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Field Evaluation of the Performance of the RTU Challenge Unit: Daikin Rebel

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Prepared for the U.S. Department of Energy
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Executive Summary

In 2011, the U.S. Department of Energy's (DOE's) Building Technologies Office, with help from Better Buildings Alliance members, developed a specification (RTU Challenge) for high-performance rooftop air-conditioning units (RTUs) with capacity ranges between 10 and 20 tons. Daikin's Rebel RTU was recognized by DOE in May 2012 as first to meet the RTU Challenge specifications. This report documents the testing of a Rebel unit and a standard unit in the field and compares the seasonal efficiency of the two units.

The unit was installed at the General Services Administration's (GSA's) Southwest Region 7, Federal Center Warehouse Building 23, located in Fort Worth, Texas, after some structural improvements to the roof and interior spaces were completed in 2015. The structural improvements were necessary to support the weight of the Challenge unit as compared to the standard unit. The standard unit is an existing RTU at the same location that is about 5 years old. The standard unit consists of one compressor for staged cooling and a constant-speed supply fan. Both units had the same rated cooling capacity of 5 tons and served side-by-side office spaces with similar footprints. The offices were common, but had a wall erected with a door to provide some separation between the spaces.

A set of sensors was used to measure the dry-bulb temperature and the relative humidity for the outdoor air, the return air, the mixed air, and the supply air. RTU total power consumption was also measured using a power transducer. These sensor measurements, together with a number of control signals, were monitored at 1-minute intervals from December 2015 to September 2016.

The average daily energy efficiency ratio (EER) was computed for each unit using the monitored data. The ratio of the average EER for the two units varied between 0.9 and 1.4. The average of the daily EER ratio for all days was approximately 1.18, which means that on average the daily EER of the Rebel unit was 18% higher than that of the standard unit.

In addition to daily EER, the seasonal cooling efficiency was also calculated over the entire monitoring period. Over the monitoring period, the standard unit and the Rebel unit had seasonal EERs of 10.5 and 12.2, respectively. The Rebel unit's seasonal EER was about 16% higher than that of the standard unit. This result was lower than the findings from our previous simulation work, which estimated that in hot and humid climates, Rebel would consume about 40% less electricity than an RTU with a constant-speed supply fan and single-stage mechanical cooling. Possible reasons for this difference included 1) based on observations, the two units in the field served different loads, while the two units in the simulation served the same load; and 2) the standard unit had higher operating efficiency than was used in the simulation runs. The seasonal EER improvement of the Rebel was also lower than the previous demonstration of a similar unit in a Florida supermarket.

Other issues related to the installation of the Rebel unit included the following:

- The Rebel unit came with a different base footprint from the existing Rheem unit. The roof structure had to be modified to support the Rebel, and duct modifications to accommodate the new unit were also required. The new Rebel unit came with an outdoor economizer and always introduced some outdoor air to the space, while the existing Rheem unit did not have an outdoor economizer (no outdoor air). This may have affected the cooling loads seen by the respective RTUs.

- The start-up and commissioning of the Rebel was less challenging than the previous Rebel demonstration installation[1], as the local Daikin distributor had more experience in installing these new units than was seen at previous demonstration sites (Wang et al. 2015). However, the distributor had to make some minor adjustments to the unit after it was installed to make it fully operational.

Occupants of the space reported no comfort issues, either positive or negative. The site requested return visits by the Daikin distributor to make minor changes to the initial startup configuration. The local GSA building automation system support team also had to make modifications to the Tridium network and to power sensors to correct issues related to trending and power meter accuracy. After the unit and meters were properly configured, the unit, as well as the metering and monitoring system, worked as expected. Over the last 12-month period, maintenance requirements for this unit were similar to those for the other units.

[1] http://www.pnnl.gov/main/publications/external/technical_reports/PNNL-23672.pdf

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Acronyms

ASHRAE	American Society of Heating, Refrigeration and Air-Conditioning Engineers
BAS	building automation system
BBA	Better Buildings Alliance
CFM	cubic feet per minute
DOE	U.S. Department of Energy
EER	energy efficiency ratio
GSA	General Services Administration
HVAC	heating, ventilation, and air conditioning
IEER	integrated energy efficiency ratio
RTU	rooftop air-conditioning unit

I. Introduction

Packaged rooftop air-conditioning units (RTUs) are used in 44% (2.5 million) of all commercial buildings, serving over 57% (46 billion square feet) of the commercial building floor space in the United States (EIA 2012). The primary energy consumption associated with RTUs is over 2.2 quads annually. Therefore, even a small improvement in efficiency or part-load operation of installed rooftop units can lead to significant reductions in energy use and carbon emissions.

Starting in 2011, the U.S. Department of Energy's (DOE's) Building Technologies Office funded a series of projects related to RTUs. Some projects were intended to improve the operating efficiency of the existing RTUs, while others were focused on improving the operating efficiency of new units. This report documents the field-testing and comparison of the seasonal efficiency of a state-of-art RTU Challenge unit and a standard unit.

II. Background

In 2011, the DOE Building Technologies Office, with help from Better Buildings Alliance (BBA) members, developed a specification for high-performance RTUs that have capacity ranges between 10 and 20 tons (DOE 2013). The goal of the specification—also known as the RTU Challenge—was to spur the market introduction of cost-effective, high-performance commercial RTUs. Two manufacturers—Daikin Rebel and Carrier WeatherExpert—produced RTUs that met the RTU Challenge specifications. These units were tested and rated at standard conditions by manufacturers, and both had an integrated energy efficiency ratio (IEER) of more than 18. Because the performance ratings at standard conditions do not necessarily represent the "true" seasonal energy efficiency, field tests were needed to provide more realistic performance comparisons under "real" conditions. This report provides results from comparing the field performance of a Rebel unit and a standard RTU.

A. Standard RTU

Depending on the vintage of a standard RTU, its rated energy efficiency ratio (EER) in the field can range from a low of 8 to a high of 12. In addition to the EER, most standard RTUs in the field have the following characteristics:

- Standard RTUs typically have a constant-speed supply fan regardless of the operational modes (e.g., heating, cooling, and ventilation).
- RTUs with capacities of 7.5-tons and larger usually have two or more stages of cooling. A multi-stage unit has two or more constant-speed compressors of equal size. The switch from first to second (or higher) stage can be based on either the space temperature deviation from the cooling set point or the time lag to reach the cooling set point.
- Most RTUs in the field use a gas furnace for heating; some use electric resistance heating. The gas furnace cycles ON and OFF to meet the space-heating loads.
- Most RTUs 7.5 tons or larger in capacity are required to have air-side economizers in most regions of the country. The only exceptions to this requirement are smaller units (<7.5 tons) and the units located in hot/humid climates (e.g., Florida, Texas).

B. Opportunity

Most standard RTUs have constant-speed supply fans designed to provide ventilation at the design rate whenever the fan is operating. Although there are hours during the day when a building may not be fully occupied or the need for ventilation is less than the maximum design rate, the ventilation rate cannot be adjusted easily with a constant-speed fan. Supply fan energy savings can be achieved by modulating the supply fan speed during the ventilation mode and potentially during mechanical heating/cooling if the unit has multiple stages of heating/cooling. When the building is occupied and the unit is in ventilation mode, the role of the supply fan is to provide fresh air to maintain proper indoor air quality in the spaces that it is serving.

Similarly, most standard RTUs currently installed in existing buildings have constant-speed compressors that cannot modulate to meet varying space loads; therefore, they are cycled on and off. Cycling creates inefficiencies. Significant savings are possible with a unit that has a variable- or multi-speed fan and variable-speed compressors to meet variable space loads.

Wang and Katipamula (2013) conducted a detailed simulation of one RTU Challenge unit (Daikin Rebel) and compared its performance to a number of reference units for a prototypical big-box retail store[2]. The model estimated the energy consumption of a prototypical big-box retail store in three locations (Houston, Los Angeles, and Chicago). The modeled energy consumption of the store using the Rebel unit was then compared to stores modeled with the three different reference units. The first reference unit (Reference 1) represented existing RTUs in the field. The second reference unit (Reference 2) represented RTUs in the market that just meet the 2013 Federal regulations for commercial equipment standards. The third reference unit (Reference 3) represented the latest ASHRAE 90.1-2010 requirements. For RTUs with cooling capacity greater than 11,000 Btu/h, ASHRAE 90.1-2010 (ASHRAE 2010) requires two-speed fan control or variable-speed fan control.

The following conclusions were drawn from the comparison of annual energy cost for the RTU Challenge unit with the three reference units:

- Using Reference 1 as the baseline, Rebel units led to about 45% lower heating, ventilation, and air conditioning (HVAC) energy costs (electricity and gas combined) in Houston and Los Angeles, and 33% lower costs in Chicago. The HVAC electricity cost savings was around 50% for all three locations.
- Using Reference 2 as the baseline, Rebel units led to about 37% lower HVAC energy costs in Houston, 40% lower costs in Los Angeles, and 29% lower costs in Chicago. The HVAC electricity cost savings were 40%, 42%, and 50%, respectively, in those three locations.
- Using Reference 3 as the baseline, Rebel units led to about 27% lower HVAC energy costs in Houston, 18% lower costs in Los Angeles, and 15% lower costs in Chicago. The HVAC electricity cost savings was 30%, 19%, and 28%, respectively, in those three locations.

Based on the simulation results, the Rebel RTU Challenge unit, if widely adopted, could lead to significant energy, cost, and emission reductions. Because the cost of these units was not available at the time of the study, no attempt was made to estimate the potential payback periods associated with any of the three reference scenarios. However, if the incremental cost for any of the three reference cases is known, one can easily estimate a simple payback period.

[2] http://www.pnl.gov/main/publications/external/technical_reports/PNNL-22720.pdf

III. Measurement and Verification Project Plan

This section describes the measurement and verification project plan that addressed the technical objectives of this field demonstration of the Daikin Rebel Unit in a Fort Worth, Texas GSA facility. This section describes the technical objectives, the plan to execute the technical objectives, and a description of the RTU Challenge unit.

A. Technical Objectives

The objective of this field demonstration is to quantify the seasonal energy efficiency of the RTU Challenge unit and to compare its seasonal performance with a standard unit in an occupied, operational building.

B. Demonstration Project Plan

Although the rated efficiency of a 10-ton RTU Challenge unit is 50% above the current ASHRAE 90.1-2013 standard, the unit that was deployed at this site was a 5-ton and is expected to be less efficient than a 10-ton Rebel. Because the standard rated test and the IEER tests represent unit performance in a controlled laboratory setting , field tests and demonstrations were conducted to show the potential savings under true operating conditions. The planned field demonstrations provided more realistic performance comparisons. The field demonstrations allowed for 1) comparison of the annual performance of the RTU Challenge unit to a standard unit, and 2) capture of lessons learned.

Because only a limited number of field demonstrations could be done, the demonstrations needed to be representative of the potential applications of the RTU Challenge units. Packaged RTUs are more widely used in retail and office type buildings. Therefore, this demonstration focused on a GSA office building.

For this demonstration, PNNL monitored the RTU Challenge unit and a standard unit (existing unit) simultaneously: 1) one standard unit, and 2) one RTU Challenge unit. Because the performance of the RTU Challenge unit and the standard unit were monitored simultaneously, the field measurement and verification were completed within 12 months. Both types of RTUs were of similar size, had the same external pressure drop, and served spaces that had similar load profiles on the same building.

C. Technology Description – RTU Challenge Unit - Rebel

The Daikin Rebel packaged rooftop system was the first unit to meet DOE’s RTU Challenge specification. The 5-ton air-conditioner has one variable-speed inverter-driven compressor, composite condenser fan(s) with a variable-speed electronic commuted motor, controls that can be integrated with optional BACnet or LonMark building automation systems (BASs), and electronic expansion valves (Figure 1). Unlike conventional units, Rebel modulates the supply fan in response to the zone conditions and modulates the compressor speed to maintain supply-air temperature set points (Daikin 2013).

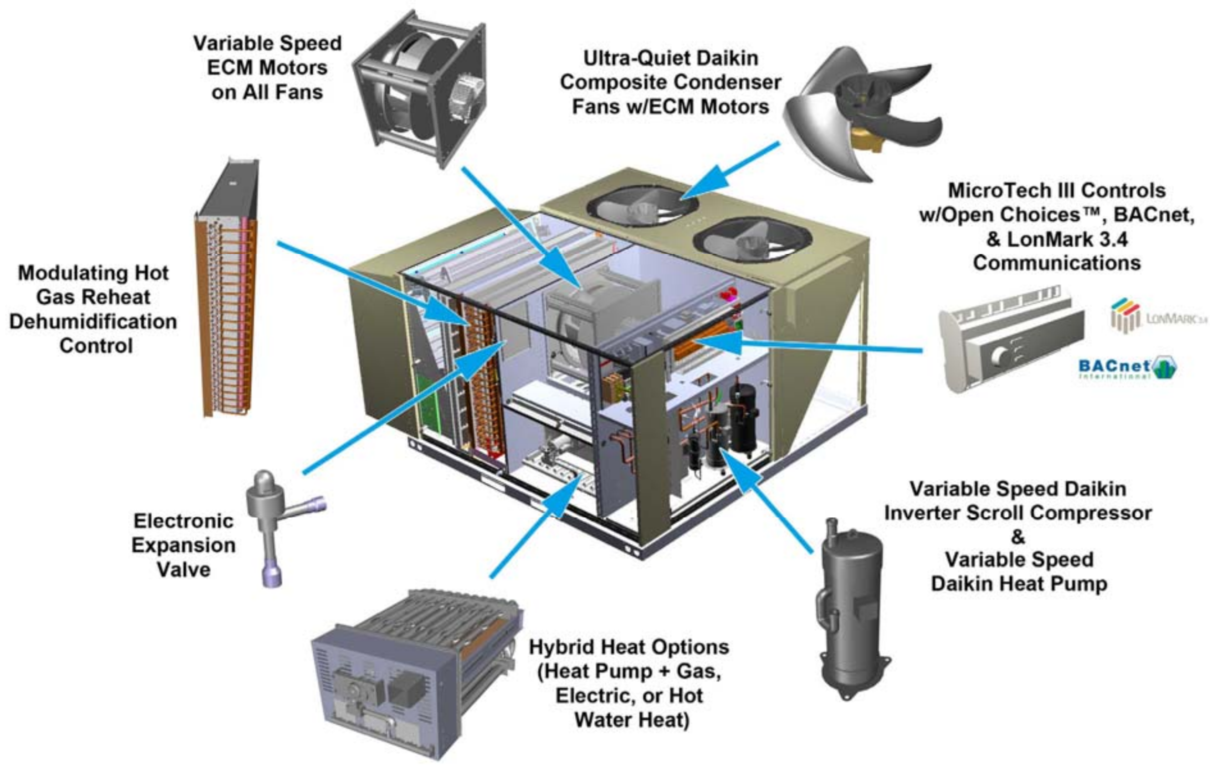

Figure 1: Daikin Rebel Unit (Source: Daikin). Reprinted with permission from Daikin

IV. Measurement and Verification Evaluation Plan

The measurement and verification evaluation plan used to quantify the seasonal performance of the units is described in this section.

A. Description of the Demonstration Sites

The demonstration took place at GSA Federal Center, Building 23, located in Fort Worth, Texas. Table 1 provides the details of the two units. The Rebel unit (Model# DPS005A) was installed as a replacement of an existing unit in June 2015 at the Building 23 location. The standard unit (Rheem Model # RLNL-A060CK) is an existing RTU at the Building 23 location that had been in the field for about 4 years prior to the Rebel unit's installation. The standard unit has one compressor for cooling and a constant-speed supply fan. Both units have a rated cooling capacity of 5 tons. The standard unit has electric resistance heating coils with a capacity of 18 kW while the Rebel unit is a heat pump with 18-kW of auxiliary heating capacity. The two units serve Building 23 storage and office spaces with similar footprints. The RTUs both are configured to operate 24/7 (no schedule).

GSA's Southwest Region 7 uses a Tridium Niagara BAS network to monitor and control most of their buildings, including Building 23 at the Federal Center complex. Because of this capability to monitor, the ability to trend and store data also exists. Therefore, GSA agreed to configure trending and storage of pertinent sensors and control signals. The trend data for this demonstration project were stored on the GSA BAS server. PNNL was provided with secure, remote access to their BAS server. Trend data was pulled once a month and analyzed for this demonstration project.

Table 1: Details of the Standard Unit and Rebel Unit

RTU Monitored	Model	Vintage	Rated Cooling Capacity (ton)	Rated EER	Rated Heating Capacity (kW)	Design Airflow Rate (CFM)
Standard	Rheem Model #RLNL-A060CK	2011	5.0	11.4	18	1700
Rebel	Daikin Model #DPS005A	2015	5.0	12.3	18	2300

B. Metering Plan

Both Rebel and the standard units in the field were similarly configured, as shown in Figure 2. The schematic (Figure 2) also shows the locations of the sensors for the two units. Outdoor air for the Rebel is obtained through the integrated economizer section. The standard unit does not have outdoor air (economizer) capability.

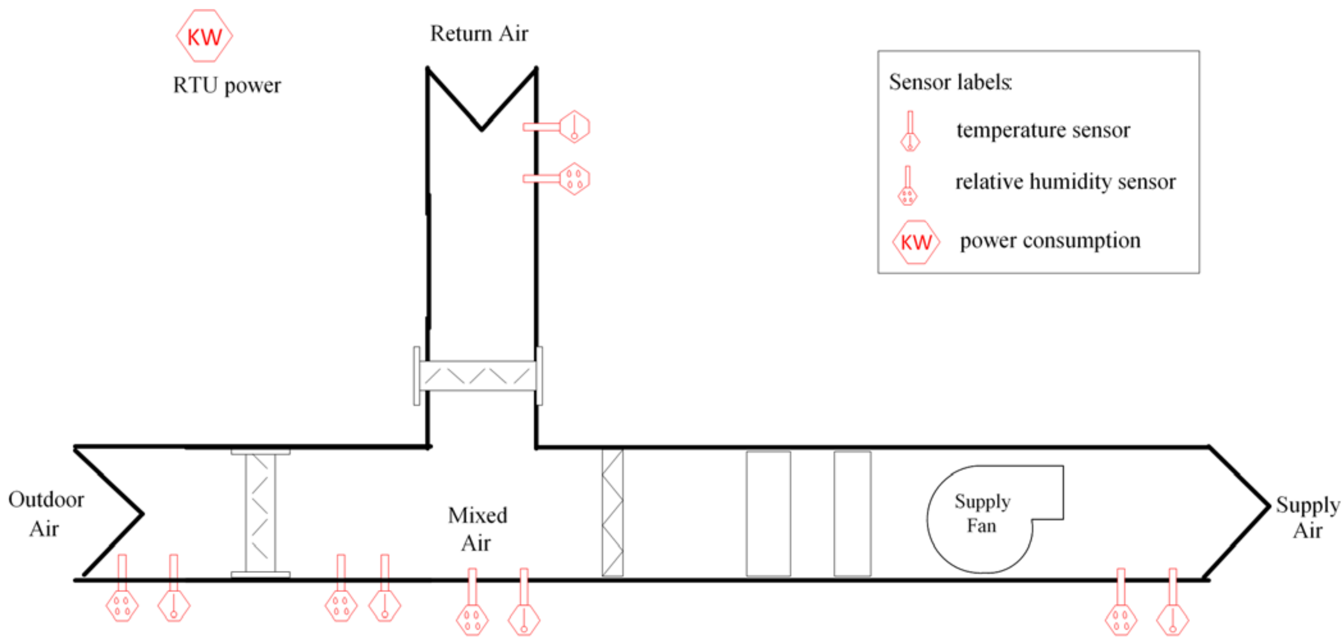

Figure 2: Schematic of Tested RTU Configuration with Sensor Locations

The following sensors were used in the field test:

- For the standard unit, a set of sensors was used to measure the dry-bulb temperature and the relative humidity for the outdoor air, the return air, the mixed air, and the supply air. The accuracy of the temperature sensor was ±0.36°F in the operating temperature range (40°F to 120°F). The accuracy of the relative humidity sensor was ±5% in the operating relative humidity range (0% to 100%).
- RTU total power consumption was measured using a power transducer with an accuracy of ±0.5% of reading.

In addition to temperature, relative humidity, and power measurements, a number of control signals were either directly monitored from the RTU controller (for the standard unit) or through a BACnet protocol translator device that is connected to the RTU controller (for the Rebel unit). Although Figure 2 does not show a supply fan power measurement sensor, supply fan power was indirectly measured. It was computed using the total unit power measurement when the compressor was not running for the standard unit with a constant-speed supply fan. Power consumption for the variable-speed supply fan was estimated based on the fan speed and fan affinity laws. Note that metering of supply fan power (independent from total power consumption) was not required for performance characterization or energy savings estimates.

For the demonstration, GSA collected data at each RTU at 1-minute intervals, storing the data locally on the GSA BAS server. PNNL was able to periodically retrieve the data through remote access to the server.

C. Airflow Characterization

Building owners and facility managers understand the concept of seasonal efficiency, but to calculate this performance metric, supply airflow measurements are required. Measurement of airflow on a continuous basis is difficult in an RTU because of the physical constraints imposed by the shape and size of the RTU. However, one-time airflow characterization is possible in the field using flow plates that can be inserted by temporarily replacing the air filters. For the standard unit, the airflow was constant, so there was just one measurement to make. For the RTU Challenge unit, the supply airflow varied with fan speed. Therefore, airflow was measured at various fan speeds to create an airflow model as a function of fan speed.

PNNL estimated the airflow using calibrated circular flow plates in a rectangular housing that were inserted in the air filter rack. This device is designed to measure the velocity pressure (total pressure – static pressure), which is then converted to actual airflow. The airflow-measuring device was placed in the air filter rack after the removal of the air filters. Once the airflow-measuring device was installed, any gaps were sealed with cardboard and cellophane to ensure all airflow was routed through the measuring devices (see Figure 3). The RTU access door was closed (but not shut tight) to ensure the pressure tubes were not pinched. A vendor device with gages was connected to the airflow-measuring device and readings were converted to CFM values. Clear cellophane (seen in Figure 3) was used to cover all access door openings (top, bottom, and sides) as well as the door handles, to ensure a tight seal and minimize all airflow leakage around the pressure tubes. The flow plates are designed so that the typical pressure drop across the measuring devices is less than or approximately equal to that of a typical filtration device that would normally be installed at the same location.

The airflow-measuring device was used to 1) measure the maximum airflow rate for the standard unit, and 2) measure the airflow rates at different fan speeds for the Rebel unit. Because the standard unit had a constant-speed supply fan, only one reading was necessary. For the standard unit, after the flow plates were installed and the access door’s gaps were sealed, a number of airflow readings were taken over a period of 30 minutes and averaged. The standard unit had a supply flow rate of 1700 CFM.

For the Rebel unit, a number of airflow readings between 30% and 100% supply fan speed were recorded after the airflow plates were installed and the access door gaps sealed. The readings were taken once every 5 to 10 minutes over a 2-hour period at different fan speeds. Multiple readings were taken at each fan speed and the readings were averaged to characterize the airflow as a function of fan speed. As shown in Figure 4, there is a linear relationship between airflow rate and fan speed for the Rebel unit, as expected.

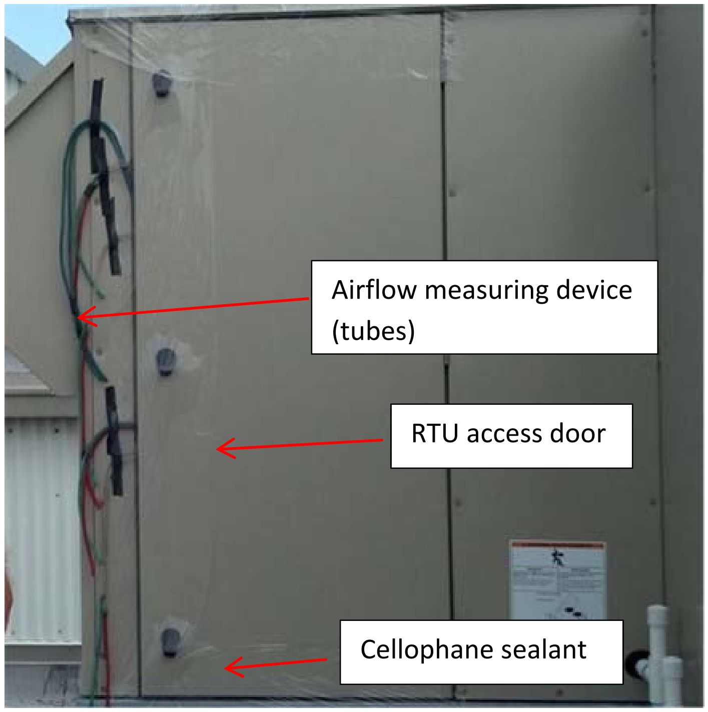

Figure 3: Air Flow Measurement in the Field

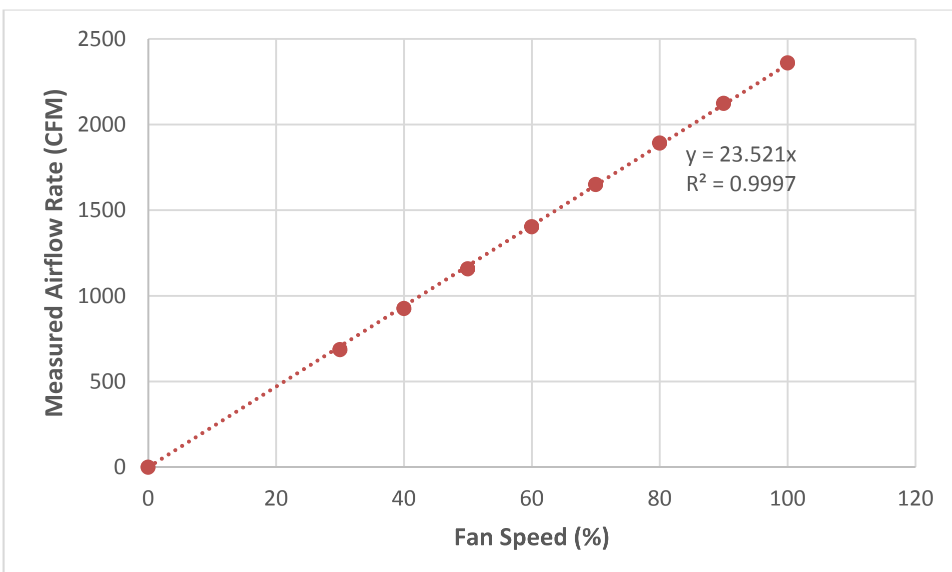

Figure 4: Correlation of Measured Air Flow as a Function of the Fan Speed for the Rebel Unit

D. Estimation of Seasonal Performance

The daily cooling efficiency of both units was computed and compared throughout the monitoring period. The seasonal efficiency was also computed as a single annual index. The estimated airflow rate was used with the measured temperature and relative humidity of mixed air and supply air streams to calculate the total delivered cooling capacity. The ratio of total daily delivered cooling and total daily unit power provided the daily efficiency of the RTUs. The seasonal efficiency of the RTUs was similarly computed as a ratio of total cooling capacity over the season and total unit power consumption over the season.

The following steps were taken to process the measured data for the RTU Challenge unit(s) and the standard unit:

Step 1. Identified and removed data records that showed evidence of incorrect measurement (outliers).

Outliers of measured data resulted from communication issues and data logging problems. These problems occurred randomly and constituted a very small fraction of the total data over the monitoring period.

Step 2. Calculated the specific enthalpy (Btu/lb) of mixed air and supply air streams based on the measured dry-bulb temperature (°F) and relative humidity.

Step 3. Calculated the mass flow rate, $\dot{m}$ (lb/h), of the supply air at each minute using the supply fan speed.

Because the standard unit had a constant speed fan, its airflow rate was fixed at 1700 CFM. Thus, the mass flow rate $\dot{m}$ was calculated as:

$$\dot{m_{ref}} = \begin{cases} 4.5\frac{lb}{ft3}\frac{min}{h} * 1{,}700\frac{ft3}{min} = 7{,}650\frac{lb}{h}\ (if\ FanCall = 1) \\ 0\ (if\ FanCall = 0) \end{cases} \tag{1}$$

where $FanCall$ was a monitored control signal indicating whether the supply fan was running (see Table 1).

Because the Rebel unit had a variable-speed supply fan, the airflow rate changed as a function of fan speed. As discussed previously, the correlation between fan speed and airflow rate was obtained using the one-time field measurements of fan speed and the corresponding airflow rate (Figure 4):

$$\dot{V} = 23.52\frac{ft3}{\min\%} * FanSpeed\ \% \tag{2}$$

where $\dot{V}$ was the volume airflow rate in CFM, and $FanSpeed$ was the speed of the variable-speed drive for the supply fan. The above linear regression was developed for fan speeds greater than 40%, which was the minimum setting for the Rebel unit.

The mass flow rate $\dot{m}$ (lb/h) for Rebel was calculated as:

$$\dot{m}_{Rebel} = 4.5\frac{lb}{ft3}\frac{min}{h} * \ \dot{V}\frac{ft3}{min} \tag{3}$$

Step 4. Calculated the cooling rate delivered at each minute:

$$\dot{Q} = MAX\{0, \dot{m}\frac{lb}{h} * (h_{MA} - h_{SA})\frac{Btu}{lb}\} \tag{4}$$

where $\dot{Q}$ was the cooling rate in Btu/h, and h_{MA} and h_{DA} were the specific enthalpy (Btu/lb) for the mixed air and the supply air, respectively (from Step 2).

Because the supply air could be cooled for several minutes after the compressor was off, compressor status was not used in Equation 4 to calculate the cooling rate. In addition, because the supply air temperature sensor was located downstream of the supply fan (see Figure 2), the cooling calculated from Equation 4 was the air conditioner's net cooling, including heat gain from the supply fan motor.

Step 5. Calculated the daily cooling energy.

Equation 5 below was used to calculate the daily cooling energy ($DailyCooling$, in kBtu) provided by the standard unit and the Rebel unit.

$$DailyCooling = \frac{\sum_i \dot{Q}_i \frac{Btu}{h}}{(60\frac{1}{h} * 1000\frac{Btu}{kBtu})} \tag{5}$$

where the subscript i indicated the monitored 1-minute record.

Step 6. Calculated the daily electricity consumption in the cooling mode.

For the standard unit, the compressor status could be determined through analysis of the total unit power consumption. If the total power is greater than a threshold value, the compressor is considered to be ON. The threshold power was determined by observing the power changes, where a clear abrupt change exists whenever the unit's compressor switches between ON and OFF.

$$DailyRTUElec_{Standard} = \sum_i UnitPwr_i/60 \quad (if\ UnitPwr_i > ThresholdPower_{Standard}) \tag{6}$$

where $UnitPwr$ was the measured total RTU power in kilowatts.

For the Rebel unit, the compressor status is determined in the same manner as that of the standard unit. Because Rebel is a heat pump, the supply air temperature is also used to make sure that the unit is in cooling mode. Thus, the following equation was used to calculate $DailyRTUElec$:

$$DailyRTUElec_{Challenge} = \sum_i UnitPwr_i/60 \quad (if\ UnitPwr_i > ThresholdPwr_{Challenge}) \tag{7}$$

Step 7. Calculated the daily cooling efficiency.

The EER was used as the metric to measure cooling efficiency. Thus, daily cooling EER (kBtu/kWh) was calculated as follows:

$$DailyEER = \frac{DailyCooling}{DailyRTUElec} \frac{kBtu}{kWh} \tag{8}$$

Step 8. Calculated the seasonal cooling efficiency during the entire monitoring period.

Seasonal EER was used to measure the seasonal cooling efficiency. It was calculated as:

$$SEER = \frac{\sum_j DailyCooling_j}{\sum_j DailyRTUElec_j} \frac{kBtu}{kWh} \qquad (9)$$

where the subscript j indicated the number of calendar days over the entire monitoring period.

E. Evaluation Plan

The goal of the RTU Challenge unit demonstration was to estimate the seasonal performance of the RTU Challenge unit and the annual percent savings that could be achieved by using the RTU Challenge unit compared with a unit that would have been used if the RTU Challenge unit were not available.

V. Results

Using the procedure outlined in Section IV, the original 1-minute interval monitored data were processed to obtain daily cooling energy, electricity consumption, and EER. The period of analysis for the standard unit included data from December 2015 through September 2016. As noted earlier, some data were filtered out because of problems with data logging and communication losses.

Figure 5 compares the daily energy efficiency, expressed as EER as a function of average daily outdoor air dry-bulb temperature, of the standard unit and the Rebel unit for the entire monitoring period. The results are missing for some days because the units lost communication those days. The figure shows that the daily EER varies between 8 and 17 Btu/Wh for the standard unit and between 12 and 17 Btu/Wh for the Rebel units. In general, the EER increased as the outdoor air temperature decreased for both units.

To compare the difference in the daily operating efficiency (EER) of the two units, the ratio of EER of the Rebel unit and the standard unit was calculated for all days and is plotted as a function of the daily average outdoor air temperature in Figure 6. The EER ratio ranged between 0.9 and 1.4. The EER ratio increased as the daily average outdoor air temperature increased.

The average of the EER ratio for all days in Figure 6 was approximately 1.18, which means that on average the daily EER of the Rebel unit was 18% higher than that of the standard unit.

In addition to daily EER, the seasonal cooling efficiency was calculated using Equation 9. Table 2 shows the seasonal EER values computed over the entire monitoring period. Over the monitoring period, the standard unit and the Rebel unit had seasonal EERs of 10.5 and 12.2, respectively. The seasonal EER for the Rebel was about 16% higher than that of the standard unit. The EER of the standard unit at this site is slightly higher than what was monitored at the other demonstration site, resulting in lower seasonal EER improvement. Also, the EER and seasonal EER vary with climate.

Table 2: Comparison of Seasonal EER between Rebel Units and the Standard Unit

RTU	Seasonal EER (Btu/Wh)	Seasonal EER improvement
Standard	10.5	NA
Rebel	12.2	16%

The meanings of seasonal EER and daily EER in this work differ slightly from those used in the performance rating standard for RTUs (AHRI 2007). Here, the units had higher external static pressure than the rating standard requirement; and the efficiency calculated in this work included frequent mode changes and thus did not represent the steady-state efficiency used in the rating standard. It is also possible that the Rebel may be experiencing an higher external static because it had an outdoor air damper, while the Standard unit was recirculating 100% of the air. Note that the daily EERs used in calculating the seasonal EER reported in Table 2 are based on daily cooling capacity calculated using Equation 5 and daily RTU electricity consumption based on Equation 7. This calculation neglects the ventilation energy consumption. Because both the Standard and the Rebel units were running the supply fan all-day long (24x7), the ventilation energy consumption is significant.

Therefore, the seasonal EER was also calculated using the total daily capacity the units provided and total daily RTU electricity consumed by the units (including the ventilation energy), irrespective of whether the compressor was ON for cooling as shown in Figure 7. Note that at lower outdoor temperatures both units experience a limited cooling load, while the supply fans for both units are ON all day long. Therefore, the modified daily EERs drop significantly. The modified seasonal EER for the Rebel was about 27% higher than that of the standard unit (Table 3). The modified seasonal EER is also accounting for the reduced supply fan consumption of the Rebel unit compared to the Standard unit.

Table 3: Comparison of Modified Seasonal EER between Rebel Units and the Standard Unit

RTU	Seasonal EER (Btu/Wh)	Seasonal EER improvement
Standard	7.23	NA
Rebel	9.17	27%

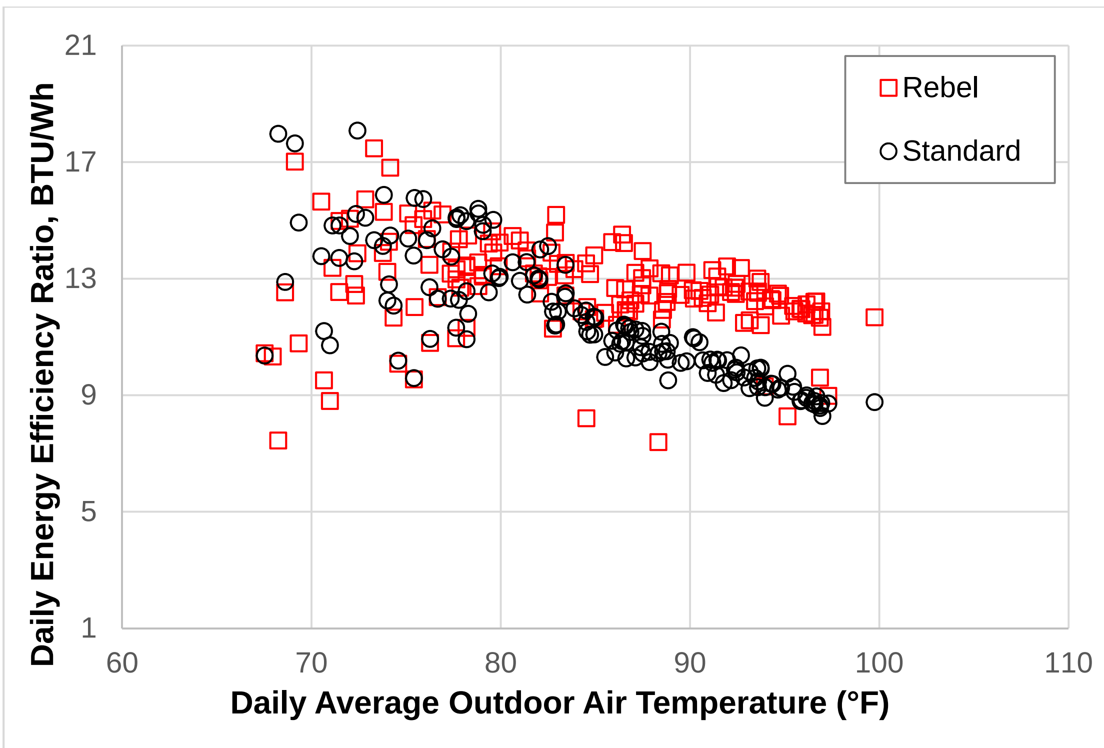

Figure 5: Comparison of the Daily Energy Efficiency Ratio of the Standard Unit and the Rebel Unit as a Function of Daily Average Outdoor Air Temperature for the Monitoring Period

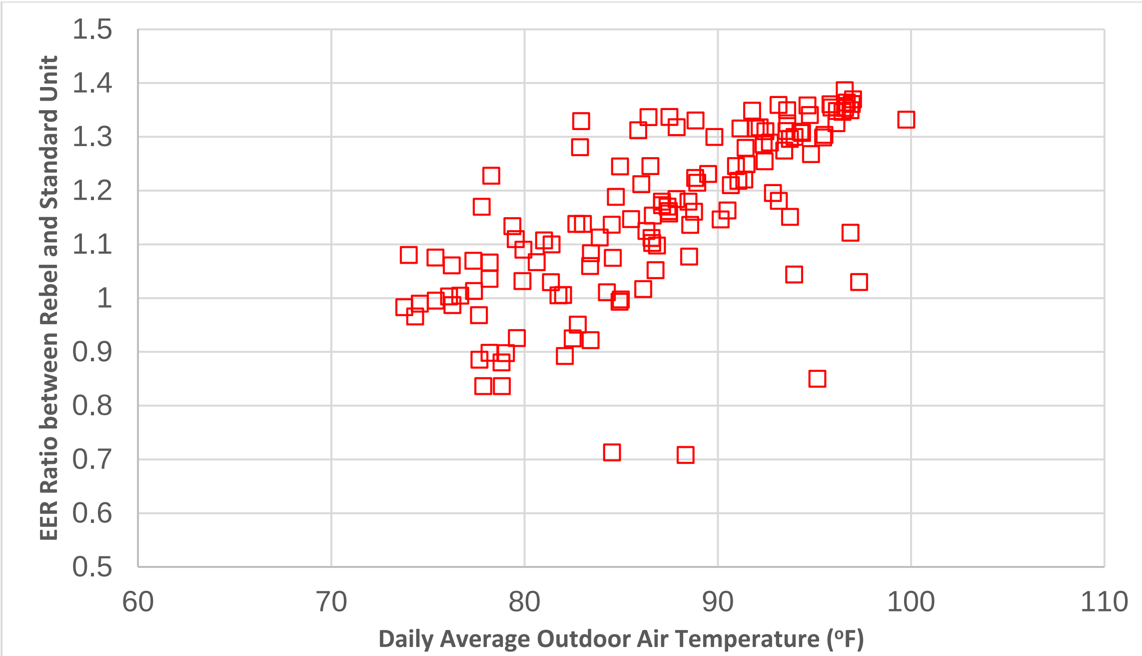

Figure 6: Ratio of the Daily Rebel Unit EER and the Daily Standard Unit EER as a Function of Daily Average Outdoor Air Temperature

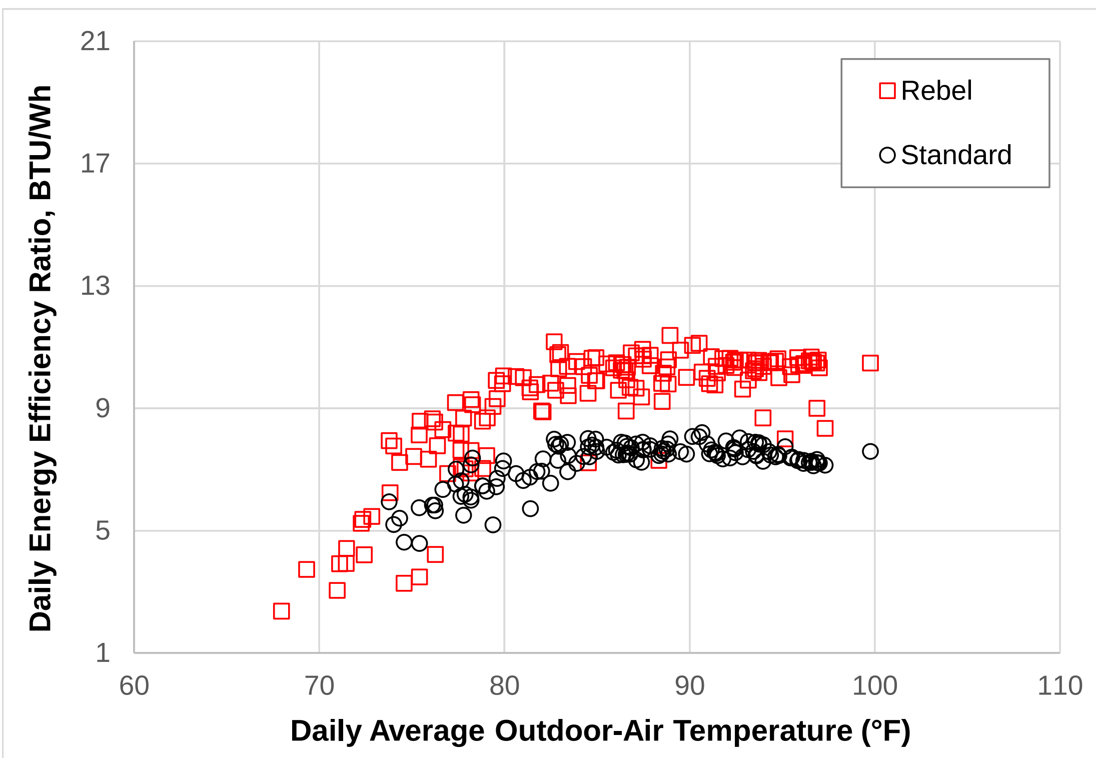

Figure 7: Comparison of the Modified Daily Energy Efficiency Ratio of the Standard Unit and the Rebel Unit as a Function of Daily Average Outdoor Air Temperature for the Monitoring Period

VI. Conclusions

As described previously, the field performance of the Rebel unit was compared with a standard RTU that was less than 5 years old. The standard RTU unit has a constant-speed supply fan and a single-stage mechanical cooling. Based on the comparisons of performance of the standard unit and the Rebel unit, the Rebel unit had 16% higher seasonal EER when ventilation energy consumption was neglected. Accounting for the ventilation energy consumption increased the Rebel unit savings to 26% compared to the Standard unit. This result was slightly lower than the findings from our previous simulation work, which estimated that in hot and humid climates, the Rebel unit would consume about 40% less electricity than an RTU with a constant-speed supply fan and single-stage mechanical cooling. Possible reasons for this difference include: 1) based on observation from the field, the two units in the field served different loads, while the two units in the simulation served the same load; 2) the standard unit had higher operating efficiency than was used in the simulation runs; 3) the Rebel unit always introduces some amount of outdoor air while the standard is recirculating 100% return air; and 4) the Rebel unit may be experiencing an higher external static pressure. The seasonal EER improvement of the Rebel unit was also lower than that of the previous demonstration of a similar unit in a Florida supermarket. The Florida demonstration site used a 7.5-ton Rebel, which was slightly more efficient that the 5-ton Rebel that was used at this site.

It was a challenge to find two units running in two different spaces that served similar cooling loads. Other issues related to the installation of the Rebel unit included the following:

- The Rebel unit came with a different base footprint from the existing Rheem unit.
- The new Rebel unit was considerably heavier than the unit it replaced, requiring roof infrastructure reinforcement changes.

Occupants of the space that was served by the Rebel unit reported no comfort issues, either positive or negative. The start-up and commissioning of the Rebel was not as challenging as the previous demonstration effort because the local Daikin distributor had more experience installing these new units. The site had to request one or two return visits by the service provider to make minor changes to the initial startup and configuration. The local GSA BAS support team also had to make a few modifications to the Tridium network and to some of the power sensors to correct issues related to trending and power meter accuracy. After everything was properly configured, the unit, as well as the metering and monitoring system, worked as expected. Over the last 12-month period, maintenance requirements for this unit were similar to those of the other units.

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