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General Outdoor Air Economizer Fault Detection and Diagnostics Assessment Method

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ABSTRACT

Outdoor air economizers (OAE) control the amount of air drawn into a building in order to reduce energy usage and improve indoor air quality. Air-side economizers are required by energy standards such as ASHRAE Standard 90.1 in many commercial applications because of their energy savings’ potential. However, many economizers do not operate as designed because of damper, sensor, and other faults which can actually lead to greater energy use. Fault detection and diagnostics (FDD) tools have been developed to identify faults when they occur, however, no general methodology for assessing these tools has yet to be proposed. This paper presents and applies a general OAE FDD assessment method. FDD tools described by Seem and House (2009), Schein et al. (2003), and Brambley et al. (1998) are analyzed with respect to various OAE faults. Additionally, these FDD methods are assessed with the method using simulated and experimental data with both single and multiple simultaneous faults.

1. INTRODUCTION

Outdoor air economizers (OAEs) are used to control the amount of outside air drawn into a building in order to reduce energy used to condition air throughout the building and improve indoor air quality. This is achieved using additional sensors and controls that increase the amount of outdoor-air when the outdoor-air temperature or enthalpy can be used to reduce or eliminate mechanical cooling for the building. Because of the potential savings, OAEs are required by energy standards such as 2009 IECC and ASHRAE Standard 90.1 in many commercial applications.

Often times, OAEs can fail to operate properly due to damper, sensor, and other faults present in an air conditioning system (California 2011). When this happens, operational problems may persist over time and energy usage can actually increase. Unlike problems in primary cooling systems, a failure within the economizer may go completely unnoticed for extended periods. Because of this, fault detection and diagnostics (FDD) tools have been developed to identify faults in these systems. Economizer FDD has been the subject of literature for many years, yet no general methodology for assessing their methodology has yet been proposed.

A methodology that is able to assess the effectiveness of an OAE FDD method would help compare the effectiveness of existing tools and facilitate testing of new FDD tools. However, identifying how a specific FDD method performs compared to other methods is a challenge. This is because complete FDD tools involve many processes, so each of these processes should to be assessed in order to measure the overall performance. This paper describes a methodology that can be used to assess the performance of fault detection and diagnostics for OAE applied to rooftop air-conditioners.

Three FDD methods described previously in the literature are tested using the assessment method and their performances are compared. The three methods tested are the Outdoor Air Econo- mizer Module described by Brambley et al. (1998), the Air Handler Performance Assessment Rules (APAR) described by Schein et al. (2003), and an integrated FDD method described by Seem and House (2009). Though not all specifically designed to detect economizer faults, the three methods all include the capability of detecting these types of faults in AHUs or RTUs. For clarity, the three methods will be referred as Methods A, B, and C as follows:
Method A was the most complete tool examined during the study because both fault detection and diagnostics was performed whereas Methods B and C include only detection algorithms. Method A has also been commercialized and used in several existing systems in the field. The tool can be applied to both dry-bulb and differential enthalpy economizers and incorporates occupancy, compressor, and fan scheduling. Furthermore, it is the only method out of the three to include a simple fault impact calculation based on the price of electricity. FDD is implemented in Method A using a logic tree whose branches are traversed using control and sensor data until the operational state of the economizer is determined.

Methods B and C are based on fault detection rule sets that can be applied to AHUs or RTUs using similar logic. The difference between the two methods is that Method B uses a set of rules whereas Method C uses a set of residuals with predefined thresholds to determine whether a fault exists. An example rule from Method C that compares the expected outdoor air fraction when the damper is 100% open with the outdoor air fraction determined from a sensible energy balance is shown in Equation (1),

\[
R_7 = 1 - \frac{MAT - RAT}{OAT - RAT}
\]

where \( R_7 \) is a residual used to detect when operation has deviated from normal. Additional parameters encountered in the methods are estimation of the supply fan temperature rise as well as the supply air set point and minimum outdoor air fraction. Both Methods B and C rely on operational state of the RTU (i.e. heating, economizing, mechanical cooling modes) to determine the systems’ expected behavior and which rules should be applied for fault detection. Fault diagnosis is not described in either Method B or C, so additional algorithms must be used in order to isolate the fault.

2. METHODOLOGY

A complete fault detection and diagnostics package can be broken down into components, each performing a separate task. Figure 1 shows six components that are common to all complete FDD tools which will be used to assess overall performance. These six components are: Configuration, Data Collection, Fault Detection, Fault Diagnostics, Impact Evaluation, and Reporting. Assessing economizer FDD requires a detailed look at each process. The fault detection and diagnostics phases, along with the impact evaluation, can be considered the most important parts of the FDD tool since all the decision making about the state of the system is performed during these steps. Moreover, poorly performing fault detection or diagnostics leads directly to an ineffective tool.

![Figure 1: Steps common to all complete FDD tools.](Image)
In particular, effective economizer FDD should provide some necessary characteristics; this includes detecting the following faults:

- not economizing when it should
- economizing when it should not
- damper not modulating
- excess minimum outdoor air
- inadequate minimum outdoor air
- air temperature sensor faults.

These faults may contribute to poor economizer control, increased energy usage, and decreased equipment life due to increased mechanical cooling runtime. For example, when an economizer brings too much outdoor air into the building with unfavorable conditions, more mechanical cooling or heating is required to compensate. A possible cause of this fault is an outdoor air damper that is not modulating, which can also lead to lost opportunities for economizer cooling when conditions are favorable. Air temperature sensor failures can lead to any of the other economizer faults and also to AHU controller faults like hunting.

Other important considerations are the sensitivity of detecting faults and the frequency of false alarms. These characteristics depend on the fault detection thresholds that can be set a priori or by on-line (e.g., statistical process control) algorithms. A threshold that is set too small may lead to earlier detection of faults, but will also cause false alarms due to the normal random nature of the data being monitored. In contrast, thresholds that are too high may eliminate or delay detection of faults that have a significant impact on performance. In the case of RTUs, smaller thresholds may be possible compared to built-up units due to tighter tolerances associated with manufacturing processes.

Fault detection thresholds play an important role in the effectiveness of an FDD method and in order to compare the FDD algorithms themselves, and not the thresholds, care must be taken to ensure that equivalent thresholds are used. To do this, fault detection thresholds should be developed based on normal operating data for a common piece of equipment. Statistical analysis should be performed on these normal data in order to set the acceptable deviation from normal behavior before a fault is detected. In addition, the expected number of false alarms should be considered when defining the thresholds used to assess FDD performance. Once the fault detection thresholds are developed, they can be implemented within the FDD tools and tested against data containing known faults.

The economizer FDD assessment method can be summarized as follows:

1. Implement FDD methods within assessment tool and connect the methods to the required data.
2. Develop fault detection thresholds using baseline data from RTU and economizer.
3. Implement these thresholds in the FDD methods and test algorithms using data containing known faults.
4. Compare fault detection rates and false alarms rates of the different methods.
5. Compare different algorithms’ diagnostics results.

The use of a common data set puts all of the methods on the same footing and allows direct comparison of performance.

Methods A, B, and C were tested using data collected in laboratory tests on a 5-ton rooftop unit equipped with an integrated economizer (Wichman 2007). Integrated economizers are designed to be packaged and controlled in combination with the mechanical cooling systems (Katipamula et al. 1999). The rooftop unit was installed inside a psychrometric chamber at Herrick Laboratories, Purdue University, to simulate outdoor and indoor conditions. Four temperature measurement grids were used to measure the outdoor air (OA), return air (RA), mixed air (MA), and supply air (SA) temperatures. A dew point hygrometer was also used to measure the moisture content of these air streams as well. ASME standard nozzles were used to measure the supply air flow rate from the rooftop unit. A thermal dispersion measurement systems manufactured by EBTRON was used to determine the outdoor air flow rate.

During testing, the outdoor air damper was modulated manually to control the outdoor air fraction (OAF) at outdoor dry bulb temperatures ranging from 12.78 °C (55 °F) to 46.11 °C (115 °F) and relative humidity from 20% to 100%. The goal of the original testing was to evaluate an economizer FDD algorithm and to develop a MAT correction method, so mechanical heating or cooling was not used during data collection.
The raw steady-state data was then used as the input to high-limit dry-bulb economizer control logic implemented in the code. With high-limit control, the outdoor air dry bulb temperature is compared with an outdoor air set point to determine if the economizer should be in economizer mode. In order to be effective, the OAT must be adequately cooler than the return air stream. This set point temperature often referred as the high-limit or changeover temperature was set to 15.56 °C (60 °F) for all the cases. The return air temperature was kept constant for all the testing conditions at 21.11 °C (70 °F). This provided a temperature difference greater than 5 °C, enough to ensure the outdoor air provides cooling and much greater than the accuracy of the thermocouple measurements.

The resulting control signal from the economizer control logic was the expected outdoor air fraction for the present operating conditions. To estimate the actual outdoor air fraction, a method based on an energy balance described by Friedman and Piette (2007) using low-cost air temperature measurements was used:

\[
OAF = \frac{MAT - RAT}{OAT - RAT}
\]  

After calculating the expected OAF and comparing with the estimated OAF, the data was then passed through the FDD algorithms. For ventilation testing, data in which the expected and estimated OAF were in agreement were classified as fault-free. Conversely, when the actual OAF deviated from the expected, the data was classified as faulty. Additionally, temperature sensor faults were also implemented by adding a constant bias to the data.

3. RESULTS FROM TESTING

The first step required to test the performance of the FDD methods was to implement the algorithms. The developers of Method A provided source code that facilitated implementation within the assessment tool. Methods B and C were programmed using MATLAB based upon descriptions in the published papers. Once the methods were implemented, the thresholds used by the algorithms to determine whether faults exist needed to be defined. To set appropriate thresholds, test data representing normal operation when the outdoor air damper was at its minimum and maximum position were used at a range of outdoor conditions.

In most economizer FDD algorithms, the outdoor air fraction (OAF) determined from an energy balance is compared to what is expected when the outdoor air damper is at minimum or maximum positions. At the maximum opening, the OAF is normally expected to be close to 1. When the outdoor air damper is at the minimum outdoor air position, the OAF should be the same as the minimum outdoor air requirement for the building.

To calculate fault detection thresholds, normal deviation of the outdoor air fraction and temperature measurements are required. To determine this, residuals between the expected OAF and the measured OAF were calculated under normal operating test data for the full range of temperatures. These residuals were calculated for two cases; when the damper was at a minimum outdoor position (10% OA) and wide open (100% OA). The residuals calculated for each of these cases is shown in Figure 2.

The minimum outdoor air residual was calculated using

\[
Min.\ OA = OAF_{\text{min}} - OAF_{\text{calc}}
\]  

where \(OAF_{\text{min}}\) is the minimum outdoor air fraction requirement and \(OAF_{\text{calc}}\) is the outdoor air fraction calculated using Equation (2). In this case, the residual has an average near zero and a range between -0.05 and 0.05. Summary statistics for the residuals are tabulated in Table 1. A tight grouping like this near zero is favorable for FDD because a relative small threshold can be selected with a low expected false alarm rate.

The maximum outdoor air fraction residual, calculated with

\[
Max.\ OA = 1 - OAF_{\text{calc}}
\]  

showed a different outcome that was not at first expected. Though the residuals showed a tight grouping (small standard deviation) as in the minimum residuals, the mean was not near zero. After reexamining the test data and
the experimental setup, it was realized that the outdoor air damper used in the rooftop unit tested had a physical limitation inherent in its design that would not allow it to provide 100% outdoor air. In actuality, the maximum outdoor air fraction that could be provided by the system was $OAF = 0.72$, which agrees with the residuals found. This means that at minimum, a difference between the expected and calculated flow rate greater than 30% must exist before a fault is diagnosed at the 100% outdoor air condition. A possible correction for this is to simply replace the “1” in Equation (4) with 0.72, which would provide a residual with a mean near zero. However, there still are problems with rules comparing the MAT with the other temperature measurements, OAT, RAT, and SAT.

![Figure 2: Residual between the expected outdoor air fraction and the measured for minimum outdoor air and 100% outdoor air. The residuals for the minimum outdoor air position show an average near zero; however the maximum outdoor air residuals show an average closer to 0.3. This is due to the damper’s inability to restrict 100% of the return air due to physical limitations inherent in its design.](image)

The inability of the damper to open full impacts the temperature-based fault detection rules found in different FDD algorithms. With 100% outdoor air, the outdoor air temperature and mixed air temperature should be equal since no mixing with return air is occurring. Likewise, since no mechanical cooling is used when economizing, the supply air should approximately equal the outdoor air temperature with 100% outdoor air. Based on this logic, the temperature residuals calculated with Equations (5) and (6) are applied when the damper should be fully open to identify faults.

$$R1 = MAT - OAT$$  \hspace{1cm} (5)  
$$R2 = SAT - OAT - \Delta T_{sf}$$  \hspace{1cm} (6)

where $\Delta T_{sf}$ is the temperature rise across the supply fan. Thus, when the outdoor air damper is unable to provide 100% outdoor air under normal operation, fault detection and diagnostics rules expecting 100% outdoor air will produce errors, as shown in Figure 3.
Figure 3: Residuals determined using Equations (5) and (6) based on temperature measurements for maximum damper opening. The different markers correspond to different outdoor air temperatures between 12.78 °C (55 °F) to 35 °C (95 °F). The spread is large compared to the OAF residuals since the damper does not fully open and significant mixing occurs between the outdoor and return air in the mixing box of the economizer.

In order to test the three fault detection methods comparatively, equivalent thresholds needed to be implemented for each method. Two different sets of thresholds were tested. The first set used the thresholds recommended by Schein et al. in their description of Method B. The second optimized set of thresholds was based upon the statistical analysis conducted on the residuals that were found using normal operation data. This optimization was developed using a 3σ approach. The actual values of the thresholds used in each case are summarized in Table 2.

Table 2. Thresholds used to test the FDD methods. The recommended thresholds by NIST were obtained in the literature and the optimized thresholds were obtained using a statistical analysis of the normal data.

<table>
<thead>
<tr>
<th>Temperatures [°C]</th>
<th>Minimum OAF</th>
<th>Maximum OAF</th>
</tr>
</thead>
<tbody>
<tr>
<td>Recommended by NIST</td>
<td>±2.0</td>
<td>±30%</td>
</tr>
<tr>
<td>Optimized Thresholds</td>
<td>±0.5</td>
<td>±10%</td>
</tr>
</tbody>
</table>

The first fault considered was not economizing when outdoor air conditions are favorable. This fault may occur when the outdoor air damper is stuck closed or for economizer controller faults. During normal operation, the outdoor air damper should be in a position to allow the maximum outdoor air. To test this, data with an OAT equal to 12.8 °C was tested with various damper positions providing an OAF = 8%, 29%, 55%, and 70%. Under these conditions, false alarms were calculated when a fault was detected when the damper was at its maximum position. The fault detection rates and false alarm rates for this fault are shown in Figure 4 for each FDD method and threshold used.
Figure 4. Comparison of the fault detection and false alarm rates when the thresholds recommended by NIST and the optimal thresholds are applied to the FDD algorithms when the economizer should be economizing but it is not. From this comparison, the three FDD methods show equivalent performance when equivalent fault detection thresholds are applied.

The second fault tested was economizing when it should not be. This fault occurs in systems when the outdoor air damper is stuck too far open or when an economizer controller fault is present. During normal operation, the outdoor air damper should be at minimum position to provide only the required amount of outdoor air for indoor air quality to minimize the mechanical cooling load. To test this fault, data with OAT = 29.4 and 35.0 °C when the OAF = 8%, 29%, 55%, and 70%. A normal condition was simulated with the OAF = 8% for calculation of false alarms. The fault detection rates and false alarm rates for this fault are shown in Figure 5 for each FDD method and threshold used.

The fault detection rates for each of the faults studied show that for equivalent thresholds, the three methods showed equal performance. This is understandable since the rules evaluated or residuals calculated in each method were equivalent. Each method relied on energy balances for the damper at the minimum position and maximum outdoor air positions, and thus the performance was similar for each case studied. The fault detection and false alarm rates are sensitive to the magnitude of the thresholds. The optimized thresholds showed better fault detection rates in each case; however, the false alarm rates were increased slightly. Ideally, the thresholds should be set to eliminate false alarms. However, an FDD system should include fault impact assessment in order to identify when faults are significant enough to repair and it is likely that false alarm conditions would filtered during this step.

Poorer performance was observed for faults associated with missed opportunities to economize due to the inability to fully open the damper for these cases. Since the damper was unable provide 100% outdoor air, the fault detection thresholds determined from the normal residuals at the maximum damper position were high. Because of this, the FDD method was not very sensitive to the outdoor air damper position and required relatively large differences in the expected OAF and measured OAF in order to detect a fault.
Figure 5. Comparison of the fault detection and false alarm rates when the thresholds recommended by NIST and the optimal thresholds are applied to the FDD algorithms for missed economizing opportunities. From this comparison, the three FDD methods show equivalent performance when equivalent fault detection thresholds are applied.

### 4. CONCLUSIONS

Outdoor air economizers can be an effective method to reduce energy and costs for buildings in climates that see cool and dry outdoor conditions throughout the year. Many economizers have been incorporated into buildings and have recently been required by several building energy guidelines. Economizers often do not work properly once installed, so economizer fault detection and diagnostics algorithms have been designed to detect these faults when they occur. A proper economizer FDD method should be able to detect and diagnose the following faults:

- not economizing when it should
- economizing when it should not
- damper not modulating
- excess minimum outdoor air
- inadequate minimum outdoor air
- air temperature sensor faults.

These faults represent those that are most likely to reduce performance of the economizer and possibly increase the actual energy used by the cooling system.

Three economizer FDD methods were studied and their performances at detecting economizer faults were compared. The FDD methods gave comparable results when equivalent thresholds were implemented for the detection of economizer faults. This is due to the similarity in the logic within the methods. The results also showed how the FDD thresholds strongly impact FDD method sensitivity and false alarm rates. It is also important to recognize the physical nature of the system before applying the fault detection rules as the sensitivity of detection can decrease and false alarm rates can increase when rules are applied incorrectly. This was observed for a system whose outdoor air damper was physically unable to provide 100% outdoor air during normal operation.

The inability of the outdoor air damper to provide 100% outdoor air for the test system was not a fault but rather an inherent physical limitation in its design. This problem exists most commonly in economizers built into rooftop air
conditioners and reduced the fault detection sensitivity of the fault detection and diagnostics methods. One approach to handling this condition would be to change the rule for maximum OAF associated with the maximum open damper position. In addition, an independent estimate of OAF would be possible using an empirically derived relationship in terms of outdoor air damper command signal. This would also enable the detection of faults when the economizer is at positions other than minimum outdoor air and 100% outdoor air, which would undoubtedly improve FDD performance.

**NOMENCLATURE**

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
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<tbody>
<tr>
<td>OAT</td>
<td>outdoor air temperature</td>
</tr>
<tr>
<td>RAT</td>
<td>return air temperature</td>
</tr>
<tr>
<td>MAT</td>
<td>mixed air temperature</td>
</tr>
<tr>
<td>SAT</td>
<td>supply air temperature</td>
</tr>
<tr>
<td>OAF</td>
<td>outdoor air fraction</td>
</tr>
<tr>
<td>OAF&lt;sub&gt;min&lt;/sub&gt;</td>
<td>minimum required outdoor air fraction</td>
</tr>
<tr>
<td>OAF&lt;sub&gt;calc&lt;/sub&gt;</td>
<td>calculated outdoor air fraction</td>
</tr>
</tbody>
</table>

**REFERENCES**


Schein, J., Bushby, S.T., House, J.M., & National Institute of Standards and Technology (U.S.), 2003, Results from laboratory testing of embedded air handling unit and variable air volume box fault detection tools.


**ACKNOWLEDGEMENT**

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