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# Lab and Field Evaluation of Fault Detection and Diagnostics for Advanced Roof Top Units

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## ABSTRACT

This paper presents results of lab and field evaluations of an Automatic Fault Detection and Diagnostics (AFDD) technology for advanced RTUs that provide cooling of small and medium commercial buildings. The primary focus of the technology is detecting overall performance degradation (COP and capacity) resulting from single and multiple faults. High confidence detection of the performance degradation and a low false alarm rate were demonstrated in the lab environment. Furthermore, a field evaluation of AFDD has been carried out on four state-of-the-art RTUs in two commercial sites in Florida. The RTUs were instrumented for online monitoring of performance degradation and fault diagnostics. The performance degradations caused by manually injected faults were successfully detected when they exceeded a preset threshold (e.g. 10% COP degradation).

## 1. INTRODUCTION

Roof Top Units (RTU) serve approximately 60% of commercial floor space and account for 150 TWh of annual electrical usage (1.56 Quads of primary energy) and \$15B in electric bills as well as \$2.5B of sales in the US. RTU performance degradation caused by operational faults may lead to a 10 - 15% HVAC energy penalty during the cooling season. This penalty can be eliminated through early detection and repair of both component and system level faults that lead to lower system performance.

AFDD is an effective approach to detect RTU performance deviations and identify related faults. It can not only reduce energy consumption, but also minimize maintenance costs and extend equipment lifespan. During the last several decades Fault Detection and Diagnostics (FDD) have been intensively investigated in the HVAC industry, including HVAC components (AHUs and VAVs etc.), systems and equipment (chillers and ACs etc.), and buildings (Rossi et al., 1996, Breuker et al., 1998 & Heinemeier, 2012). Recently, some FDD technologies have been applied in high-end advanced vapor compression refrigeration systems (Li et al., 2007, Li et al., 2014). However, the initial cost is a main barrier to their application, especially for retrofit markets. The current study focuses on RTU performance degradation evaluation of a cost-effective AFDD technology for advanced RTUs that are gaining more popularity in small and middle size commercial buildings. Both laboratory and field testing results will be presented.

## 2. AFDD METHODOLOGY

Of the multiple impacts caused by RTU faults, performance degradation is one of the most important concerns to end users because it directly results in higher monthly energy bills and reduced cooling capacity resulting in comfort complaints. In this paper a two-step approach is described to address this important concern: 1) RTU performance degradation detection, then 2) fault diagnostics to determine the root cause(s). The technical approach is described below.

2.1 AFDD Method with Performance Assessment Focus

The overall AFDD system includes performance degradation detection, fault diagnostics, fault impact analysis, and service recommendations. Figure 1 shows the layout of the AFDD implementation for advanced RTUs.

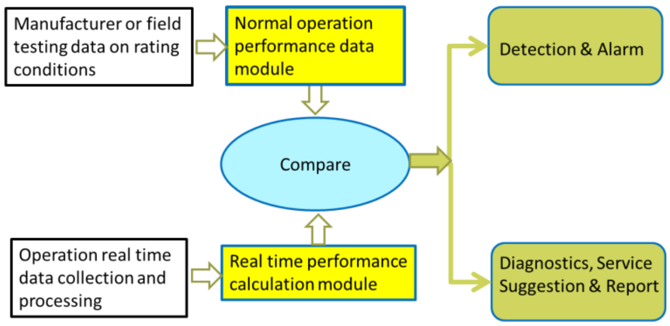



Figure 1 Overall Layout of AFFD Implementation

Detecting RTU performance degradation is the first step. Both the RTU reference (baseline) and current performance are required to define the performance degradation. The RTU reference performance module is developed with RTU nominal operation data obtained under no fault conditions. The RTU real-time performance module utilizes virtual refrigerant flow rate and compressor power sensors and minimum additional physical sensors (such as temperature sensor at condenser outlet) to estimate the actual performance of the RTU system. The refrigerant flow rate and compressor power estimation in the module are based on the compressor map or energy balance based virtual flow rate sensors. Real-time RTU performance degradation is assessed by comparing the real time RTU performance (cooling capacity and COP) with the expected performance from the reference module under the same conditions. An alarm will be issued if the degradation is over a preset limit (for example, 10% of cooling capacity or COP). Meanwhile, the AFDD procedure moves into the next step – fault diagnostics.

The fault diagnostics module includes typical faults that occur during RTU operation, such as condenser and evaporator fouling, compressor leakage, liquid line restrictions, and refrigerant over and under charge. After determining the faults, the last step is to assess the impacts of the faults on RTU operation and recommend corresponding services or repairs if necessary. For a commercial application, both the reference and real performance modules along with the fault diagnostics module can be integrated with the existing RTU control board and provide RTU operating information to facility operators and owners.

2.2 Performance Degradation Algorithm

As discussed above, RTU performance degradation is assessed by comparing the real-time RTU performance (cooling capacity and COP) with the expected performance under the same operation conditions without any fault, i.e.

$$\varepsilon_Q = 1 - \frac{Q}{Q_{ref}} \tag{1}$$

$$\varepsilon_{COP} = 1 - \frac{COP}{COP_{ref}} \tag{2}$$

RTU performance degradation is monitored in real-time and an alarm will be issued once either capacity or COP degradation exceeds a preset valve ($\epsilon_{limit}$)

$$\epsilon_Q \text{ or } \epsilon_{COP} > \epsilon_{limit} \tag{3}$$

RTU real-time performance is estimated as shown in the flow chart in Figure 2. Once real-time RTU performance is identified, RTU performance degradation can be evaluated with Eqs.1 and 2.

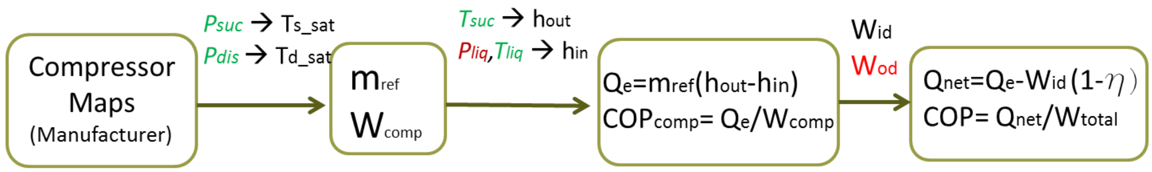



Figure 2 Real-Time Performance Calculation Flow Chart

2.3 Fault Diagnostics Algorithms

Common RTU fault diagnostic methods are briefly discussed as follows. They include refrigerant charge, condenser and evaporator fouling or blockage, compressor leakage and liquid line restriction.

The condenser fouling diagnostics are based on a comparison between a virtual estimation of the real-time air flow rate and its reference (or expected) flow rate. When the ratio of these two variables is lower than a preset limit (for example, 80%), a condenser fouling alarm is issued. The virtual air flow rate is estimated from the refrigerant heat load and measured air inlet and outlet temperatures. The reference air flow rate is obtained from manufacturer data sheet or field testing data under conditions with no condenser fouling. The evaporator fouling diagnostics is similar to the condenser fouling case. The evaporator refrigerant inlet enthalpy is approximated by using compressor discharge pressure and expansion valve inlet temperature. For high pressure refrigerants such as R410A, this approximation is accurate enough.

The compressor leakage is assessed by comparing the virtual refrigerant flow rate from the compressor map with another virtual refrigerant flow rate from the compressor energy balance. A compressor leakage alarm will be issued when the virtual refrigerant flow rate ratio is more than a preset limit, for instance, 105% for the RTU tested in the lab. For the liquid line restriction fault, two surface mounted temperature sensors are attached to the condenser outlet and TXV inlet. The difference between their corresponding saturation pressures is used to check whether the liquid line is restricted or not. An alarm will be issued when this pressure difference is more than a preset limit.

All of the above fault diagnostics algorithms were implemented in an advanced RTU testing platform built in the UTRC Psychrometric Lab on the LabView platform.

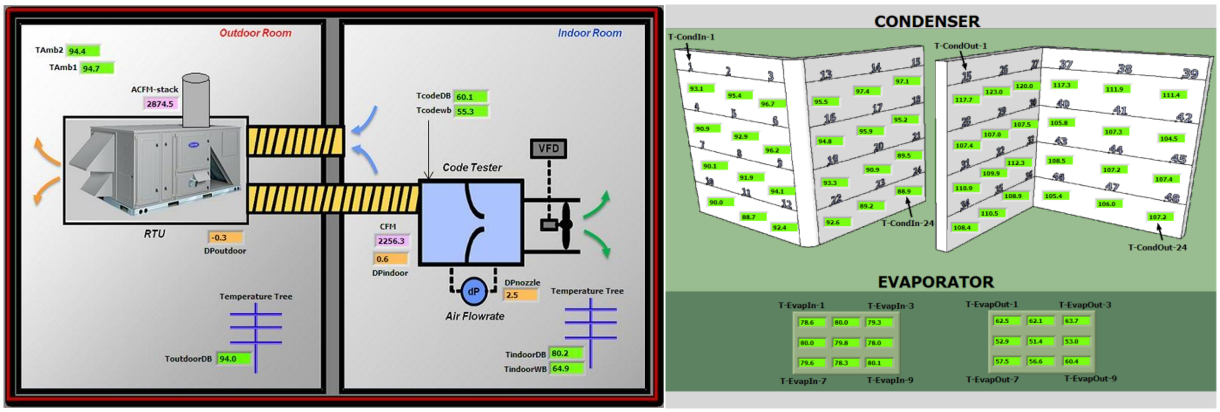
## 3. EVALUATION IN LABORATORY ENVIRONMENT

It is important to understand actual RTU behavior including its performance degradation under different fault conditions in order to develop an AFDD capability with minimum additional cost for RTU applications. A series of fault injection tests were performed on an advanced RTU testing platform as described below.

3.1 Advanced RTU Testing Facility

An advanced 6-ton WeatherExpert RTU LC unit was down-selected and acquired from Carrier for our AFDD lab evaluation. The refrigerant was R410A. This performance evaluation focused on refrigerant charge, condenser and evaporator blockage, liquid line restriction, and compressor leakage. The acquired RTU was modified in order to simulate these faults. A discharge port was added in addition to the original charge port. These ports allow for the easy addition and removal of refrigerant from the system to easily inject the refrigerant charge faults. For simulating condenser and evaporator blockages, multiple layers of polypropylene screens were attached to evaporator and condenser coils to create extra air pressure drops for air blower and fans. To simulate liquid line restrictions, a 3-way valve and an electric control valve were added after the filter/dryer. At the first position of the 3-way valve, no additional restriction was added. When it switched to its second position, liquid flowed through the control valve whose opening is adjustable to create different level restrictions. A parallel line with a ball valve and an electric control valve was added between the inlets and outlets of compressors. The ball valve was shut off during normal operation. Under the leakage fault conditions, the ball valve was on and the control valve opening controled the leakage intensity.

The RTU was instrumented for studying its behavior under single or multiple fault conditions. Along the refrigerant loop, there were multiple pressure and temperature sensors to measure refrigerant pressures and temperatures. A Micromotion flow meter was installed between the condenser and filter/dryer to measure refrigerant flow rate. As shown in Figure 3, there were 24 (4x6) and 9 (3x3) thermocouple grids at both air inlets and outlets to measure air inlet and outlet temperatures of the condenser and evaporator respectively. An air flow rate measurement device was attached on the outlet of one of the two condenser fans to get the condenser air flow while a code test device was used to measure evaporator air flow.




a) Facility Layout b) TCs Distribution

Figure 3 Testing Facility Layout and Instrumentation Configuration

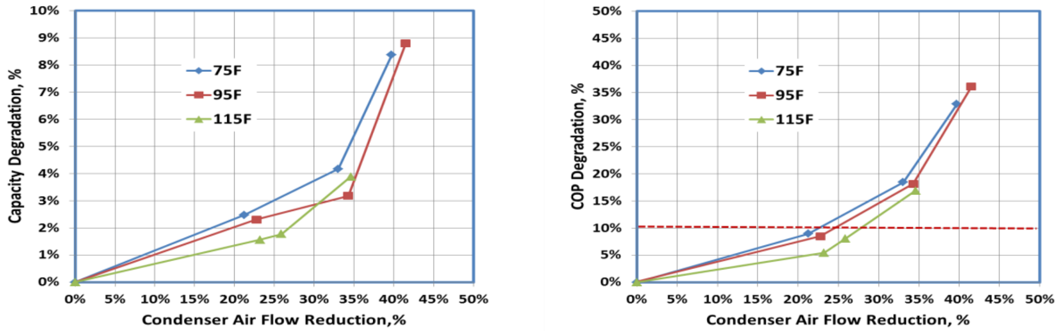
## 3.2 Advanced RTU Testing under Single and Multiple Faults

Table 1 briefly summarizes the test conditions under different faults and fault intensity levels. For each fault, the testing was conducted by starting without any fault condition, then gradually increasing the fault intensity under different outdoor air temperatures (75, 95 and 115ºF) while the indoor condition is kept at 80ºF (dry bulb)/67ºF(wet bulb).

Table 1 Advanced RTU AFDD Testing Matrix

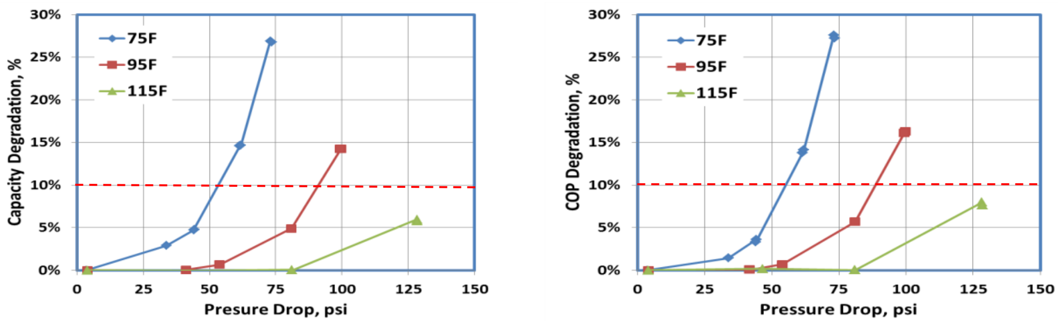
| Faults | Condenser Blockage | Liquid Line Restriction | Compressor Leakage | Evaporator Blockage | Condenser Blockage & Compressor Leakage | Condenser and Evaporator Blockage |
|---|---|---|---|---|---|---|
| Test Runs | 18 | 24 | 19 | 7 | 4 | 3 |
| Fault Intensities | 0 – 41.5% | 0 – 125 psi | 8 Levels | 0 – 50% | 4 comp. leakage levels under 25% cond. blockage | 0-29% cond. blockage under 50% evap. blockage |

The intensity of the condenser fouling/blockage fault was increased by adding more layers of plastic screens or increasing the blocking area. It was measured by the condenser air flow reduction percentage in comparison with the condenser air flow without the fault. Both cooling capacity and COP degradations increase as the condenser fouling/blockage fault intensifies. However, the cooling capacity is not as sensitive as COP. As shown in Figure 4, the cooling capacity reduces only 8-9% versus 33-36% reduction for COP when the air flow is reduced about 40% due to the fouling/blockage. The 10% performance degradation threshold (either capacity or COP) occurs when the condenser fouling/blockage fault causes 23 – 28% air flow reduction. The degradation gets worse under lower outdoor temperatures.




a) Cooling Capacity Degradation b) COP Degradation

Figure 4 RTU Performance Degradation under Condenser Blockage



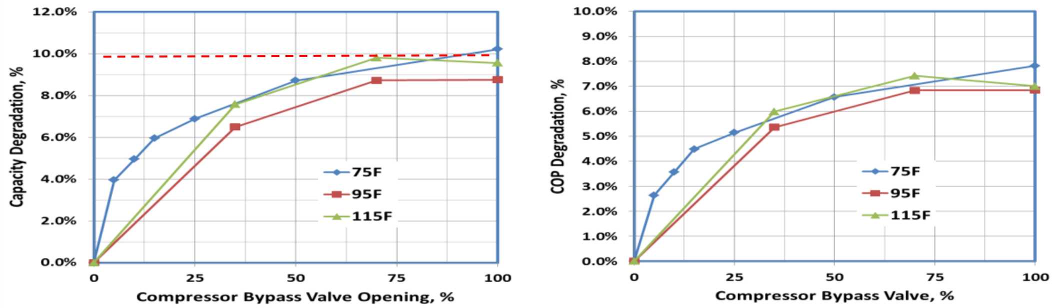

a) Cooling Capacity Degradation b) COP Degradation

Figure 5 RTU Performance Degradation under Liquid Line Restriction

The fault intensity of RTU liquid line restriction is increased when the in-line control valve opening gradually decreases and the liquid line pressure drop increases. The pressure drop across the valve is adopted to measure the liquid line restriction intensity. As shown in Figure 5, the RTU performance degradation is strongly impacted by the outdoor temperature. This is because the expansion valve opening is bigger at a lower outdoor temperature and the refrigerant flow rate decreases after the expansion valve is fully open. At 75ºF outdoor temperature, the RTU performance is very sensitive to the liquid line restriction. Both capacity and COP degradation pass the 10% threshold when the pressure drop is over 55 psi. At 95ºF outdoor temperature, the RTU performance does not degrade unless the pressure drop caused by the liquid line restriction is above 50 psi. The 10% threshold occurs after the pressure drop reaches 90 psi. At 115ºF outdoor temperature, no obvious performance degradation occurs when the pressure drop is less than 80 psi.

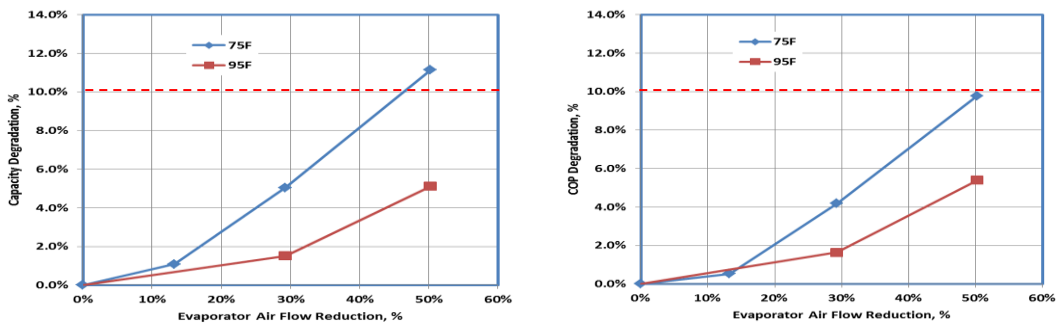
For the compressor leakage fault, its intensity is controlled and measured by the bypass valve opening. When the control valve is fully open, the leakage is estimated to be approximately 20-25% of the compressor mass flow. As shown in Figure 6, both cooling capacity and COP show a similar trend. At 95ºF outdoor temperature the degradation is the lowest under the same leakage valve opening. This is the combining results of the refrigerant flow reduction and the increment of the enthalpy difference across the evaporator. The 10% cooling capacity degradation is reached when the leakage valve opening is over 90% at 75ºF outdoor temperature.

Intensity of the evaporator fouling/blockage fault is measured by the evaporator air flow reduction percentage in comparison with the evaporator air flow without fault. As shown in Figure 7, both cooling capacity and COP degradations increase as the evaporator fouling/blockage fault intensifies. The 10% performance degradation threshold (either capacity or COP) occurs when the condenser fouling/blockage fault causes 45 – 50% air flow reduction at 75ºF outdoor temperature. The degradation is worse under lower outdoor temperatures.




a) Cooling Capacity Degradation b) COP Degradation

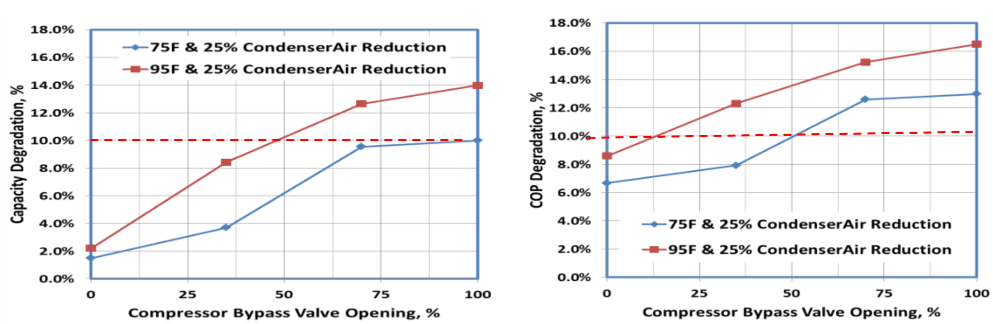
Figure 6 RTU Performance Degradation under Compressor Leakage




a) Cooling Capacity Degradation b) COP Degradation

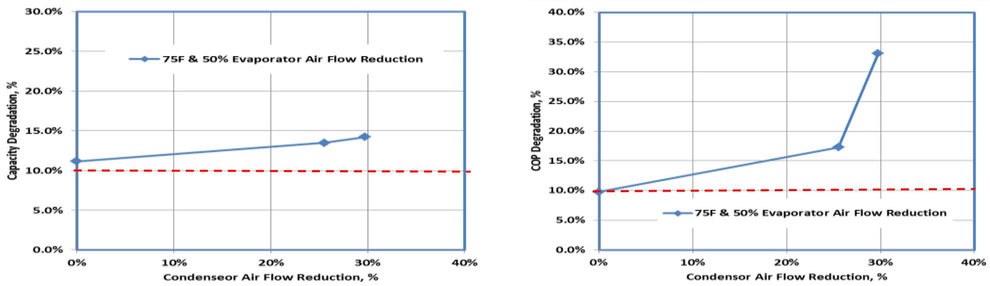
Figure 7 RTU Performance Degradation under Evaporator Blockage

RTU performance degradation can be caused by one, two or multiple faults. A series of tests on performance degradation caused by both the condenser fouling/blockage and compressor leakage were performed under 75 and 95 ºF outdoor temperatures. The condenser fouling fault was set at about 25% of condenser air flow reduction during testing while the compressor leaking valve opening varied from 0% to 100%. As shown in Figure 8, the performance degradation was more at 95F outdoor temperature than at 75ºF under the same leaking valve opening and condenser blockage. COP degraded more than the cooling capacity under the same condition. The 10% performance degradation threshold occurs at roughly 50% and 12.5% of the leaking valve opening for 75 and 95 ºF outdoor temperatures respectively. Another series of tests on performance degradation caused by both the evaporator and condenser fouling/blockage was performed preliminarily under 75 ºF outdoor temperature. The evaporator fouling fault was set at about 50% of air flow reduction during testing while the condenser air flow reduction increases up to 30%. As shown in Figure 9, the cooling capacity degradation is not as sensitive as the COP degradation. The COP degradation increases from 10% to 33% while the condenser air flow is reduced to 30%.




a) Cooling Capacity Degradation b) COP Degradation

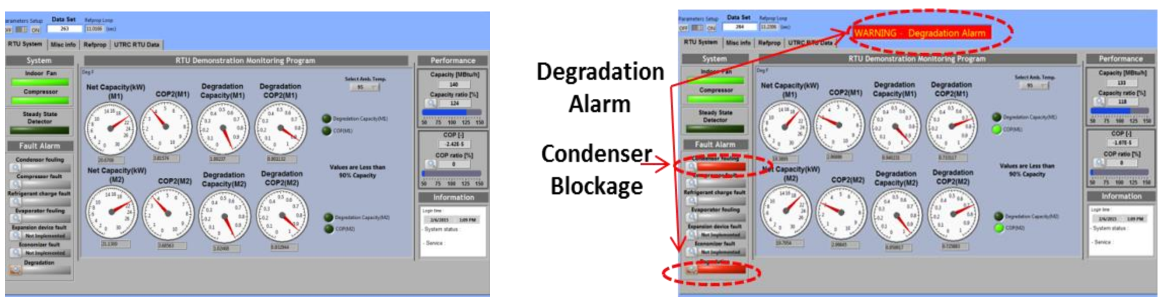
Figure 8 RTU Performance Degradation under Compressor Leakage




a) Cooling Capacity Degradation                b) COP Degradation

Figure 9 RTU Performance Degradation under Compressor Leakage

## 3.3 Real-Time AFDD Implementation




a) Normal Condition                b) Fault Condition

Figure 10 LabView Interfaces of RTU AFDD Implementation

The AFDD algorithms described in Section 2 were implemented on a LabView platform with capabilities of real-time performance degradation monitoring and fault diagnostics by modifying the LabView codes developed by Kim (2013). Figure 10a shows an interface under a normal operating condition without fault. The gauges on the first row show RTU performance and its degradation calculated with measured data. The gauges on the second row show the same parameters calculated from the compressor map based virtual sensors. The virtual sensor based RTU performance degradation AFDD accuracy is evaluated with the physical sensor based performance degradation results. Figure 10b shows a LabView interface of an operation condition with condenser blockage fault. When either the cooling capacity or COP degradation is over a preset threshold (10%), a degradation warning sign is flashing and a condenser blockage fault sign also turns red.  The validation by injecting other faults shows that the algorithms not only can identify RTU performance degradation but also correctly diagnose which fault causes the degradation.

## 3.4 Evaluation of RTU Performance Degradation Detection Accuracy

The real-time RTU performance calculation relies on the accuracies of refrigerant flow rate and compressor power estimates that are based on the manufacturer's compressor map. Based on the testing data under normal conditions and fault conditions with more than 10% performance degradation, a statistical analysis has been performed to evaluate the FDD accuracy. As shown in Figure 11, the false alarm rate is less than 1% when COP degradation is more than 4.4% and the confidence rate to issue a 10% degradation alarm is more than 90% when COP degradation is above 13.4%.  For RTU cooling capacity degradation detection, as shown in Figure 12, the false alarm rate is less than 1% when the cooling capacity degradation is more than 2.0% and the confidence rate to issue a 10% degradation alarm is more than 90% when the cooling capacity degradation is above 13.0%.

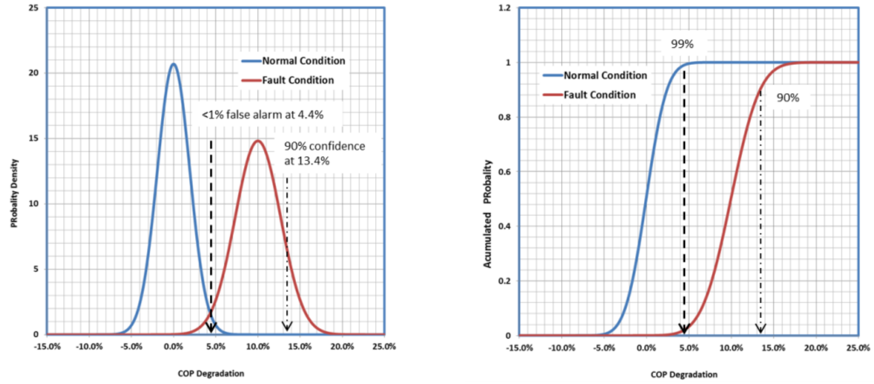



Figure 11 Accuracies of RTU COP Degradation Detection

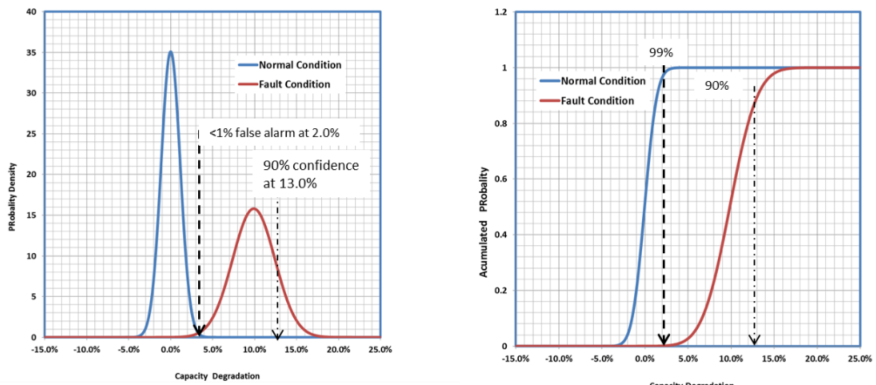



Figure 12 Accuracies of RTU Cooling Capacity Degradation Detection

## 4. EVALUATION IN FIELD ENVIRONMENT

### 4.1 Site Selection and Instrumentation

Two convenience stores in Florida were selected for field evaluation because both sites experience a hot and humid climate and have the same Carrier WeatherMaster 50HCQ series high efficiency heat pump RTUs. Figure 13 shows RTUs before and after adding additional instrumentation. Both stores have a 7.5 ton cooling capacity RTU cooling the store's open space and a 5 ton RTU to cool the store's office space.


a) RTU before Instrumentation b) RTU after Instrumentation

Figure 13 RTUs before and after Instrumentation

In addition to the existing OEM sensors, six additional temperature sensors and two additional air humidity sensors are added for RTU AFDD. The two humidity probes are for measuring air relative humidity at the evaporator inlet and outlet. Meanwhile a WebCRTL accessing board (ALC I/O Flex 8160 expander), a 24 volt DC power supply and an enclosure were added to the data acquisition (DAQ) system. The recorded data then are retrieved, processed and analyzed remotely for performance degradation detection and fault diagnostics.

### 4.2 AFDD Field Implementation

Overall AFDD implementation for the field RTUs is shown in Figure 14. Relevant RTU operation data are collected and displayed through the online WebCRTL platform. The Data Management System (DMS) developed by UTRC retrieves data from the WebCTRL platform and stores it in a data center. Executable AFDD modules analyze the retrieved data and output results about the RTU's performance degradation and fault diagnostics report.

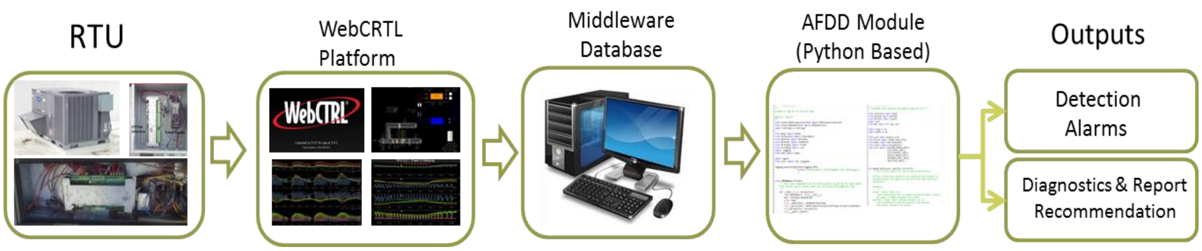



Figure 14 Flowchart of Field AFDD Implementation

### 4.3 Field Testing Results under Fault Injection

A series of fault injection field tests were carried out during March 31- April 1, 2016. The injection faults included condenser blockage, evaporator blockage and compressor bypassing. In addition to a single fault injection, tests were also conducted with injection of multiple simultaneous faults.

Figure 15 shows results of performance degradation detection of the 7.5 ton RTU at one field testing site with fault injection. The red dash line boxes in Figure 15 highlight the results with condenser blockage; with 50% condenser area blockage RTU cooling capacity slightly decreases while total power increases about 3-4% and COP decreases by 5%. When the condenser blockage increases to 75%, the cooling capacity decreases to 6-7% and the total power jumps by 20%. Consequently, COP drops by 23-25%. As highlighted with the green dash line box, under the evaporator blockage test, the total power slightly decreases and the cooling capacity decreases around 5% and 15% at 35% and 50% evaporator blockage, respectively. The black dash line box in the figure highlights the results under simultaneous condenser and evaporator blockage. Under a simultaneous 50% condenser and 35% evaporator blockage, the cooling capacity decreases 6-8% and total power increases 6-8%. Consequently, the COP decreases around 15%. A compressor leakage was injected through bypassing a portion of the refrigerant flow from the discharge port to the suction port of the compressor. As highlighted with the magenta dash line box in Figure 9, the cooling capacity calculated by the virtual refrigerant flow rate from the compressor map increases. However, the real refrigerant flow rate is lower than the virtual flow rate because of the compressor bypassing. Hence, the virtual refrigerant flow rate is inappropriate when a compressor fault exists. A refrigerant flow indicator is developed from the compressor energy balance. The compressor flow indicator shows a significant flow deviation under the compressor bypassing. It is detectible for the injected compressor leakage.

### 4.4 Results of Online AFDD Field Evaluation

The AFDD described in Section 4.2 was implemented on RTUs at both field testing sites. Field operation data of the RTUs are retrieved from WebCRTL, analyzed and reported on an online computer terminal with the Python based module. Figure 16 shows the screening results of AFDD implementation on the 7.5 ton RTU at one field testing site. During January 1 to April 6, 2016, the only faults detected are the faults injected during the testing campaign in April 1, 2016.

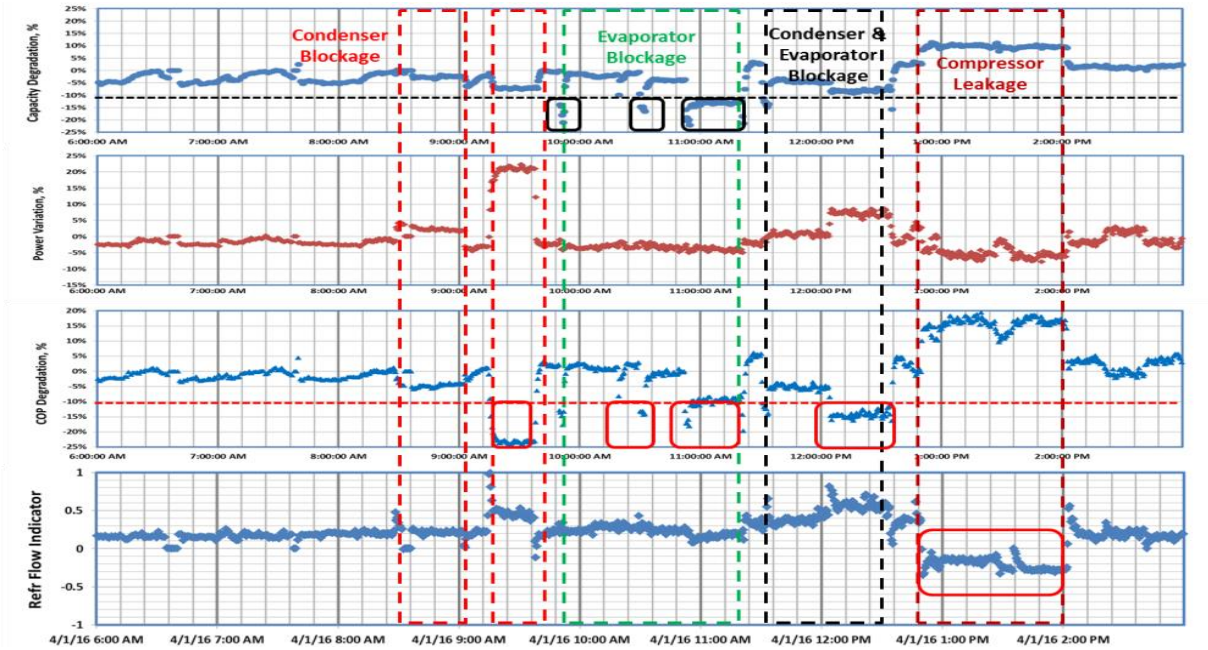



Figure 15 Results of Fault Injection Test

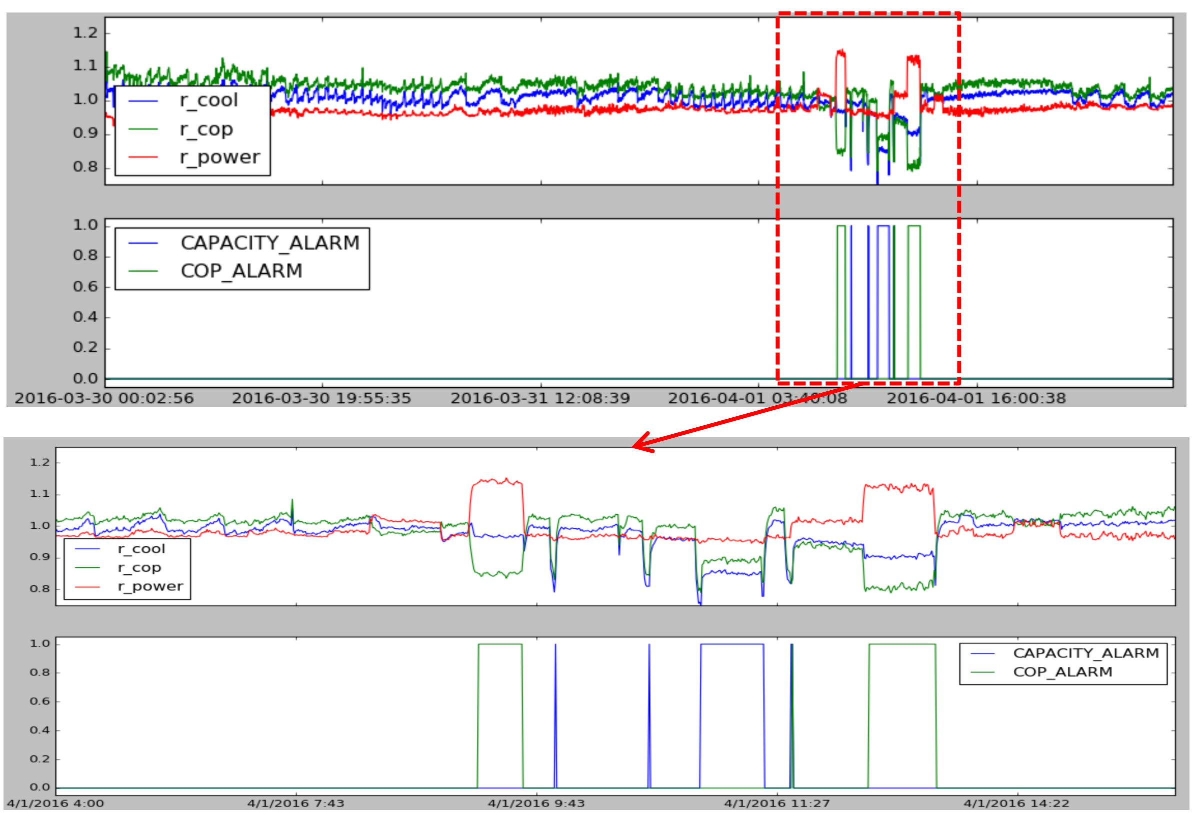



Figure 16 Results of AFDD Field Evaluation on 7.5 ton RTU

The detailed results during April 1 (Figure 16) confirm the injected faults including the condenser blockage, evaporator blockage, and simultaneous condenser and evaporator blockage. When the RTU performance degradation limits (including cooling capacity and COP) are set at 13% for issuing a fault alarm, the confidence of detecting a 10% performance degradation is over 90%. As important, no false alarm was issued during this period. Although this is not enough data to identify the false alarm rate; from the statistics of the lab testing data, the false alarm rate of the AFDD field evaluation is expected to be less than 1%. Online RTU performance degradation monitoring on both sites are still ongoing.

## 5. CONCLUSIONS

AFDD is an effective approach to detect RTU performance deviations caused by operational faults, reduce energy consumption, and extend RTU lifespan. A two-step AFDD method with performance assessment focused has been developed for RTUs of small and medium size commercial buildings. RTU performance degradation is assessed by comparison of RTU real-time performance from the virtual sensor based performance module and its expected performance from the reference module. Once the performance degradation exceeds a preset threshold, an alarm is issued and the fault diagnostics algorithm is started.

The developed AFDD technology was evaluated in both laboratory and field environments. An advanced RTU was instrumented and tested in UTRC's psychrometric facility under single and multiple faults conditions. The applied faults include condenser and evaporator blockage, liquid line restrictions and compressor leakage. The RTU performance degradation behaviors under these faults conditions have been characterized. A real-time AFDD module on the LabView platform has been developed and validated for RTU performance degradation monitoring and fault diagnostics in the lab environment. Statistical analysis on the lab testing data indicates the confidence on issued 10% performance degradation alarms is more than 90% when the COP and cooling capacity degrades 13.4% and 13.0% respectively.

The field evaluation has been carried out on four advanced RTUs in two field testing sites in Florida. The field AFDD module is built on WebCTRL for field data acquisition, DMS for field data storage and Python based AFDD module for data analysis and result output. The RTU performance variation behavior under different manually-injected faults have been identified. The developed AFDD module has been implemented for the field RTU operation performance monitoring. The performance degradations caused by the manually injected faults are detected successfully when they pass the preset threshold.

## NOMENCLATURE

| | | |
|---|---|---|
| Q | cooling capacity | (kW) |
| COP | efficiency of performance | (-) |
| m | mass flow rate | (kg/s) |
| W | power | (kW) |
| h | enthalpy | (kW/kg) |
| h | fan efficiency | (-) |
| e | performance degradation | (%) |
| T | temperature | (ºC, ºF) |
| P | pressure | (kPa) |
| r | ratio | (-) |

**Subscript**

| | |
|---|---|
| ref | reference |
| Q | capacity |
| COP | coefficient of performance |
| suc | suction |
| dis | discharge |
| liq | liquid |
| comp | compressor |
| sat | saturation |
| e | evaporator |
| out | outlet |

| | |
|---|---|
| in | inlet |
| id | indoor |
| cool | cooling capacity |

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