for sensible

heat gains and humidifiers for latent heat gains. On this building, detailed building activities, such as building envelope retrofits, addition of alternative building components, and any HVAC systems changes, were logged, and the building system's performance was closely monitored, which was used to model and calibrate the VRF-DOAS simulation model. In addition, a dedicated weather station was installed on the roof. The data gathered from the weather station was used to pack a weather file that can be used in modeling and calibration procedure. The VRF system installed in the FRP is a heat pump type 12-ton (42 kW) system with a DOAS and contains two scroll compressors. (Figure 1 (b) and (c)). Table 1 summarizes the FRP and VRF system characteristics (Im et al. 2015).
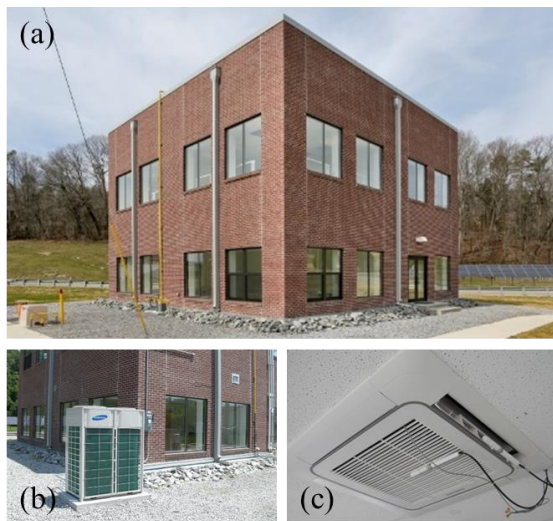

Figure 1. A test facility: (a) two-story flexible research platform, (b) a VRF outdoor unit, and (c) a VRF indoor unit.

Table 1. Building characteristics of two-story flexible research platform

Location	Oak Ridge, Tennessee, USA
Building size	Two-story, 40×40 ft (12.2×12.2 m), 14 ft (4.3 m) floor-to-floor height
Exterior walls	Concrete masonry units with face brick, RUS-11 (RSI-1.9) fiberglass insulation
Floor	Slab-on-grade
Roof	Metal deck with RUS −18(RSI −3.17) polyisocyanurate insulation
Windows	Double-pane clear glazing, 28% window-to-wall ratio
Baseloads	0.85 W/ ft² (9.18W/ m²) lighting power density, 1.3 W/ ft² (14.04W/ m²) equipment power density
VRF system	12 ton (42 kW) VRF system with a DOAS

A variable refrigerant flow with dedicated outdoor air system (VRF-DOAS)

The VRF system had a 12-ton (42 kW) outdoor unit, one DOAS unit, and ten indoor units as shown in Figure 2. The system capacity of the corresponding indoor and outdoor units was chosen based on the load calculations from Manual N (Rutkowski 2008). Ten indoor units' capacities varied from 2.2 kW to 5.3 kW for heating, and 2.5 kW to 5.9 kW for cooling, respectively (Im & Munk 2015). As seen in Figure 2, the ten indoor units and the DOAS were connected to the same VRF outdoor condensing unit, and the DOAS provides conditioned OA to ten thermal zones. In addition, the OA requirement for the FRP building was estimated according to the ASHRAE Standard 62.1-2013 (ASHRAE 2013). Note that the VRF system in this study was a heat pump–type system that provides only cooling or heating at any single time and cannot provide simultaneous heating and cooling for different thermal zones.
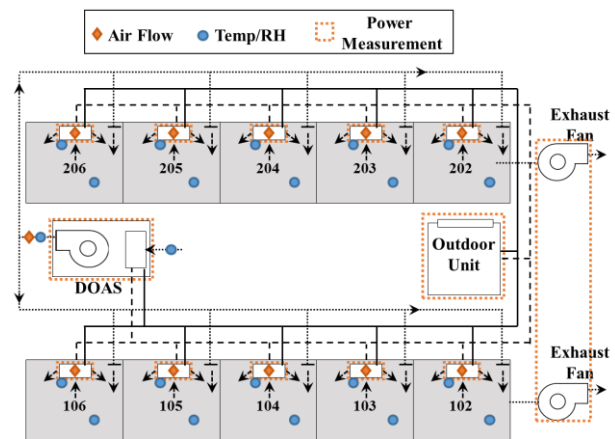

Figure 2. VRF-DOAS schematic and monitoring points

During the test period (i.e., July 11, 2015 through March 6, 2016), there were several other tests undergone with different types and control modes of HVAC systems at the FRP. Therefore, only the days when the VRF system fully conditioned the FRP were selected for the model calibration. Those are 6 days during August 15, 2015 through September 20, 2015 for cooling season, and 19 days during October 10, 2015 through February 19, 2016 for heating season.

Measured data for the VRF system includes:

1) One-time airflow measurements for each indoor unit,

2) Continuous air flow measurement for the DOAS supply side for the VRF system,

3) Power consumption for the VRF outdoor unit, each VRF indoor unit, and the DOAS (Im et al. 2015).

Calibration Approaches

To properly model and calibrate the VRF-DOAS system installed at the FRP, the following steps were performed: (1) modification of the existing EnergyPlus v8.1 source code to be able to simulate the physical settings of VRF-DOAS described in the previous section; (2) after modeling the building envelope and HVAC systems, calibration of building envelope model and internal heat gain inputs to ensure that the simulated delivered cooling and heating loads are comparable with the measured data; and (3) calibration of VRF-DOAS model for the total building energy consumption based on the definition from ASHRAE Guideline 14-2014 (ASHRAE 2014).

Step 1: EnergyPlus source code modification

EnergyPlus 8.1 allows for performance curve based quasi-steady state simulation of VRF systems. The EnergyPlus 8.1 source code was modified to model the current VRF-DOAS setting in the FRP; particularly the usage of VRF heating and cooling coils to condition OA in the DOAS described in the previous section. In the original version 8.1 of EnergyPlus, OA could be introduced only through individual zonal VRF indoor units with an OA mixer or an air-loop DOAS with HVAC DX coils from a separate HVAC system such as a single or two speed DX coils (DOE 2013). Therefore, the EnergyPlus 8.1 source code was modified to allow for OA to be provided through an air-loop DOAS directly to individual zones and to be conditioned with VRF heating and cooling coils connected to the outdoor unit supplying the indoor unit for each zone of the VRF system. EnergyPlus has three stages of simulation: Zone load calculations, air loop calculations, and zone equipment calculations. This requires the data from VRF coils simulated in the air loop stage to be passed to the zonal equipment stage and then be aggregated with the zone VRF coil capacities. Thereafter, the VRF outdoor unit is simulated with steady state performance curves to calculate energy usage. If the capacity of the outside unit is exceeded, the air loop VRF coil is assumed to have priority, and the zonal coil capacities are systematically reduced until the capacity is no longer exceeded.

With this source code modification, two new objects, VRF air-loop cooling and heating coils (object names Coil: Cooling: DX: VRFAirloopCoil and Coil: Heating: DX: VRFAirloopCoil), were added to enable a DOAS system coupled with a VRF outdoor unit to provide 100% conditioned OA to individual zones, as illustrated in Figure 2. Figure 3 demonstrates the simulation process of the modified EnergyPlus version. The new VRF air-loop coil objects modeled to calculate the coil performance based on performance curves in the same manner compared to the single-speed DX heating and cooling coils modeled in EnergyPlus 8.1. The coil capacities were accounted into the VRF condenser calculations along with the average inlet wet-bulb conditions for each coil linked to the VRF condenser. In the current modification, only one VRF condenser can be used. The model uses performance information at rated conditions along with curve fits for variations in total capacity, energy input ratio, and part-load fraction to determine the performance of the unit at part-load conditions. In this modification process, manufacturers' data in the EnergyPlus VRF HP model (Raustad, R. 2013) were used for the coefficients of performance curves. This simulation is a quasi-steady state simulation and does not attempt to model the dynamics and controls of the VRF system. After the source code modification, the new EnergyPlus executable file and input data dictionary (idd) file were generated and made available to model the VRF-DOAS system installed in the FRP.
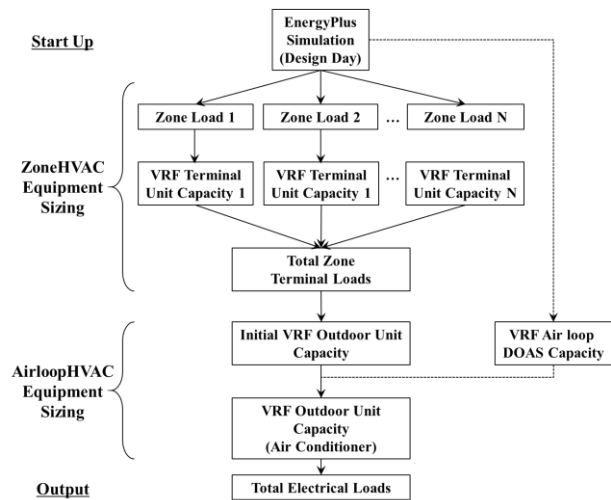

Figure 3. Process of the modified EnergyPlus version 8.1 for VRF-DOAS

Step 2: Calibration 1 - Building load calibration

As a first step of the calibration, the initial building envelop model was calibrated, and the building's simulated delivered cooling and heating loads were compared with the calculated delivered heating and cooling loads based on air side measured data.

Building envelop model, first, was calibrated by modifying the input values for the categories shown below.

1) Weather data
2) Infiltration
3) Interior light intensity and schedule
4) Plug load intensity and schedule

Actual weather data from the dedicated weather station was collected and used to pack weather data file for EnergyPlus.

For infiltration updates, a blower door test was performed to measure the airtightness of the FRP. The measurement was used to calculate the infiltration value for the FRP building model in EnergyPlus based on an infiltration calculation method (Gowri et al. 2009).

The intensities and schedules of the interior lights and equipment values (plug loads) were also updated based on the measured lighting and plug loads in the FRP. Figure 4 shows the output trends of the interior lights after

modification in the EnergyPlus model. The interior lights shown in Figure 4 are hourly average values in EnergyPlus shown in terms of the electric energy for ten zones for six representative days during the measurement period.

Figure 5 shows comparison of the interior plug loads for the measured and simulated data after modification in EnergyPlus. The interior plugs provided in Figure 5 are also hourly average values in EnergyPlus for all ten zones for six representative days during the entire comparison period.
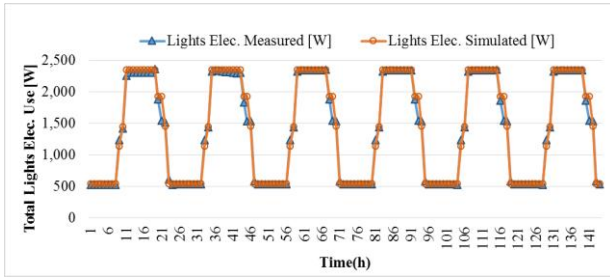
Figure 4. Hourly Interior lights electricity use
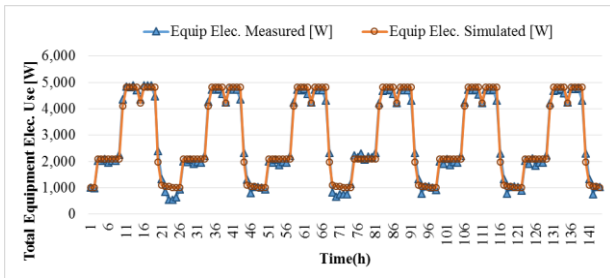
Figure 5. Hourly Interior equipment electricity use

After updating the building envelop model, the delivered cooling and heating loads were compared to the simulated values. System delivered loads were calculated by Eq. (1), where $\dot{m}_a$, h_{return}, and h_{supply} are used for the mass flow rate of dry air through heating and cooling coils, return air enthalpy, and supply air enthalpy, respectively.

$$Load_{Delivered} = \dot{m}_a \times (h_{return} - h_{supply}) \quad (1)$$

Step 3: Calibration 2 - VRF-DOAS system

The VRF-DOAS model was also calibrated after the building load calibration. The calibrated building load model in Step 2 was used to calibrate the VRF-DOAS simulation model based on the measured data from the FRP. The following items were added and modified in the VRF calibration process:

1) DOAS using the modified version of EnergyPlus 8.1
2) DOAS outdoor air (OA) set point temperature
3) VRF operation schedule
4) Heating and cooling COPs of the VRF system

An air-loop DOAS was implemented in the VRF simulation model using the modified version of EnergyPlus 8.1 as described in step 1 section, based on the specifications of the installed DOAS in the FRP. As illustrated in Figure 2, this implementation allows for OA to be provided through an air-loop DOAS directly to individual zones. With the DOAS, OA can be conditioned with VRF heating and cooling coils that are connected to the outdoor units for the zonal VRF indoor units.

The DOAS schedule and the OA supply air temperature set point were determined based on the measured data for the VRF system in the FRP. The DOAS operation in the model was controlled by an energy management system (EMS). The DOAS was always turned on during all hours in summer, but it was operated only during occupied hours during heating season (December–March).

The VRF operation schedule was then modified according to the actual VRF system operation. Since the VRF system installed in the FRP cannot provide simultaneous cooling and heating, the VRF cooling and heating operation schedules were specified separately for the cooling (April–November) and heating (December–March) period, which is the same case for actual operation schedule of the VRF system. The thermostat set point temperature and schedule were set to 24°C and 21.1°C for cooling and heating during occupied hours, respectively.

Finally, the heating and cooling COPs of the VRF model were modified based on the actual performance of the VRF system in the FRP, which were observed from the measured data. The nominal COP values used for the cooling and heating coils were set to 3.0 and 2.5, respectively.

Statistical evaluation of a VRF-DOAS simulation model

As a final step of the calibration, the measured and simulated data were compared to calibrate the whole building simulation model. ASHRAE Guideline 14 (ASHRAE 2014) was used to evaluate the validity of the calibrated models. With this guideline, two calibration criteria, the Normalized Mean Bias Error (NMBE) and Coefficient of Variation of Root Mean Square Error (CV-RMSE), were used to determine how well a simulation model fits with the measure data.

CV-RMSE and NMBE were calculated by Eq. (2) and (3), where s_i, m_i, and $\bar{m}$ represent the simulated results, the measured data, and the average measured data at instance i with $p = 1$, respectively. It states that models are declared to be calibrated if they produce NMBE within ± 10% and CV-RMSE within ± 30% when hourly data are used, or 5% and 15%, respectively, with monthly data.

$$CV(RMSE) = 100 \times \frac{\sqrt{(\sum_{i=1}^{n}(m_i-s_i)^2/(n-p))}}{\bar{m}} \quad (2)$$

$$NMBE = 100 \times \frac{\sum_{i=1}^{n}(m_i-s_i)}{(n-p)\times\bar{m}} \quad (3)$$

Discussion and Results Analysis

Comparison of building delivered loads

Figure 6 represents scatter-plots of hourly delivered load of VRF-DOAS model as a function of hourly average OA temperature during the occupied hours. The simulated delivered loads of the VRF-DOAS were compared with the measured data for 25 days during occupied hours. As seen in this figure, the comparison shows that the simulated delivered loads for the VRF-DOAS system are well matched after building components' updates. This calibration step ensures that the simulated building load (envelope + internal gains) matches the delivered cooling and heating loads, which would be a prerequisite to the HVAC system and control calibration.
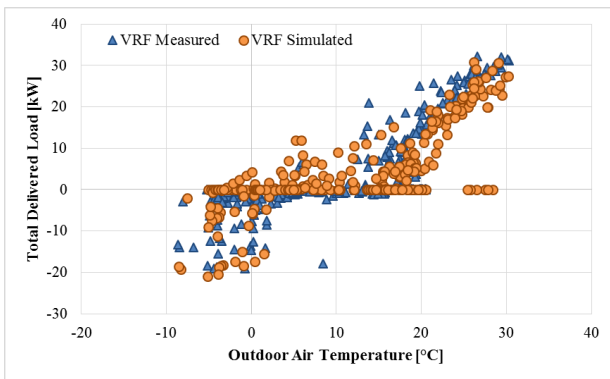
Figure 6. Measured versus simulated hourly VRF Total delivered loads

Comparison of HVAC and whole-building energy use

The simulated HVAC energy use is compared against the measured data. Figure 7 and Figure 8 show the hourly patterns of the simulated VRF system and whole-building energy usage compared with the measured consumption for 6 typical days, from August 2015 through February 2016. From the hourly comparison patterns, the simulation results of the calibrated VRF-DOAS model shown in Figure 7 and Figure 8 agree with the measured data in most hours; however the hourly data reveals that the simulation model often under-predict the high HVAC energy usage in the beginning of system start-up in the morning. This can be caused by various sources of uncertainty in a building performance simulation process (D. Coakley et al. 2014), including the uncertainty of thermal mass and material properties.
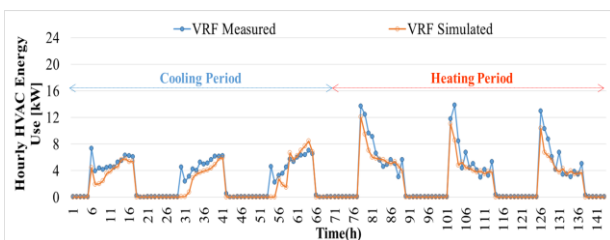

Figure 7. Hourly comparison of HVAC energy use between measured and simulated data for 6 typical days
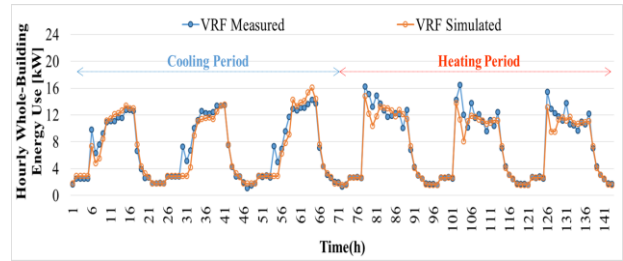

Figure 8. Hourly comparison of the whole-building energy use between measured and simulated data for 6 typical days

Figure 9 shows scatter-plots of the simulated hourly VRF-DOAS system energy usage with the measured data versus hourly average OA temperature during the entire cooling and heating period. Since the VRF-DOAS model is a heat pump type of VRF systems, which cannot provide simultaneous cooling and heating to different zones, the VRF-DOAS was operated by a master thermostat, which is located in room 106 on the first floor.

The simulation results from the calibrated VRF-DOAS model reasonably fit well with the measured data. In a similar fashion to Figure 9, Figure 10 illustrates that comparison between measured and the simulated whole-building energy consumption shows reasonably good agreement in the cooling and the heating operation.
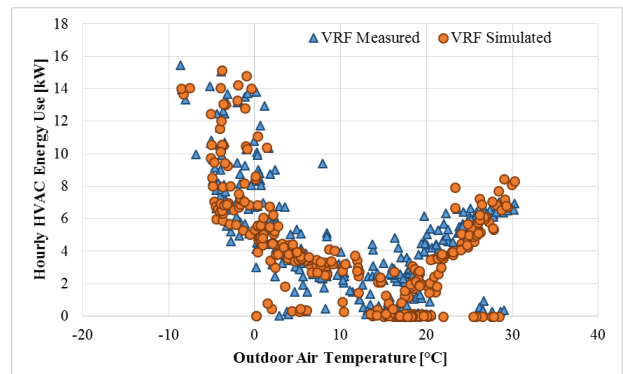

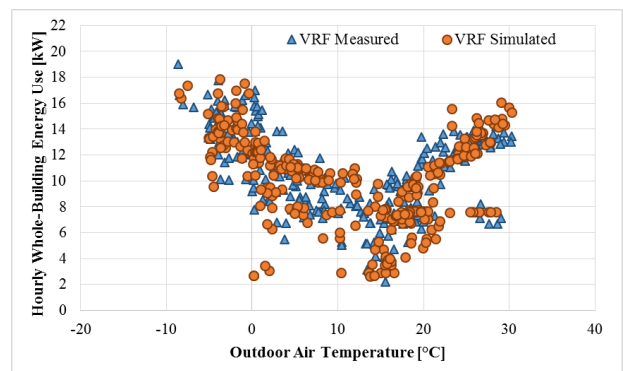*Figure 9. Measured versus simulated hourly HVAC system energy use during the entire comparison period*

Figure 10. Measured versus simulated hourly total energy use during the entire comparison period

Comparison of statistical evaluation for the simulated and measured results

Figure 11 shows the whole-building energy use for the before and after calibration of the VRF-DOAS model, which indicates that the difference in the whole-building energy based on the measured data decreased from 9.3% (376.1 kWh) to 1.9% (78.8 kWh) for the chosen 25 days from August, 2015, through February, 2016. Table 2 presents the detailed values of building energy consumption among the measured data, the initial model data (i.e., before calibrated data) and the data after calibration. The results show that the differences between the measured data to the data after calibration are 8.3% (66.1 kWh) for lights, 7.4% (123.8 kWh) for equipment, 17.9% (272.0 kWh) for cooling and heating systems, and 4.8% (3.3 kWh) for VRF fans. The differences for lighting and equipment are due to altered operations of those on some test days from the regular schedules.
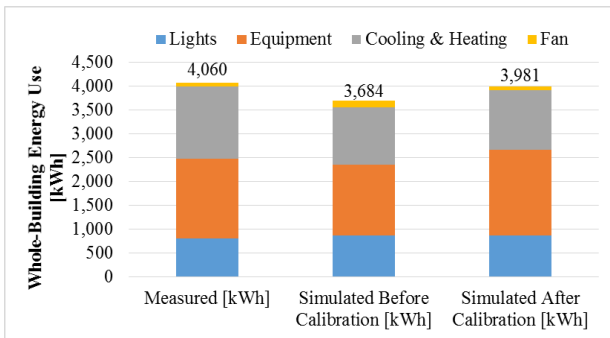

Figure 11. Comparison of the whole-building energy use of the VRF-DOAS model

Table 2. The Whole-building energy use of the VRF-DOAS model

	Lights	Equip.	Cooling & Heating	Fan	Total
Measured [kWh]	795.0	1,674.8	1,521.7	68.2	4,059.7
Simulated before calibration [kWh]	864.3	1,483.4	1,203.1	132.8	3,683.6
Simulated after calibration [kWh]	861.1	1,798.6	1,249.7	71.5	3,980.9
Diff. before calibration [%]	8.7%	11.4%	20.9%	94.6%	9.3%
Diff. after calibration [%]	8.3%	7.4%	17.9%	4.8%	1.9%

Table 3 summarizes the CV-RMSE and NMBE for the VRF-DOAS model before and after calibration. The calculated analysis results in the calibrated model of the VRF-DOAS are reasonably calibrated based on the criteria from the ASHRAE Guideline 14-2014. The calculated results indicate that CV-RMSE and NMBE for hourly data are 15.7% and 3.8%, respectively, after the calibration, which are all within the acceptable criteria

ranges. For daily comparison, CV-RMSE and NMBE are 8.7% and 0.2%, respectively, after the calibration.

Table 3. Statistical evaluation of the VRF simulation model

		Before calibration (%)	After calibration (%)
Daily	CV-RMSE	20.1	8.7
	NMBE	9.6	0.2
Hourly	CV-RMSE	32.3	15.7
	NMBE	10.9	3.8

Conclusion

Modeling and calibration of a VRF system with a DOAS were performed using a modified EnergyPlus program based on the measured data from FRP. The calibration processes in three main stages: (1) VRF-DOAS source code modification of EnergyPlus 8.1, (2) building load calibration, and (3) VRF-DOAS system updates for final calibration until the statistical comparison shows acceptable match under the criteria defined in the ASHRAE Guideline 14-2014.

The calibration results show that hourly CV-RMSE and NMBE would be within 15.7% and 3.8%, respectively. The results also show that the whole-building energy usage after calibration of the VRF-DOAS model is 1.9% (78.8 kWh) lower than that of the measurements during comparison period.

These results indicate that after a proper calibration with detailed monitored building performance data, the heat pump type VRF-DOAS model can reasonably predict the performance of the actual VRF system under the criteria defined in ASHRAE Guideline 14-2014. In addition, it would be preferred to calibrate the simulated building thermal load before performing HVAC system level calibration if possible.

Acknowledgement

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