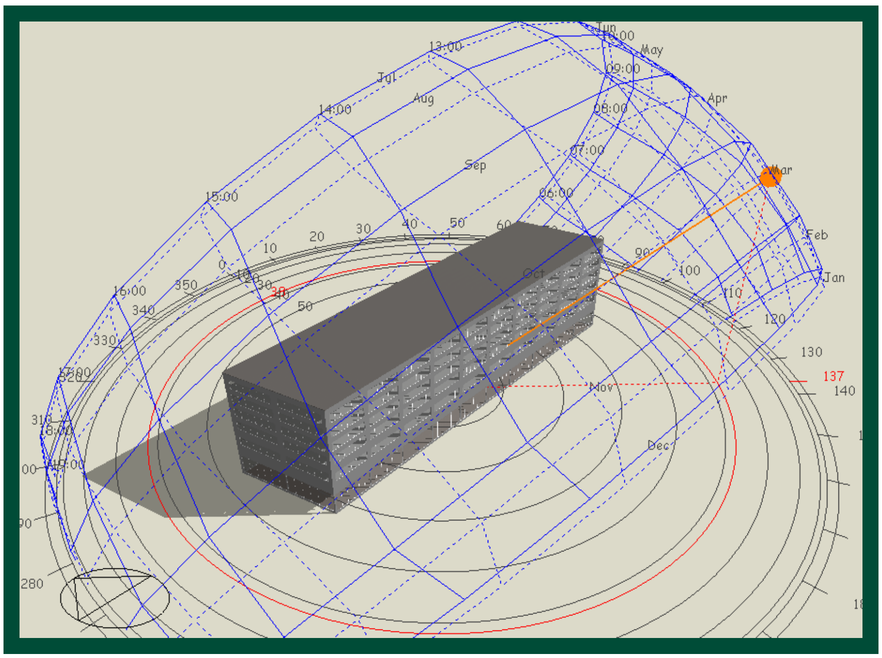
Modeling Variable Refrigerant Flow Heat Pumps in Commercial Buildings

HT.10.SCE.251 Report



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EXECUTIVE SUMMARY

Southern California Edison (SCE) needs an accurate, nonproprietary and reliable way of estimating Variable Refrigerant Flow with Heat Recovery (VRF-HR) system energy use to determine savings for energy efficiency. This is accomplished by quantifying and verifying the energy use of traditional HVAC systems and a similar effort regarding VRF systems. Currently building energy simulation modeling tools do not accurately model VRF-HR system energy use. This performance data will enable modeling of VRF-HR system energy use by simulation tool developers for use in utility programs. The laboratory tests section details the process in which data was collected to assist software developers.

The variable refrigerant flow (VRF) heat pump air conditioner (AC) is a heating, ventilation, and air-conditioning (HVAC) system model in the United States Department of Energy's (DOE) building energy simulation program. The performance of a VRF AC system is based on multiple performance characteristics. Full-load performance data defines the variations of capacity and power when outdoor or indoor conditions change. Part-load performance identifies how the capacity and power change when the heat pump condenser's variable compressor changes speed. The performance of a VRF AC system may also change when the total indoor terminal unit capacity is greater than the total outdoor unit capacity. The ratio of indoor terminal unit to outdoor condenser unit capacity is referred to as the combination ratio (CR). These performance aspects will be described in detail throughout this paper.

There have been well validated and robust vapor compression system models. These advanced vapor compression system modeling tools can be linked with complex component models, e.g. phase-by-phase heat exchanger models or segment-by-segment heat exchanger models. But most of these system simulation models are limited to single-stage vapor compression configurations, with a single condenser and evaporator pair. VRF system modeling can be challenging, since there are many variables to handle; for example, compressor speed and different indoor air dry and wet bulb temperatures in individual zones, etc. Since the indoor units are in parallel configuration, and they impact each other by connecting to the same compressor and outdoor heat exchanger, a simultaneous solver like is necessary for system solving. Integrating complex heat exchanger models leads to more difficulties, since they will add many more equations, which are usually not amenable for simultaneous solving. Due to these complexities, open publications and research results for VRF system modeling using complex component models are still limited. In this project, the project team have enhanced the existing modeling capability to handle VRF multi-split systems, using advanced heat exchanger models, so as to simulate VRF space cooling, space heating, and simultaneous space cooling and heating modes ,also known as VRF-HR.

Manufactures' performance data for capacity and power are used to create full-load and part-load performance curves for cooling and heating operating modes. When performance variations for full-load capacity or power cannot be modeled using a single performance curve, the data set is divided into lower and upper temperature regions and dual performance curves are used. Objects may also be created to substitute when performance curves do not provide the required accuracy. These performance curves or tables are then used as input data for the variable refrigerant flow heat pump model. The techniques described in this paper can be used to create performance curves for any software development model.

In addition to the manufactures performance data, model validation was carried out utilizing VRF-HR performance mapping from a laboratory test project and field monitoring of a test building.

The observed savings in the validation models are shown in the area of cooling savings, due to low fan energy and minimized duct losses. The simulations compared the baseline HVAC systems to VRF-HR systems, with parametric analysis of three building types and in eight climate zones in SCE service territory.
The findings from the project represent a path towards the development of a computer algorithm, which could later be incorporated into various software platforms. The data collected presented difficulties stemming from the vast differences among input parameters of software platforms. There were limitations in some software to adequately address simultaneous heating and cooling.

The continued development of software and modeling algorithms are beneficial to the advancement of the opportunities for accurate simulation of VRF-HR systems. This future work will help fine tune the computer model in part-load operation, model assumption when switching between cooling and heating in heat recovery mode, defrost operating modes, and validations with detailed field monitored data. The following are considerations for advancement of accurate simulation software:

- Further collaboration between utilities, software developers, VRF manufacturers, and other stakeholders to continue to develop the testing parameters and share data
- Continued Field tests are needed to provide additional performance metrics, including compressor speed and refrigerant temperatures.
- Results should be made public so that other researchers, software coders and end users could benefit from the control algorithms. Test standards could be developed to enhance the validity and usefulness future test results.
- ASHRAE has recently created a VRF technical track and this projects results feeds directly into that type of program, and will likely spawn future research.
- Continued engagement of the U.S. Department of Energy (DOE) to implement a computer model for a VRF-HR heat pump in the DOE's EnergyPlus™ whole building energy simulation software (EnergyPlus 2012)

ACRONYMS

ANSI	American National Standards Institute
AHRI	The Air-Conditioning, Heating, and Refrigeration Institute
Btu	British thermal units
CFM	Cubic feet per minute
COP	Coefficient of Performance
CZ	California Climate Zone
DEER	Database for Energy Efficient Resources
DX	Direct Expansion
EDB	Entering indoor Dry Bulb temperature
EER	Energy Efficiency Ratio
EIR	Electric Input Ratio
EPRI	Electric Power Research Institute
EWB	Entering indoor Wet Bulb temperature
HP	Conventional residential split-system Heat Pump, SEER as designated
HVAC	Heating, Ventilating and Air-Conditioning
kW	kiloWatt
MBtuh	Millions of British thermal units, per hour
ODB	Outdoor Dry Bulb temperature
OWB	Outdoor Wet Bulb temperature
VAV	Variable Air Volume
VRF-HR	Variable Refrigerant Flow with Heat Recovery

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INTRODUCTION

Variable Refrigerant Flow (VRF) systems are multi-zone units that circulate refrigerant from an outdoor compressor to multiple indoor fan coil units. Different combinations of indoor ductless and ducted units can be used for these systems depending on the application and layout of the building. VRFs incorporate inverter driven compressors and fans that modulate the flow of refrigerant in the system in response to the actual cooling and heating demand. Thus, they provide significantly better part load performance over conventional packaged and split-systems, while maintaining more precise temperature control. VRF with Heat Recovery technology is a subset of VRF systems that allows individual indoor units to heat or cool as required, while the compressor load benefits from the internal heat recovery. A heat-recovery system operates by managing the refrigerant through a gas flow device, can simultaneously heat and cool, depending on the requirements of each building zone. Heat-recovery systems increase VRF efficiency via energy transfer from one zone to meet the needs of another, when operating in simultaneous heating and cooling mode.

VRF systems are modular in design. The compressors range in size from 6 tons up to 30 tons and more capacity can be added as needed for the application by increasing the number of outdoor units. Unlike traditional packaged multi-zone air conditioners that must condition all zones and must reheat the supply air to accommodate different temperature set points, VRFs control each zone by modulating the amount of refrigerant that is delivered to each fan coil unit within the zone. Refrigerant delivery is being modulated to deliver varying amounts of refrigerant to zones with a lower demand and other zones can be completely turned off during times of little to no cooling or heating demand. The inverter-controlled compressor responds to the lower demand by reducing its speed and results in an effective reduction in capacity during part-load conditions.

VRF modeling capabilities in non-proprietary building and energy simulation tools has been lagging (Geotzler, 2007). There have been attempts to develop a VRF heat-pump-system computer model and incorporate it into an unofficial version of the EnergyPlus engine (Zhou et al., 2007, 2008; Li and Wu, 2010; and, Li et al., 2010). A VRF heat-pump computer model was implemented in DOE's EnergyPlus™ whole building energy simulation software, and first released in V7.0 in December 2011 (U.S. Department of Energy, 2011). The heat recovery version was first released in V7.2 in October 2012 (U.S. Department of Energy, 2012).

BACKGROUND

As variable refrigerant flow (VRF) systems gain acceptance, building owners are increasingly interested in identifying the energy savings potential of these system types. In addition, electric utility companies must project the impact that these heating, ventilating and air conditioning (HVAC) system types will have on their peak demand and energy use forecast. The impact that new HVAC system types have on electric energy use is estimated through simulation models and verified through field demonstrations where a conventional HVAC system is replaced by a VRF system and energy use is monitored over an extended period of time. Results from typical field demonstrations may take on the order of one year or more, therefore, efforts to simulate these system types accurately using computer modeling are rapidly evolving.

Field testing all possible system combinations and building arrangements is a challenging and expensive task, therefore complementary approach to field testing are to model HVAC system performance with energy modeling software and when appropriate, to use results of prescribed equipment rating or performance testing as a metric for calculating relative building energy use profiles.

Over the course of the last several years, a VRF rating standard was developed and resulted in the ANSI/AHRI standard 1230: Performance Rating of Variable Refrigerant Flow (VRF) Multi-Split Air-Conditioning and Heat Pump Equipment. This standard identifies the methodology for determining standard cooling, heating and simultaneous cooling and heating operational efficiency. The intent of the standard is to allow comparison of VRF equipment performance, within the VRF equipment class, and with that of unitary equipment at similar operating conditions. This rating standard is intended as an equipment comparison mechanism and is not designed to predict building energy use, which is dependent on the equipment operation, the building operation and the interaction of the equipment with the building. With that in mind, rating standards do offer a method for predicting relative building energy use between two similar equipment types installed in identical building environments.

Many utility programs base incentive amounts and calculated energy savings on the marginal difference between rated efficiencies within particular classes of HVAC equipment, such as packaged rooftop air conditioners & heat pumps. The idea being that if all other things remain unchanged: building envelop, occupancy, etc., but a piece of equipment is changed to a more efficient system, then the relative difference in rated efficiency of the equipment will reasonably translate to energy savings for the building.

Comparison of VRF to traditional unitary equipment in this similar manner would represent a partial change in approach since two different classes of HVAC equipment would be compared. The crafters of the 1230 Rating Standard attempted to address this by making the testing conditions and methodology as similar to the unitary standards (ANSI/AHRI 210/240 and 340/360) as possible by allowing for VRF systems to be operated at manufacturer-determined fixed operating conditions (compressor & fan speeds and expansion valve openings). One is then left with a rating standard which tests equipment at fixed operation, while the same equipment in the field may vary its operation in accordance with changing load. This creates questions as to the direct applicability of the rating test as an accurate representation of actual field performance relative to other fixed-speed unitary equipment. It is currently considered difficult, at best, to use rating performance as a proper metric for judging building energy performance with VRF systems. Although this remains an active area of research since having that method (in a reliable form) could greatly simplify the incentivizing and program process. In the meantime, near-term efforts are focused on building modeling to predict energy savings potential.

Software models like EnergyPlus, Energy Pro and eQuest are used for design and system selection of HVAC and building systems. Such tools simulate the performance of the building envelope and systems within the building, and enable users to compare different types of potential HVAC systems, to size systems, simulate noise levels, estimate electric load profiles, calculate likely operating costs, and predict system functionality. These modeling tools can likewise be used for energy efficiency programs to evaluate potential energy and power savings for a proposed HVAC system upgrade.

Inclusion of VRF systems in available modeling tools has been evolving. EnergyPro, Energy Plus and Trane Trace included VRF heat pump systems, and some designers developed post-processing methods to simulate VRF heat recovery systems. VRF manufacturers often provide some type of modeled performance comparison in their marketing materials and/or on their websites in support of the technology.

Though modeling of VRF systems has been performed, there are publications showing models that have been evaluated against actual performance data. A series of articles produced from work done at the University of Maryland's Center for Environmental Energy Engineering from 2006 through 2009 provides some comparisons. The 2009 paper in Energy and Buildings entitled "Simulation Comparison of VAV and VRF Air Conditioning Systems in an Existing Building for the Cooling Season" provides a starting point. This paper showed a modeled savings of 27-58% with VRF compared with variable air volume (VAV), depending on installation configuration and climate. A similar paper by Liu & Hong, 2010 in Energy & Buildings compares VRF (using EnergyPro) to a comparable ground source heat pump (using eQuest) and concludes that the ground source heat pump generally outperforms an air source VRF, though comments from the Liu & Hong paper indicate that insufficient model validating data is available for the VRF component. There remains significant debate in the greater industry as to the proper approach for modeling VRF systems, including questions such as to how to account for ventilation air, and how to approach simultaneous heating and cooling.

Much of the effort to bring VRF modeling into existing building energy software packages has been motivated by the California Code of Regulations (CCR)and Title 24 (the section defining energy efficiency standards for residential and non-residential buildings). The CCR and Title 24 require documenting the energy efficiency value of technologies. Most notably, EnergyPro, developed by the company EnergySoft, is accepted as a compliance standard with California's Title 24 EnergyPro. It is the most widely used simulation software by VRF manufacturers and likely the one used most by designers and energy practitioners of VRF systems. eQuest and Trane Trace were also used by design community representatives. Energy Plus is gaining acceptance in the modeling community and has recently had a VRF-HR module added to it, with inclusion of data provided from this effort.

TECHNOLOGY/PRODUCT EVALUATION

Building modeling for air conditioning and heating loads can be divided into two key parts: a building heat load analysis, and a building energy use analysis. The heat load analysis determines the size of heating and cooling equipment needed and the energy analysis predicts energy use and compares alternative HVAC systems.

BUILDING HEAT LOAD ANALYSIS

The size of heating and cooling equipment can be calculated based on factors including building shape, orientation, wall/roof components, windows (fenestration), insulation, lighting, occupancy and usage scheduling. The building is divided into 'zones' which are basically the area of the floor plan served by a single indoor unit. A single thermostat controls each zone temperature. Calculations are performed to determine 1) the maximum overall building heating/cooling load (sometimes termed 'block load'), and 2) the individual maximum heating/cooling load for the individual zones ('zone' loads).

The program uses local weather data in conjunction with physical building parameters to generate the heating/cooling load profile for a typical year. Programs analyze the HVAC system loads on an hourly basis (i.e., 24 hours/day x 365 days = 8,760 hrs/year), and generate the overall peak demand for the heating/cooling system along with individual zone load sizing data.

LOAD DIVERSITY

Zone loads are the calculated heating and cooling requirements of a finite space. The block loads are the sum of the zone loads at a specific time. The sum-of-the-zone loads typically exceed the block load. Sometimes, these amounts can differ by as much as 150%. This disparity is referred to as 'load diversity' and is caused by different zone loads peaking at different times during the day. An example may be that an east exposure could experience its maximum cooling demand in the morning, while a west exposure may need heating in the morning. Conversely, a west exposure will usually experience peak cooling conditions in the afternoon, while an east zone may require heating due to being shaded in the afternoon.

The block load is used to determine the maximum size of the heating and cooling plant. The individual zone loads are used to size the indoor unit(s) needed to serve the individual spaces within the building.

VRF modules in energy simulation software were originally built around manufacturer provided performance data. There are two general approaches to equipment and/or building energy modeling: empirical and component (or physics-based). Currently all publically available VRF models are empirical, meaning that system performance is calculated as a function of pre-measured system operation. Conversely, component based modeling calculates system performance from the fundamental physics of the thermodynamic processes. The component technique has potential to be more accurate and more flexible, but it is developmentally more difficult and requires significant computing resources. Efforts in component-based modeling are in the research stages with institutions like Oak Ridge National Laboratory and Purdue University leading.

The existing empirical models have been questioned to a degree because data used to map VRF performance has largely come from manufacturers without any independent verification. In addition, the highly flexible and scalable nature of VRF makes it difficult to have a full data set that covers all possible operating environments. Systems range from 6 – 30+ tons with ~4-100 indoor units per system and can operate in cooling, heating or mixed modes. This flexibility and scalability is a strong attribute for application of VRF to a variety of building types, but it complicates accurate modeling.

Electric Power Research Institute (EPRI), in conjunction with Southern California Edison, Bonneville Power Administration and the Florida Solar Energy Center (FSEC), has embarked on an effort to provide independently measured performance information on VRF systems through a combination of laboratory testing and field-testing to building energy model developers. This data is used to accomplish several ends:

1) to inform the model developers about actual system operation in modes or operating regimes that may not be covered by available manufacturer data;
2) to provide independent data for VRF system performance that directly compare with manufacturer provided data;
3) to use field data from multiple sites for model testing and adjustment, and
4) to run simulations on a set of typical buildings, with and without accompanying field data

LABORATORY TESTING

VRF-HR systems are inverter-driven heating, HVAC systems, similar to residential ductless heat pumps. However, VRF-HR systems are typically larger, installed in commercial buildings, include more indoor units per outdoor unit and are capable of simultaneous heating and cooling. Building simulation models are used to estimate VRF-HR system energy use, but until 2012, models have not been based on independently tested performance data. Laboratory testing in 2011 & 2012 created VRF-HR performance data sets for inclusion in and to inform software modules for the following four types of VRF-HR systems:

System A: 2-pipe, heat-recovery system

System B: 3-pipe, distributed, heat-recovery system,

System C: 3-pipe, distributed, heat-recovery system, with ducted indoor units

System D: 3-pipe, distributed, heat-recovery, with non-ducted indoor units.

These VRF-HR data sets were provided to EnergyPlus, eQuest and EnergyPro modelers for use in developing their commercially available building simulation products. Data sets were also provided to Oak Ridge National Laboratory (ORNL) and Purdue University, who are separately pursuing component-based models of variable-speed, multi-zone heat pumps, with the eventual goal of component based VRF-HR models. (The data sets were provided to ORNL and Purdue as a courtesy and it is not a specific objective of this project to develop component-based models.)

EXAMPLE LABORATORY METHODOLOGY

Laboratory data collected for two VRF-HR systems (VRF-HR), tested in EPRI's Thermal Environmental Lab, was analyzed for developing parametric relationships between observed outputs and controlled input parameters. The controlled input parameters in cooling mode are the outdoor dry bulb temperature (OD-DBT) and the return air wet bulb temperature (RA-WBT). In heating mode, the controlled input parameters are outdoor wet bulb temperature (OD-WBT) and the return air-dry bulb temperature (RA-DBT). The output parameters in heating and cooling mode are the capacity of the system, power draw, supply air temperatures, energy efficiency ratio ((EER), in cooling mode) and coefficient of performance ((COP) in heating mode).

This document provides parametric equations that can be used to calculate any of the observed output (capacity, power, EER / COP and supply air temperature) given the input conditions for the systems tested.

SIMULATION AND VALIDATION METHODOLOGY

Performance curves of the VRF system simulation model were generated using the catalog data of the System A model installed at the EPRI test. These performance curves along with lab-measured rated conditions lab measured values were used to model the VRF system in EnergyPlus. The EnergyPlus building input file was created using the building design and detailed drawings of the EPRI test building. The VRF system installed at EPRI had four terminal units that served one thermal zone each.

Infiltration rate levels were based on the DOE EnergyPlus reference buildings. The initial reference infiltration rates were also adjusted to match the facility operating conditions. Other required building input parameters, such as occupancy, lighting, plug loads, and thermostat set-points, were specified based on the DOE reference building model inputs and the EPRI test facility conditions. A custom weather file was created using the actual measured outdoor dry-bulb temperature, relative humidity, and TMY3 weather data of Knoxville, TN. This was done to increase the accuracy of the simulation results by using real outdoor condition data. Since there were no measured solar irradiance, wind speed, and wind direction data, local TMY3 data was used to create customized weather.

After the EnergyPlus model input was created, detailed simulations were run, and EnergyPlus outputs were compared against field measured data. The measured data comparison includes the total daily electric energy consumption of indoor and outdoor units. The predicted (simulated) total electric power includes the VRF heat pump, terminal unit fan power, and terminal unit parasitic electric power. The predicted VRF heat pump electric power includes electricity used by the compressor, crankcase heater, and the condenser fan. The predicted parasitic electric power includes electricity used by the zone terminal unit's controls, or other associated devices. The simulation results comparison with the field measured data is presented in the following section.

COOLING MODE ANALYSIS

Based on the controlled input parameters, laboratory testing of the two VRF-HR systems (System A and System B) was performed to collect a data set. The data set consisted of controlled input parameters and observed output. For example, Table 1 shows the cooling mode data from System B. The controlled parameters in this data set are the OD-DBT and the RA-WBT. The observed output is the measured capacity, power and EER. To develop the parametric equations a bi-quadratic curve is considered. A linear curve can also be fitted if the data regression line fits the observed data with higher accuracy than a more involved bi-quadratic. Due to the number of constants involved, a cubic curve is not investigated, and most energy modeling software does not use such a curve.

A bi-quadratic equation for capacity will be in the form described in Equation 1:

EQUATION 1. BI-QUADRATIC EQUATION FOR CAPACITY

$$Capacity = A + B*(OD-DBT) + C*(OD-DBT)2 + D*(RA-WBT) + E*(RA-WBT)2 + F*(OD-DBT)*(RA-WBT)$$

For the peak hours

Where:

Capacity is the parameter of interest

OD-DBT is the outdoor dry bulb temperature (controlled parameter)

RA-WBT is the return air wet bulb temperature (controlled parameter)

A, B, C, D, E and F are constants obtained by regression analysis

A generic form of the biquadratic (Equation 2) can be written as:

EQUATION 2. GENERIC BI-QUADRATIC EQUATION

$$Y = A + B*(X1) + C*(X1)2 + D*(X2) + E*(X2)2 + F*(X1)*(X2)$$

Where:

Y is any parameter of interest (in this case – capacity, power, EER or supply air temperature)

X1 and X2 are the controlled input parameters

A, B, C, D, E and F are constants obtained by regression analysis.

TABLE 1 : COOLING MODE DATA FOR SYSTEM B WITH ALL FOUR INDOOR UNITS RUNNING (COMBINATION RATIO OF 133%)

OUTDOOR DBT (°F)	INDOOR WBT (°F)	TOTAL CAPACITY (BTU/HR)	POWER W	EER BTU/W-HR	COP
75	60	52,702	4,530	11.63	3.41
85	60	48,871	5,169	9.45	2.77
95	60	46,553	5,615	8.29	2.43
105	60	38,225	6,193	6.17	1.81
75	63	53,683	4,611	11.64	3.41
85	63	52,443	5,167	10.15	2.97
95	63	49,198	5,726	8.59	2.52
105	63	46,014	6,302	7.30	2.14
65	67	58,437	4,547	12.85	3.77
68	67	59,296	4,562	13.00	3.81
75	67	60,581	4,750	12.75	3.74
85	67	55,521	5,244	10.59	3.10
95	67	54,568	5,781	9.44	2.77
105	67	48,795	6,295	7.75	2.27
75	70	62,618	4,893	12.80	3.75
85	70	59,282	5,360	11.06	3.24
95	70	56,125	5,959	9.42	2.76
105	70	49,924	6,433	7.76	2.27

Performing a regression analysis on the capacity data from Table 1 the following constants are obtained:

	COEFFICIENTS
A	-184,822
B	1,098
C	-8.78
D	5,277
E	-33.81
F	1.82
A	-184,822
B	1,098

Equation 3, in this case, takes the form:

EQUATION 3. BI-QUADRATIC EQUATION WITH INPUT COEFFICIENTS

$$Capacity = -184{,}822 + 1098 * (OD - DBT) - 8.78 * (OD - DBT)2 + 5277 * (RA - WBT) - 33.81 * (RA - WBT)2 + 1.82 * (OD - DBT) * (RA - WBT)$$

The R^2 for this fit is 0.96 which indicates that there is a good fit between the modeled capacity and the actual lab measurements.

A linear equation instead of a quadratic could also be used. The generic form in case of a linear equation is:

EQUATION 4. LINEAR EQUATION DERIVED FROM BI-QUADRATIC

$$Y = A + B * (X1) + C * (X2)$$

Where:

Y is any parameter of interest (in this case, capacity, power, EER or supply air temperature)

X_1 and X_2 are the controlled input parameters

A, B and C are constants obtained by regression analysis

A regression analysis on capacity data in Table 1 in the form of Equation 4 yields the following coefficients:

	COEFFICIENTS
A	14,552
B	-315
C	1,011

EQUATION 5. LINEAR EQUATION WITH CONSTANTS

$$Capacity = 14{,}552 - 315 * (OD - DBT) + 1011 * (RA - WBT)$$

The R^2 for this fit is 0.92 which is good but the R^2 for Equation 3 is higher indicating a better fit. In all cases for this analysis, a quadratic fit (similar to Equation 2), is used unless indicated otherwise.

A similar approach is used for heating mode and for simultaneous heating and cooling mode.

MODEL DEVELOPMENT WORKFLOW

Step 1. Building Model Geometry: Most advanced thermal energy modeling software can be utilized to make informed decisions about building materials and systems to provide the most sustainable and cost effective building possible. The model provides input to (1) the building's architectural systems, (2) glazing systems and glazing quantities, (3) placement and orientation of building, (4) insulation values, (5) wall, roof, and floor systems, and (6) shading devices to achieve a high performance building that minimizes life cycle cost through architectural systems. The building geometry process involves creating Computer Aided Design (CAD) fidelity drawings, importing the CAD geometry to the energy modeling software, and defining energy-related parameters (envelope, glazing, HVAC systems; activity).

Step 2. Zoning of Model: Proper zoning of the model is critical to evaluating the performance of a VRF system. VRF systems are most efficient when simultaneous heating and cooling loads occur. The model zoning must the necessary fidelity to capture the unique operating conditions where simultaneous heating and cooling occurs. For design studies, this zoning can be varied to determine optimal VRF zones. For existing building, the zoning must accurately capture the actual building-zoning configuration.

Step 3. Benchmark Comparison: At this stage, ASHRAE 90.1 values, Energy Star, and loads analysis are used as benchmarks against which to compare the model. If the model does not compare favorably to normed values, then the engineer returns to Step 1 and rebuilds the geometry. If the model is satisfactory, the engineer continues to Step 4.

Step 4. Mechanical Equipment Model: Here the modeler minimizes initial and life cycle costs through proper sizing of heating and cooling systems. Load calculations are accomplished through the following optional software: Energy10, Trane Air Conditioning Economics (TRACE), Hourly Analysis Program (HAP), EnergyPro, EQuest, or EnergyPlus. Configure the VRF target zones for easy conversion to VRF systems.

Step 5: Analyze full Model Performance: Now the full model's performance is measured against published standards. Baseline performance is used for comparison to VRF equipped model.

Steps 6-9. Modify the Baseline Model to Incorporate VRF Systems: (See the attachments located in the appendix for detailed steps of the conversion of the baseline model to the VRF-enabled model.)

Step 6. Export the EnergyPlus Input Data File (.idf): If necessary, translate the .idf file to EnergyPlus v7.2 format (short term).
Step 6a. Import .idf into EnergyPlus v7.2. Test for conformance.

Step 7. Build VRF system models and systems using EnergyPlus data (EnergyPlus has developed specialized performance curves for VRF systems). For initial development, edit VRF-targeted zones directly from baseline to VRF enabled systems. Build and test the new .idf file.

Step 7. Advanced: After initial development/testing completed, develop an EnergyPlus macro file (.imf) to modify baseline systems to VRFs and generate new model.

Step 8. Analyze data from baseline and VRF enabled models. Calculate energy performance metrics. Provide insight to building and mechanical system configuration to achieve best energy performance.

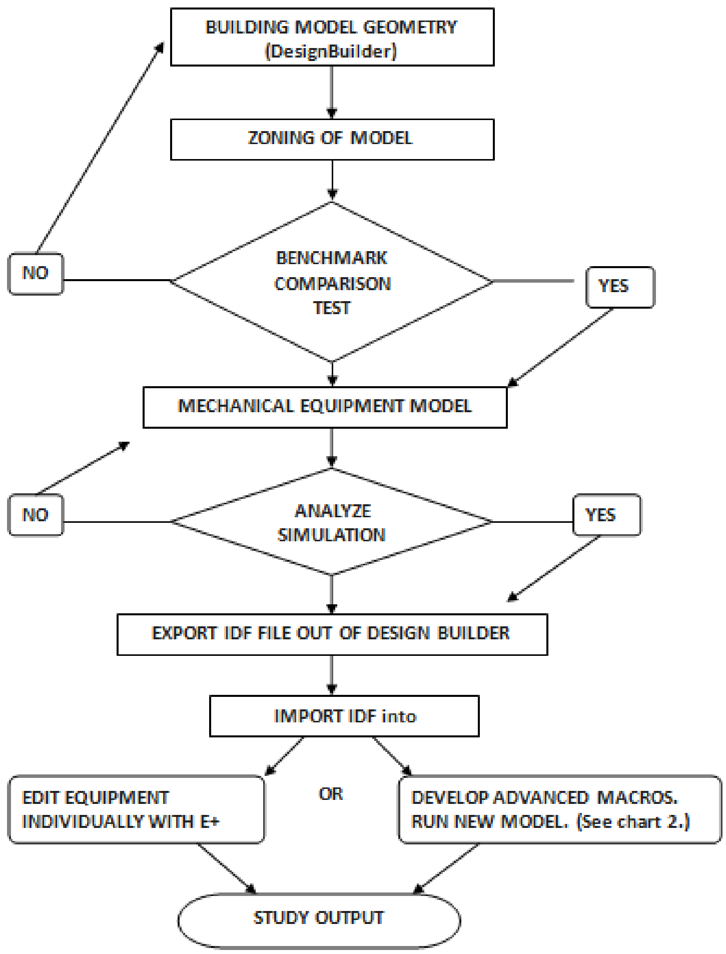

FIGURE 1. BUILDING MODEL WORKFLOW (DESIGN BUILDER TO ENERGYPLUS)

The above workflow description represents a means from exporting a model built with a user-friendly interface and inputting the information into the base EnergyPlus platform. Exporting the data into the base EnergyPlus platform under version 7.2, the VRF-HR module can be used to simulate VRF-HR equipment.

MODEL VALIDATION

The information gathered during the field demonstrations are compared to computer simulations to identify whether a VRF computer model can accurately simulate electrical energy use and peak demand. The information gathered from the field demonstration for a particular building type and location is used to identify key parameters for the VRF computer model. Investigating differences in energy use between the actual field demonstration and the computer model will improve the computer model inputs and assumptions. The computer simulation can then be applied to predict VRF performance in other climate regions to replace the long and costly field monitoring approach. Computer modeling also allows simulation of the air-distribution system for conventional HVAC system types and compares the energy savings expected when using ductless VRF systems.

EPRI has contracted to Florida Solar Energy Center (FSEC) to use the new Energy Plus VRF-HR module to model building and VRF system energy use in several example buildings. This effort wasincluded in the analysis and modeling of one of the laboratory systems. The unit used in the laboratory test was then installed to provide air conditioning service to an EPRI building. The detail of the algorithm development is described in the appendix attachment 2 in a report titled “Evolution of the EnergyPlus VRF Computer Model”.

FINDINGS

In general, the VRF system energy savings are primarily attributed to the elimination of the duct losses, minimizing fan energy requirement, and small benefits from VRF operational characteristics. The VRF system's annual energy savings compared to conventional HVAC types reported does not come from the part-load efficiency benefits of the VRF system.

Figure 2 illustrates the measured and predicted (simulated) daily total daily electric energy. Also shown on the same plot are the measured average return air temperatures of the four terminal units and outdoor temperature. One observation is that the daily electric energy and operation of the VRF system is driven by the outdoor boundary condition. Both the predicted and measured daily electric energy profile follows the outdoor air temperature trend. Figure 3 shows the predicted and measured monthly total electric energy consumption of the VRF system. The monthly predicted total electric energy use deviations for August, September, October, and November are 2.2%, -3.0%, -13.1%, and -23.4%, respectively. This is a reasonable agreement when there is uncertainty in the EnergyPlus model input parameters, such as: internal gain rates, infiltration level, and lack of real weather data solar irradiation, wind speed, and directions.

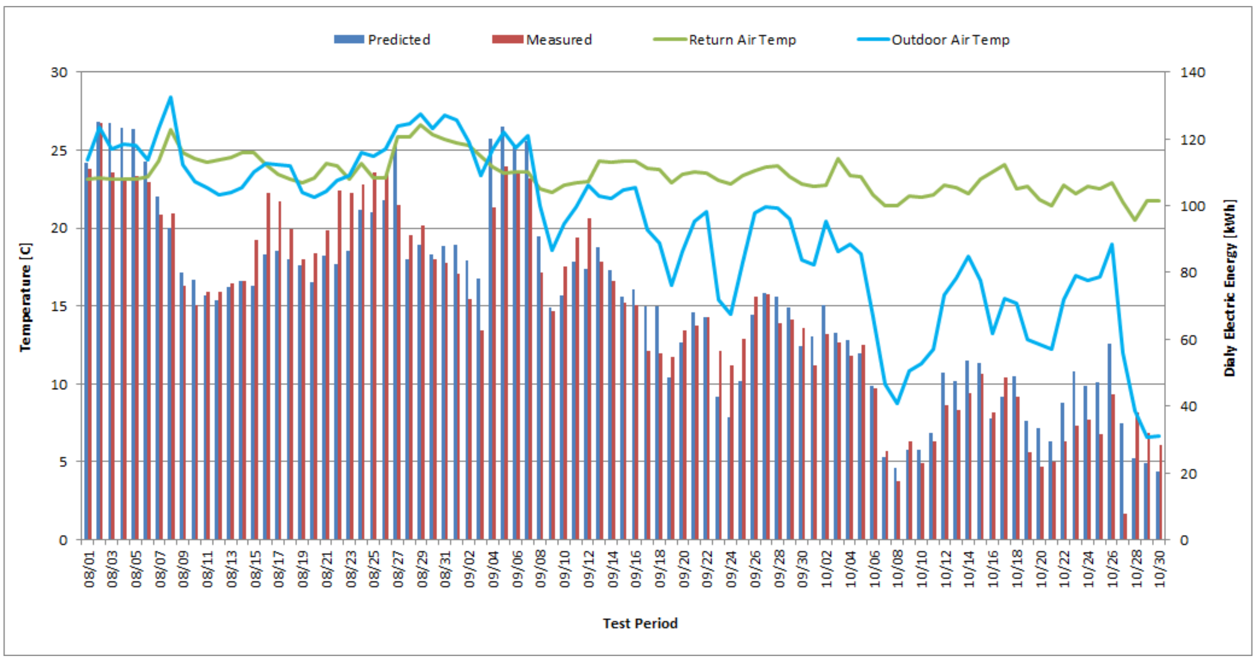

FIGURE 2 MEASURED AND PREDICTED DAILY TOTAL ELECTRIC ENERGY USE

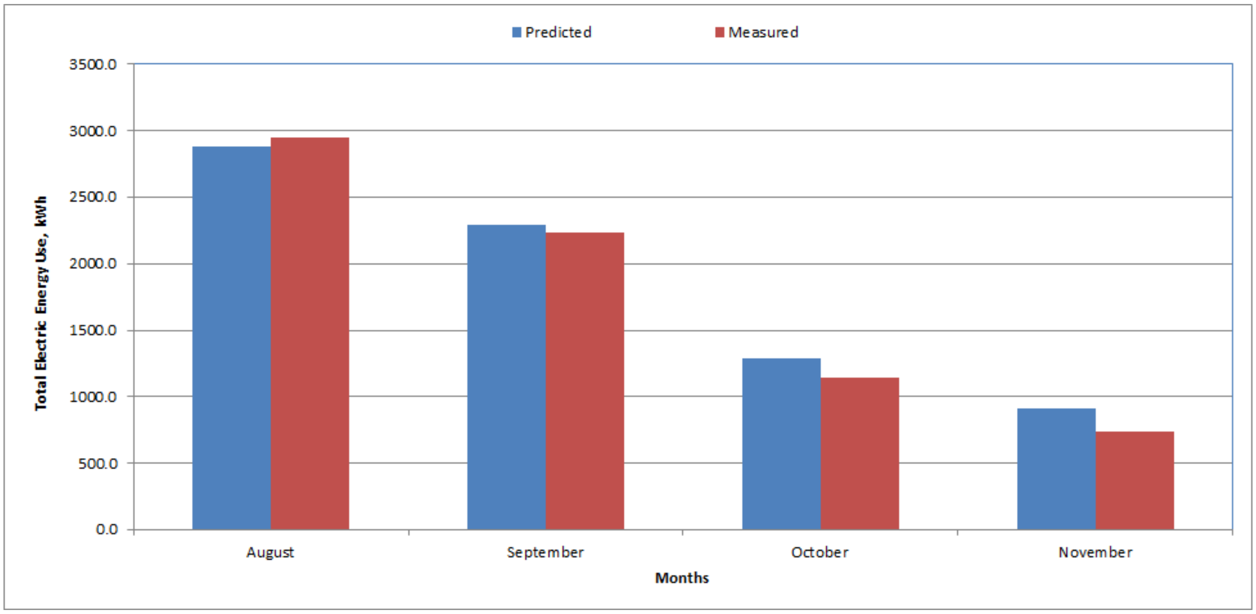

FIGURE 3 MONTHLY VRF TOTAL ELECTRIC ENERGY CONSUMPTION

The following items contributed to the difficulty of creating a true model from the laboratory data:

- Heat recovery operation is limited to a narrow operating range.
- Performance mapping of heat recovery operation is critical to understanding operation.
- Compressor speed is difficult to measure
- Refrigerant side performance is impossible to measure with flooded suction lines.
- Both the control algorithms and AHRI 1230 fixed-test conditions (e.g., fixed compressor speed setting) are not publically available.
- The AHRI 1230 test method may lead to exaggerated performance predictions, since the system operation will not be optimized in a real building.
- Lab tests are time consuming and cost prohibitive.

CONCLUSIONS

Further research work is required to extensively validate the computer model with full monitoring of the model input and output parameters in a more controlled environment or building. This future work will help fine tune the computer model in part-load operation, model assumption when switching between cooling and heating in heat recovery mode, defrost operating modes, and validations with detailed field monitored data. The following activities are recommended for future work:

- Further collaboration between utilities, software developers, VRF manufacturers, and other stakeholders to continue to develop the testing parameters and share data
- A continuation of laboratory and field tests is needed to provide additional performance metrics, including compressor speed and refrigerant temperatures. Conducting a field validation study with detailed monitored model input parameters, such as indoor conditions, various internal loads, building constructions, and actual weather data, is essential to characterize the computer model prediction accuracy and fine tune model assumptions. This study would provide VRF modeling guidance and establish a reasonable energy saving benchmark for the VRF system compared to conventional HVAC systems.
- Continued laboratory tests are required to evaluate and understand the operation of the equipment in heat recovery mode during the partial cooling and heating operations.
- The defrost operation needs to be studied in detail including formation that can lead to a model development for incorporation into the VRF computer model. Based on such experimental studies capacity and power correction correlation for defrost operation mode can be formulated.

APPENDIX A – STEPS TO DEVELOPING A VRF MODEL IN E+ 7.2

1. Build the VRF model data
   a. Select and define E+ input data for the VRF Heat Pump model. E+ provides some data for these curves. Each VRF must be separately specified (performance parameters can be the same)
      i. Performance curves
         1. Cooling capacity ratio = f(Low temperature curve): CoolCapFT
         2. Cooling capacity ration boundary = f(temperature): CoolCapFTBoundary
         3. Cooling capacity ratio = f(high temperature curve): CoolCapFTHi
         4. Cooling energy Input ratio = f(Low temperature curve): EIRFT
         5. Cooling energy Input ratio boundary = f(temperature): EIRFTBoundary
         6. Cooling energy Input ratio = f(high temperature curve): EIRFTHi
         7. Cooling energy Input ratio = f(Low part-load ratio): EIRLoPLR
         8. Cooling energy Input ratio = f(Hi part-load ratio): EIRHiPLR
         9. Cooling combination ration correction factor
         10. Cooling part-load fraction correlation
         11. Heating capacity ratio = f(Low temperature curve): HeatCapFT
         12. Heating capacity ration boundary = f(temperature): HeatCapFTBoundary
         13. Heating capacity ratio = f(high temperature curve): HeatCapFTHi
         14. Heating energy Input ratio = f(Low temperature curve): EIRFT
         15. Heating energy Input ratio boundary = f(temperature): EIRFTBoundary
         16. Heating energy Input ratio = f(high temperature curve): EIRFTHi
         17. Heating energy Input ratio = f(Low part-load ratio): EIRLoPLR
         18. Heating energy Input ratio = f(Hi part-load ratio): EIRHiPLR
         19. Heating combination ration correction factor
         20. Heating part-load fraction correlation
      ii. Piping curves
         1. Piping correction factor for length in cooling mode
         2. Piping correction factor for height in cooling mode
         3. Piping correction factor for length in heating mode
         4. Piping correction factor for height in heating mode
      iii. Design values
         1. Rated cooling capacity
         2. Rated cooling COP
         3. Minimum/Maximum outdoor temperature for cooling
         4. Rated heating capacity
         5. Rated heating COP

            6. Minimum/Maximum outdoor temperature for heating
      iv. Piping
            1. Length
            2. Height
      v. Compressor
            1. Number
            2. Capacity ratio
            3. Design parameters
      vi. Condenser
            1. Type
            2. Design parameters based on type (air/water)
            3. Input/output nodes
      vii. Miscellaneous inputs
            1. Defrost strategy/control

2. Build the DX VRF heating/Cooling coil models. Coil models must be specified for each zone to be served by a VRF (coil parameters can be the same, but must specify for each zone)
    a. Rated cooling capacity
    b. Cooling capacity ratio = f(temperature): VRFCoolCapFT
    c. Cooling capacity ratio = f(flow fraction): VRFCoolCapFFF
    d. Rated heating capacity
    e. Heating capacity ratio = f(temperature): VRFHeatCapFT
    f. Heating capacity ratio = f(flow fraction): VRFHeatCapFFF

3. For each targeted VRF zone
    a. Identify the baseline zones from .idf file
    b. Modify zone from PTAC to HVAC:TerminalUnit:VariableRefridgerantFlow
        i. Modify inlet/outlet nodes to match targeted VRF
        ii. Designate supply air parameters, fan outdoor air mixer
        iii. Designate DX Variable Refrigerant Heating/Cooling coils
        iv. Designate supply fans
        v. Designate outdoor air mixers
        vi. Repeat for all zones for single VFF
    c. Repeat for all VRFs

4. Miscellaneous
    a. VRF operation schedules

STATISTICAL ANALYSIS

To evaluate the consistency and dependency of measured and simulated data, the sample correlation coefficient (r) is determined as follows:

$$r = \frac{\sum_{i=1}^{n}(X_s - \overline{X}_s)(X_m - \overline{X}_m)}{\sqrt{\sum_{i=1}^{n}(X_s - \overline{X}_s)^2}\sqrt{\sum_{i=1}^{n}(X_m - \overline{X}_m)^2}}$$

EQUATION 6. STATISTICAL ANALYSIS EQUATION

The calculated correlation coefficient is presented in Table 2. Correlation hypotheses are verified through a t-test with a significance level (α) of 5%, and the hypotheses of correlation coefficients are accepted.

TABLE 2 SAMPLE CORRELATION OF MEASURED AND SIMULATED TOTAL ELECTRIC POWER DATA

Item	Total Power
Sample correlation coefficient (r)	0.92
Cv (RMSE)	26%
Sample size	118

The coefficient of variation of root mean square error Cv (RMSE) between measured and simulated data is calculated as follows:

EQUATION 7. ROOT MEAN SQUARED ERROR

$$C_v(RMSE) = \frac{\sqrt{\frac{\sum_{i=1}^{n}(X_s - X_m)^2}{n}}}{\overline{X}_s}$$

Cv (RMSE) is a normalized measure of the variability of root mean square error between measured and simulated total power. In this case, Cv (RMSE) is calculated as 26 % that is a reasonable variability between measured and simulated data.

APPENDIX B - ATTACHMENTS

Project Models:

1.

MyakoV2001.dsb

2. Evolution of the EnergyPlus VRF Computer Model Report

VRFComputerModelD
evelopmentReport.pc

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