Rooftop Unit AFDD: Smart Monitoring and Diagnostic System and Proactive Diagnostics

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Presentation Outline

Current State of Building and RTU Operations

Automated Fault Detection and Diagnostics

Smart Monitoring and Diagnostics System

Proactive RTU Diagnostics

Concluding Remarks
Current State of Building Operations

Energy waste is caused by:

- Lack of use of energy-savings control strategies
- Override of automatic controls
- Improper actions
- Incorrect original installation

Results in up to 30% energy waste in buildings

Lack of cost-effective controls solutions for small buildings
Poor operations and maintenance practices
State of Rooftop Units

- Packaged air conditioners and heat pumps (RTUs)
  - Serve about 58% of all cooled commercial buildings,
  - Serving about 69% of the cooled commercial building floor space (EIA 2003)

- Consume almost 2.1 Quads for primary energy

- Installed efficiency of RTUs is low

- Operating efficiency is also low due to lack of:
  - Advanced controls to improve part load performance
  - Lack of adequate equipment maintenance
  - A field study including 503 RTUs, at 181 commercial building sites in 5 states showed only 9% are maintained properly
Automated Fault Detection and Diagnostics

- There is need for automated fault detection and diagnostics (AFDD) tool
- Process to automatically detect, diagnose and evaluate the impact of the fault
  - Generate actionable information
  - Can be passive or proactive
- Passive approaches work in most cases, but sometimes active approach will identify the fault quickly
- Widespread use of AFDD can improve the efficiency of the building stock and support condition-based maintenance practices for RTUs
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Smart Monitoring and Diagnostic System (SMDS)

- Low Hardware Cost
- Low Installation Cost
- Auto Configuration
Illustration of SMDS Approach

Initial (Baseline) Relationship

No Significant Change

Significant Change
Single-Stage RTU with Constant Speed Supply Fan

Inputs

**Raw Data:**
- Total RTU Power
- OAT

**STEP 1**
Identify Steady-state Cycles

**STEP 2**
Distinguish Operating States

**STEP 3**
Apply Linear Regression

Output

Performance Degradation Fault or No Fault

Baseline Performance Curve

Post-Baseline Performance Curve

Characteristic RTU Performance Curve
Conversion of Raw Data to Processed

- 30,240 data points
- measured at 1-minute intervals
Determine Magnitude of Change

\[ \Delta \text{Range} \]

\[ P_{\text{inc}} = \frac{\Delta P}{P_{\text{baseline}}} \]

If \( P_{\text{inc}} > 5\% \) ➔ Degradation Alert
Daily Operation Status and Weekly Degradation Reporting

► Operational faults
  ■ Compressor runs continuously for 24 hours during the day
  ■ RTU (compressor and/or fan) runs continuously all day
  ■ RTU does not turn on during the entire day
  ■ RTU supply fan cycles with the compressor only, not providing ventilation when the compressor is off and the unit is not cooling

► Compressor short cycling
  ■ A compressor “on” cycle shorter than $t_{on\text{-}limit}$
  ■ A compressor “off” cycle shorter than $t_{off\text{-}limit}$

► Degradation in performance is reported on a weekly basis
## Performance Results

<table>
<thead>
<tr>
<th>Units</th>
<th>Faults</th>
<th>Occurrence</th>
<th>Data Period (days w/ sufficient raw data)</th>
</tr>
</thead>
<tbody>
<tr>
<td>RTU 1</td>
<td>Short Cycling 2.3% Degradation</td>
<td>25 days 73 days</td>
<td>9/12-6/24 (236 days)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>No degradation</td>
<td></td>
</tr>
<tr>
<td>RTU 2</td>
<td>Short Cycling 1.7% Degradation</td>
<td>38 days 66 days</td>
<td>9/12-6/24 (224 days)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>No degradation</td>
<td></td>
</tr>
<tr>
<td>RTU 3</td>
<td>Fan Cycling only with Compressor</td>
<td>37 days 2 days 5 days</td>
<td>9/12-6/24 (230 days)</td>
</tr>
<tr>
<td></td>
<td>Short Cycling 1.1% Degradation</td>
<td>No degradation</td>
<td></td>
</tr>
<tr>
<td>RTU 4</td>
<td>Fan Cycling only with Compressor</td>
<td>29 days 1 day 26 days</td>
<td>9/12-6/24 (231 days)</td>
</tr>
<tr>
<td></td>
<td>Short Cycling 4.2% Degradation</td>
<td>No degradation</td>
<td></td>
</tr>
<tr>
<td>RTU 5</td>
<td>Short Cycling 1.3% Degradation</td>
<td>27 days 1 day</td>
<td>9/12-6/24 (252 days)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>No degradation</td>
<td></td>
</tr>
<tr>
<td>RTU 6</td>
<td>Short Cycling 1.1% Degradation</td>
<td>40 days 2 days</td>
<td>9/12-6/24 (232 days)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>No degradation</td>
<td></td>
</tr>
<tr>
<td>RTU 7</td>
<td>Short Cycling 2.2% Degradation</td>
<td>11 days 40 days</td>
<td>9/12-6/24 (216 days)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>No degradation</td>
<td></td>
</tr>
</tbody>
</table>
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<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>(days w/ sufficient raw data)</td>
</tr>
<tr>
<td>RTU 1</td>
<td>System Off for the Day Short Cycling 0% Degradation</td>
<td>4 days 73 days</td>
<td>9/12-6/24 (130 days)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Not enough cooling</td>
<td></td>
</tr>
<tr>
<td>RTU 2</td>
<td>System Off for the Day Short Cycling 0% Degradation</td>
<td>3 days 66 days</td>
<td>9/12-6/24 (182 days)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Not enough cooling</td>
<td></td>
</tr>
<tr>
<td>RTU 3</td>
<td>System Off for the Day Fan Cycling only with Compressor Short Cycling 0% Degradation</td>
<td>5 days 2 days 5 days Inconclusive Data</td>
<td>9/12-6/24 (237 days)</td>
</tr>
<tr>
<td>RTU 4</td>
<td>System Off for the Day Fan Cycling only with Compressor Short Cycling 0% Degradation</td>
<td>3 days 1 day 26 days Inconclusive Data</td>
<td>9/12-6/24 (143 days)</td>
</tr>
</tbody>
</table>
Passive vs. Proactive Diagnostics

- Passive diagnostics sometimes take a while to detect and diagnose the actual cause of the problem.
- Proactive diagnostics can quickly identify the fault and the cause of the fault.

Outdoor-Air Economizer Diagnostician

How to read this chart:

- A fault is indicated for Jan. 5th between 1 and 2 PM.
- The result file indicates "insufficient outdoor air when economizing."
- No faults were detected during the diagnostic.
- Missing data or unfavorable conditions resulted in an inconclusive diagnostic.

Outdoor-Air Economizer Diagnostician - Jan 2013

Day Of Month

1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23 24 25 26 27 28 29 30

Hour Of Day

1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23 24
Proactive AFDD: Air-Side

- **AFDD Capabilities:**
  - Comparing discharge-air temperature with mixed-air temperature (AFDD0)
  - Checking damper modulation (AFDD1)
  - Sensor faults (outdoor-, mixed- and return-air temperature) (AFDD2)
  - Not economizing when RTU should (AFDD3)
  - Economizing when RTU should not (AFDD4)
  - Excess outdoor air (AFDD5)
  - Inadequate outdoor ventilation air (AFDD6)

- **Unique:** Diagnostics algorithms will initiate proactive tests on schedule (e.g., commanding damper, etc.)

- **Energy Impacts:** Energy impacts will be estimated for AFDD3, AFDD4 and AFDD5 faults
Sensor and Damper Diagnostics

![Graph showing various temperature readings and command values over time.]

- **Temperature [°F]**
  - Outdoor-air Temperature
  - Mixed-air Temperature
  - Return-air Temperature
  - Discharge-air Temperature

- **Command [%]**
  - AFDD0
  - AFDD1

- **Time Stamps**:
  - 6:30 PM
  - 6:45 PM
  - 7:00 PM
  - 7:15 PM

- **Values**:
  - 86.49
  - 77.23
  - 81.21
  - 81.40
  - 78.18
  - 82.48
  - 83.13
  - 79.52
  - 0
  - 10
  - 20
  - 30
  - 40
  - 50
  - 60
  - 70
  - 80
  - 90
  - 100
  - 75
  - 77
  - 79
  - 81
  - 83
  - 85
  - 87
  - 89
  - 91
  - 93
  - 95

- **Legend**:
  - Blue: Outdoor-air Temperature
  - Red: Mixed-air Temperature
  - Purple: Discharge-air Temperature
  - Cyan: Damper Postion
  - Green: Return-air Temperature
Economerizer and Ventilation Diagnostics

OA Damper correctly goes to minimum

Outdoor-air Fraction, Status

Temperature [°F], Command [%]

AFDD3
AFDD4
AFDD5
AFDD6

OAF should be at 100% when economizing

No excess OA

Adequate OA ventilation

Outdoor-air Damper

Mixed-air Temperature

Compressor Status

Outdoor-air Temperature (Biased)

Mixed-air Temperature (Unbiased)

Return-air Temperature

Cooling Call

7:30 PM
7:45 PM
8:00 PM

Outdoor-air Temperature

Outdoor-air Fraction
Proactive AFDD Air Side Results

RTU Automated Fault Detection and Diagnostics

- **AFDD6**: Insufficient outdoor air intake
- **AFDD5**: Excessive outdoor air intake
- **AFDD4**: Economizing when not called for
- **AFDD3**: Not economizing when called for
- **AFDD2**: Temperature sensor fault
- **AFDD1**: Outdoor air damper not modulating
- **AFDD0**: Temperature sensor consistency
- **AFDD**: Miscellaneous Faults

Fault: Outdoor air fraction is significantly less than 100% when conditions are favorable of economizing.
Energy Impact: 2.88 kWh/h
Energy Cost Impact: 0.29 $/h
Summary and Next Steps

- Both active and passive diagnostics algorithms have been released as open source – [http://github.com/volttron](http://github.com/volttron)
  - Meet California Title 24 mandatory requirements
- Proactive diagnostics will work with any controller
  - But the open source implementation only includes MOBUS or BACnet drivers
- Many problems with RTUs can be traced back to damper leakage and unreliable sensors
- AFDD has also been integrated with demand response
- Integrating AFDD with advanced controls
- Future of AFDD is bright, lots of action and interest both from public and private sector
Questions?
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SMDS -
http://buildingsystems.pnnl.gov/building/smds.stm

Proactive Diagnostics -
http://buildingsystems.pnnl.gov/building/afdd.stm

Automated RTU DR -
http://buildingsystems.pnnl.gov/building/adr.stm

VOLTTRON - https://transactionalnetwork.org/
http://github.com/volttron