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A rule-based fault detection method for air handling units

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Abstract

Air handling unit performance assessment rules (APAR) is a fault detection tool that uses a set of expert rules derived from mass and energy balances to detect faults in air handling units (AHUs). Control signals are used to determine the mode of operation of the AHU. A subset of the expert rules which correspond to that mode of operation are then evaluated to determine whether a fault exists. APAR is computationally simple enough that it can be embedded in commercial building automation and control systems and relies only upon the sensor data and control signals that are commonly available in these systems. APAR was tested using data sets collected from a "hardware-in-the-loop" emulator and from several field sites. APAR was also embedded in commercial AHU controllers and tested in the emulator.
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1. Introduction

Building heating, ventilation, and air conditioning (HVAC) equipment routinely fails to satisfy performance expectations envisioned at design because of problems caused by improper installation, inadequate maintenance, or equipment failure. These problems, or "faults," include mechanical failures such as stuck, broken, or leaking valves, dampers, or actuators; control problems related to failed or drifting sensors, poor feedback loop tuning or incorrect sequencing logic; fouled heat exchangers; design errors; or inappropriate operator intervention. Such faults often go unnoticed for extended periods of time until the deterioration in performance becomes great enough to trigger comfort complaints or gross equipment failure. The term "fault detection and diagnostics" (FDD) refers to mathematical techniques used to detect and diagnose these types of faults.

By identifying and diagnosing faults to be repaired, FDD techniques can benefit building owners by reducing energy consumption, improving operations and maintenance (O&M), and increasing effective control over environmental conditions in occupied spaces. The energy-saving potential of FDD is estimated at 10–40% of HVAC system energy consumption, depending on the age and condition of the equipment, maintenance practices, climate, and building use [1–4]. There are also significant non-energy benefits of FDD. By identifying minor problems before they become major problems, the useful service life of equipment can be extended. Also, repairs can be scheduled when convenient, avoiding downtime and overtime work. Depending on the building use, better control of the temperature, humidity, and ventilation rate of the occupied spaces can improve employee productivity, guest/customer comfort, and/or product quality control.

There are a number of FDD tools that are currently emerging from research [5,6]. In general, these tools take the form of stand-alone software products in which either trend data files must be processed off-line or an interface to the building control system must be developed to enable on-line analysis. A different approach is to embed FDD in the local controller for each piece of equipment so that the FDD algorithm is executed as a component of the control logic. In this case, the algorithm will have local access to sensor data and control signals, eliminating the need to communicate this information over the building control network. This approach is highly scalable and therefore suitable to larger HVAC systems. Any faults that are detected can be reported to the building operator using the building automation system's alarm/event handling capability.

House et al. [7] introduced a rule-based FDD method for air handling units and tested it using simulation and field data. The purpose of the study described here was to extend this work by examining the performance of the FDD method in detecting

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Nomenclature

MT_{max}	maximum number of mode changes per hour
T_{co}	changeover air temperature for switching between modes 3 and 4
T_{ma}	mixed air temperature
T_{oa}	outdoor air temperature
T_{ra}	return air temperature
T_{sa}	supply air temperature
$T_{sa,s}$	supply air temperature set point
ΔT_{min}	threshold on the minimum temperature difference between the return and outdoor air
ΔT_{rf}	temperature rise across the return fan
ΔT_{sf}	temperature rise across the supply fan
Q_{oa}/Q_{sa}	outdoor air fraction = $(T_{ma} - T_{ra})/(T_{oa} - T_{ra})$
$(Q_{oa}/Q_{sa})_{min}$	threshold on the minimum outdoor air fraction
u_{cc}	normalized cooling coil valve control signal [0,1], where $u_{cc} = 0$ indicates the valve is closed and $u_{cc} = 1$ indicates it is 100% open
u_d	normalized mixing box damper control signal [0,1], where $u_d = 0$ indicates the outdoor air damper is closed and $u_d = 1$ indicates it is 100% open
u_{hc}	normalized heating coil valve control signal [0,1], where $u_{hc} = 0$ indicates the valve is closed and $u_{hc} = 1$ indicates it is 100% open

Greek symbols

ε_{cc}	threshold parameter for the cooling coil valve control signal
ε_d	threshold parameter for the mixing box damper control signal
ε_f	threshold parameter accounting for errors related to airflows (function of uncertainties in temperature measurements)
ε_{hc}	threshold parameter for the heating coil valve control signal
ε_t	threshold for errors in temperature measurements

commonly found mechanical and control faults under a variety of weather conditions, system types, and usage patterns. This study also evaluated the feasibility of embedding FDD in commercial HVAC controllers.

2. Methodology

2.1. System description

The fault detection method described in this paper was developed for application to single duct variable-volume or constant-volume air handling units (AHUs). The rules that are used for FDD focus on temperature control in an AHU. Hence, the system description will be restricted to components and control strategies directly related to temperature control. Fig. 1 is a schematic diagram of a typical single duct air handling unit (AHU).

The AHU controller typically controls the supply air temperature to maintain a setpoint temperature at a location in the supply duct downstream of the supply fan. Outdoor air enters the AHU and is mixed with air returned from the building. The mixed air passes over the heating and cooling coils, where if necessary, it is conditioned prior to being supplied to the building. The typical operating sequence for AHUs consists of four primary modes of operation during occupied periods for maintaining the supply air temperature and the ventilation at preset levels. The relationship of the four operating modes to the control of the heating coil valve, cooling coil valve, and mixing box dampers is shown in Fig. 2. Sequencing logic determines the mode of operation as dictated by various thermal relationships including the internal and external loads on the zones served by the AHU.

In the heating mode (mode 1 in Fig. 2), the heating coil valve is controlled to maintain the supply air temperature at its setpoint and the cooling coil valve is closed. The mixing box dampers (outdoor, exhaust, and recirculation air dampers) are positioned to allow the minimum outdoor air fraction necessary to satisfy ventilation requirements. As the outdoor air temperature increases, the AHU transitions from heating to cooling with outdoor air (mode 2). In this mode, the heating and cooling coil valves are closed and the mixing box dampers are modulated to maintain the supply air temperature at its setpoint. As the cooling load continues to increase, the mixing box dampers eventually saturate with the outdoor and exhaust air dampers fully open and the recirculation air damper fully closed, and the AHU changes over to mechanical cooling. When the AHU is operating in one of the mechanical cooling modes (modes 3 and 4), the cooling coil valve modulates to maintain the supply air temperature at its setpoint, the heating coil valve is closed, and the mixing box dampers are positioned for either 100% outdoor air fraction or the minimum outdoor air fraction needed to meet ventilation requirements. There are several different types of mixed air controls, generally the control logic compares the outdoor and return air temperatures or enthalpies to determine the proper position of the mixing box dampers such that mechanical cooling requirements are minimized. Hence, the third primary mode (mode 3) of operation is mechanical cooling with 100% outdoor air and the fourth primary mode (mode 4) of operation is mechanical cooling with minimum outdoor air.

2.2. AHU performance assessment rules (APAR)

The basis for the fault detection methodology is a set of expert rules used to assess the performance of the AHU. The tool developed from these rules is referred to as APAR (AHU performance assessment rules). APAR uses control signals and occupancy information to identify the mode of operation of the AHU, thereby identifying a subset of the rules that specify temperature relationships that are applicable for that mode. The two main mode classifications are occupied and unoccupied. For occupied periods, the modes are further categorized as described previously. For convenience, the operating modes are:

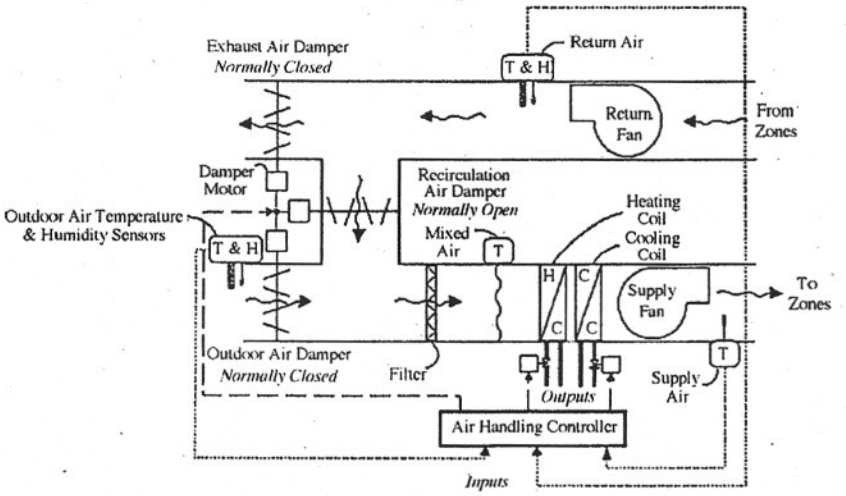

Fig. 1. Schematic diagram of a single duct air handling unit.

- Mode 1: heating,
- Mode 2: cooling with outdoor air,
- Mode 3: mechanical cooling with 100% outdoor air,
- Mode 4: mechanical cooling with minimum outdoor air,
- Mode 5: unknown.

Because the direct digital control (DDC) output to the actuators of the heating and cooling coil valves and the mixing box dampers are known, the mode of operation can be ascertained. Although not depicted in Fig. 2, a fifth mode of operation referred to as "unknown" operation has been defined and listed above. The unknown mode applies to the case in which the AHU is running in an occupied mode, but none of the control output relationships defined for modes 1–4 are satisfied. The unknown mode could be associated with mode transitions and/or with faulty operation such as simultaneous heating and cooling.

Once the mode of operation has been established, rules based on conservation of mass and energy can be used along with the sensor information that is typically available for controlling the AHU. For example, normal operation in the mechanical cooling mode with 100% outdoor air (mode 3) dictates that the outdoor and mixed air temperatures must be approximately equal. Defining T_{oa} and T_{ma} as the outdoor air and mixed air temperatures, respectively, the rule (defined as Rule 10) is written as

$$\text{Rule 10}: \quad |T_{oa} - T_{ma}| > \varepsilon_t$$

where ε_t is a threshold that depends on the uncertainty (or accuracy) of the measurements. The rules are written such that a fault is indicated if a rule is true. In the example above, the rule states that if the outdoor and mixed air temperatures are not the same (i.e., if true) a fault has occurred.

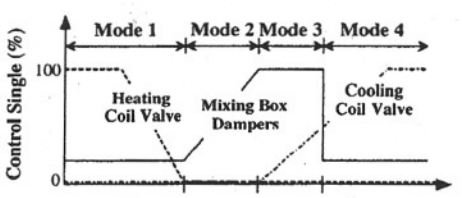

Fig. 2. Typical operating modes of an air handling unit.

As a detailed description of the 28 APAR rules and the reasoning behind them is provided elsewhere [7], the rules are simply listed in Table 1, which groups the rules according to mode of operation. As indicated in the column heading for the rule expression, a true expression indicates a fault. The rules are based on mass and energy balances on various subsystems of the AHU, for example, Rules 1, 7, 11, and 16 treats the relationship of temperatures in the coil subsystem of the AHU for modes 1–4, respectively. For these four rules, only the relational operator in the rules change from one mode to another. A typical rule from this group requires the supply air temperature to be lower than the sum of the mixed air temperature and the temperature rise across the supply fan in the mechanical cooling modes. There are also groups of rules treating the mixing box subsystem, the zone subsystem, economizer operation, comfort requirements, and controller logic/tuning. Hence, although there are 28 rules, in reality only a small number of temperature and control signal relationships are used to define the rules.

APAR does not search for the existence of a specific set of faults. Rather, any fault that causes a rule to be satisfied would be detected and additional effort would be necessary to isolate the source of the problem. In general, the rule set can identify the following faults:

- Stuck or leaking mixing box dampers, heating coil valves, and cooling coil valves;
- Temperature sensor faults;
- Design faults such as undersized coils;
- Controller programming errors related to tuning, setpoints, and sequencing logic;
- Inappropriate operator intervention.

It is typical of APAR rules that several different faults can cause a single rule to be violated. As a consequence, a few simple

Table 1
APAR rule set

Mode	Rule no.	Rule expression (true implies existence of a fault)
Heating (mode 1)	1	$T_{sa} < T_{ma} + \Delta T_{sf} - \varepsilon_t$
	2	For $\lvert T_{ra} - T_{oa}\rvert \geq \Delta T_{min}$: $\lvert Q_{oa}/Q_{sa} - (Q_{oa}/Q_{sa})_{min}\rvert > \varepsilon_f$
	3	$\lvert u_{hc} - 1\rvert \leq \varepsilon_{hc}$ and $T_{sa,s} - T_{sa} \geq \varepsilon_t$
	4	$\lvert u_{hc} - 1\rvert \leq \varepsilon_{hc}$
Cooling with outdoor air (mode 2)	5	$T_{oa} > T_{sa,s} - \Delta T_{sf} + \varepsilon_t$
	6	$T_{sa} > T_{ra} - \Delta T_{rf} + \varepsilon_t$
	7	$\lvert T_{sa} - \Delta T_{sf} - T_{ma}\rvert > \varepsilon_t$
Mechanical cooling with 100% outdoor air (mode 3)	8	$T_{oa} < T_{sa,s} - \Delta T_{sf} - \varepsilon_t$
	9	$T_{oa} > T_{co} + \varepsilon_t$
	10	$\lvert T_{oa} - T_{ma}\rvert > \varepsilon_t$
	11	$T_{sa} > T_{ma} + \Delta T_{sf} + \varepsilon_t$
	12	$T_{sa} > T_{ra} - \Delta T_{rf} + \varepsilon_t$
	13	$\lvert u_{cc} - 1\rvert \leq \varepsilon_{cc}$ and $T_{sa} - T_{sa,s} \geq \varepsilon_t$
	14	$\lvert u_{cc} - 1\rvert \leq \varepsilon_{cc}$
Mechanical cooling with minimum outdoor air (mode 4)	15	$T_{oa} < T_{co} - \varepsilon_t$
	16	$T_{sa} > T_{ma} + \Delta T_{sf} + \varepsilon_t$
	17	$T_{sa} > T_{ra} - \Delta T_{rf} + \varepsilon_t$
	18	For $\lvert T_{ra} - T_{oa}\rvert \geq \Delta T_{min}$: $\lvert Q_{oa}/Q_{sa} - (Q_{oa}/Q_{sa})_{min}\rvert > \varepsilon_f$
	19	$\lvert u_{cc} - 1\rvert \leq \varepsilon_{cc}$ and $T_{sa} - T_{sa,s} \geq \varepsilon_t$
	20	$\lvert u_{cc} - 1\rvert \leq \varepsilon_{cc}$
Unknown occupied modes (mode 5)	21	$u_{cc} > \varepsilon_{cc}$ and $u_{hc} > \varepsilon_{hc}$ and $\varepsilon_d < u_d < 1 - \varepsilon_d$
	22	$u_{hc} > \varepsilon_{hc}$ and $u_{cc} > \varepsilon_{cc}$
	23	$u_{hc} > \varepsilon_{hc}$ and $u_d > \varepsilon_d$
	24	$\varepsilon_d < u_d < 1 - \varepsilon_d$ and $u_{cc} > \varepsilon_{cc}$
All occupied modes (mode 1, 2, 3, 4, or 5)	25	$\lvert T_{sa} - T_{sa,s}\rvert > \varepsilon_t$
	26	$T_{ma} < \min(T_{ra}, T_{oa}) - \varepsilon_t$
	27	$T_{ma} > \max(T_{ra}, T_{oa}) + \varepsilon_t$
	28	Number of mode transitions per hour > MT_{max}

rules can be used to find many different faults. Although a list of candidate faults is provided based on the satisfied rule(s), further information, such as a plot of trend data, is usually needed to identify the specific cause of the fault.

2.3. Operational and design data requirements

APAR uses the following occupancy information, setpoint values, sensor measurements, and control signals:

- Occupancy status;
- Supply air temperature set point;
- Supply air temperature;
- Return air temperature;
- Mixed air temperature;
- Outdoor air temperature;
- Cooling coil valve control signal;
- Heating coil valve control signal;
- Mixing box dampers control signal;
- Return air relative humidity (for enthalpy-based economizers only);
- Outdoor air relative humidity (for enthalpy-based economizers only).

This information is generally available for most AHUs controlled with a DDC system. If one or more sensors are not available, certain rules will no longer be applicable. For instance, in the absence of a mixed air temperature sensor, nine rules (Rules 1, 2, 7, 10, 11, 16, 18, 26, and 27) will be eliminated from consideration in APAR. Conversely, the presence of additional sensors would expand the rule set and provide an opportunity to either detect more faults, or to detect faults during modes of operation in which they would normally be hidden. For instance, if a temperature sensor was installed between the heating and cooling coils, leakage through the heating valve could be detected during the mechanical cooling modes (modes 3 and 4), whereas normally it would be masked in these modes.

In addition to the operational data listed above, certain design data are needed to implement the rules. The required design data are:

- Minimum and maximum values of control signals for the heating coil valve, cooling coil valve and mixing box dampers for normalizing the control signals;
- Percentage outdoor air necessary to satisfy ventilation requirements;
- Changeover temperature from mechanical cooling with 100% outdoor air to mechanical cooling with minimum outdoor air (or equivalent condition for enthalpy-based economizer);
- Description of sequencing/economizer cycle strategy (used to verify that the rules are suitable to a particular AHU installation).

2.4. Threshold selection

In addition to the sensors, control signals, and setpoint information, there are other parameters that must be specified for APAR. For instance, estimates of the temperature rise across the supply fan (and return fan, if one exists) must be provided; a reasonable default is 1.1 °C. A model-based value correlated to the airflow rate or the control signal to the fan could be used as the basis for this estimate; however, some amount of training data would likely be necessary to establish the correlation.

Thresholds used in evaluation of rules such as ε_t in Rule 10 must also be specified. A fault threshold expresses the severity of a fault required to trigger an alarm and is necessary because of uncertainty in the data and operating conditions. If a threshold is too great, the associated fault(s) must be relatively severe to be detected. If, on the other hand, a threshold is too small, normal variation in operating conditions may result in false alarms. These threshold values were determined heuristically for this study.

2.5. Instrumentation accuracy requirements

APAR uses existing sensor points in the control system to perform the fault detection calculations. It has been demonstrated that the typical industrial grade sensors that are already installed for control purposes have sufficient accuracy [8]. Laboratory grade instruments are not required. Higher quality sensors that have been installed and calibrated properly will allow the use of tighter thresholds (less severe faults can be detected) than lower quality sensors, or those that have been poorly calibrated or installed.

3. Results and discussion

3.1. Emulation study

A hardware-in-the-loop emulation environment that combines simulations of a building and its HVAC system with actual commercial HVAC equipment controllers was used in order to conduct tests under a wide variety of controlled conditions. Emulation provides a test environment that is closer to a real building because it uses real building controllers but, like simulation, it also provides controlled and reproducible conditions. Details of the emulator design and operation are documented by Bushby et al. [9]. A variety of sensor, actuator, and control logic faults, along with fault free conditions, were imposed:

3.1.1. Temperature sensor drift

A temperature sensor drift was introduced as a sensor offset for a range of 0.0 to ± 4.0 °C, increased linearly over the emulation period.

3.1.2. Temperature sensor failure

A temperature sensor failure was introduced by disconnecting the leads to the appropriate sensor terminals on the AHU controller.

3.1.3. Stuck valve or damper

A stuck valve or damper fault was introduced by overriding the normal control signal to the damper with a control signal corresponding to the specified position.

3.1.4. Economizer control logic fault

Normally, economizer operation is enabled when the outdoor air enthalpy is less than the return air enthalpy and disabled when the outdoor air enthalpy is greater than the return air enthalpy. This fault was introduced by reversing the logic used to control the economizer, so that economizer operation is disabled when the outdoor air enthalpy is less than the return air enthalpy and enabled when the outdoor air enthalpy is greater than the return air enthalpy. The fan speed and temperature controls operate normally.

Two sets of experiments were conducted. For the first set, a software implementation of APAR was created to process data collected from the emulation [8]. For the second set, the AHU control application programs running in the AHU controllers in the emulator were modified to include logic implementing the APAR algorithm [10]. The following two examples are from the second data set.

3.2. Example: mixed air temperature sensor fault

A mixed air temperature sensor fault was introduced as a sensor offset beginning at 0 °C and increased linearly over the emulation period to +4 °C. The sensor drift was positive, meaning that the measured mixed air temperature was greater than the actual mixed air temperature.

Fig. 3 shows AHU data from the occupied portion of 1 day during the emulation of this fault, which was conducted using cooling season (July) weather data. As is typical for cooling season, the outdoor air temperature and humidity are too high for economizer operation, so the mixing box dampers are positioned to bring in the minimum amount of outdoor air needed for ventilation. The AHU controller modulates the cooling coil valve to maintain the supply air temperature at its setpoint, while the heating coil valve remains closed.

Based on this combination of control signals, APAR determines the system to be operating in mode 4 (mechanical cooling with minimum outdoor air) and evaluates the

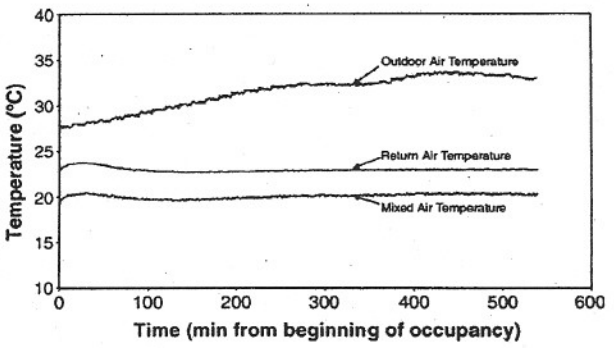

Fig. 3. Emulation study AHU mixed air temperature sensor drift.

applicable rule set. The mass and energy balance on the mixing box subsystem of the AHU yields the relationship that the mixed air temperature should be between the return and outdoor air temperatures. Two of the rules for the mixing box subsystem that apply to mode 4 are Rules 26 and 27. Rule 26 states that if the mixed air temperature is less than the minimum of the return and outdoor air temperatures then a fault has been detected, while Rule 27 will generate a fault report if the mixed air temperature is greater than the maximum of the return and outdoor air temperatures. Both of these rules are subject to a threshold, in this example a value of 1.7 °C was used. Of course, the actual mixed air temperature is always between the return air and outdoor air temperature, since it is the result of blending the outdoor and return air streams. Fig. 3 shows that, due to the sensor drift, the measured mixed air temperature is less than the return air temperature (the minimum of the return and outdoor air temperatures) by approximately 3 °C. Rule 26 is satisfied, indicating that this fault has been successfully detected.

3.3. Example: recirculation damper stuck closed fault

Fig. 4 shows AHU data from the occupied portion of 1 day during the emulation of this fault, which was conducted using cooling season (July) weather data. As in the previous example, the outdoor air temperature and humidity are too high for economizer operation, so the mixing box dampers are commanded to bring in the minimum amount of outdoor air needed for ventilation. The outdoor air and exhaust air dampers operate normally, according to the damper control signal from the AHU controller. However, within the emulation, the recirculation air damper is set to the fully closed position, corresponding to 100% outdoor air. The qualitative effect of the stuck recirculation damper can be seen by comparing the mixed air temperature to the return and outdoor air temperatures. If the dampers were positioned correctly, the mixed air temperature should be very close to the return air temperature, but it is actually much closer to the outdoor air temperature, due to the excessive amount of outdoor air being drawn into the AHU. The AHU controller modulates the cooling coil valve to maintain the supply air temperature at its setpoint, while the heating coil valve remains closed. Based on this combination of control

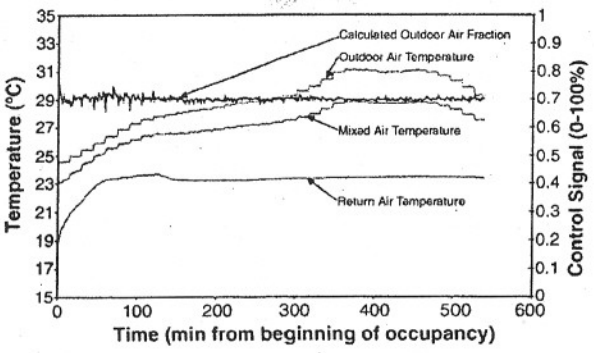

Fig. 4. Emulation study AHU recirculation damper stuck closed.

signals, APAR determines the system to be operating in mode 4 (mechanical cooling with minimum outdoor air) and evaluates the applicable rule set.

One of the rules in the set for mode 4 is Rule 18, which calculates the outdoor air fraction by dividing the difference between the mixed and return air temperatures by the difference between the outdoor and return air temperatures. If the calculated outdoor air fraction is not equal to the minimum amount of outdoor air needed for ventilation, Rule 18 is satisfied, indicating that this fault has been detected. This rule is subject to a threshold, in this example a value of 0.30 was used. Since the difference between the return and outdoor air temperatures is in the denominator, the accuracy of the calculated outdoor air fraction will decrease as the difference between the return and outdoor air temperatures decreases. In order to prevent false alarms, it is necessary to first check whether there is a sufficient difference between the return and outdoor air temperatures in order to proceed, in this example a difference of 5.6 °C is required. Fig. 4 shows that there is a sufficient difference between the return and outdoor air temperatures from approximately 250 min after the beginning of the occupied period until the end of the occupied period. Fig. 4 also shows that the calculated outdoor air fraction is approximately 0.7, which differs from the minimum outdoor air fraction (in this example, 0.15) by 0.55, which is greater than the threshold of 0.30. Rule 18 is satisfied, indicating that this fault has been successfully detected.

4. Field study

A field study was conducted in which AHU data was collected from several field sites [11]. The sites included an office building and a restaurant, as well as community college and university campuses, featuring constant- and variable-air-volume systems. Several examples of faults, which were detected are presented here.

4.1. Example: AHU mode switch fault

Fig. 5 shows a plot of the cooling coil valve and mixed air damper control signals from one of the AHUs examined in the study (the heating coil valve remained closed throughout the time period shown in Fig. 5). Of interest is the 3-h period from 420 min until 600 min after the beginning of occupancy on the day shown in Fig. 5. During this 3 h time span, APAR observes the AHU operating in three different modes: mode 2 (cooling with outdoor air), mode 3 (mechanical cooling with 100% outdoor air), and mode 4 (mechanical cooling with minimum outdoor air). Rule 28, which applies to all modes, counts the number of mode switches per hour. If more than a threshold number of mode switches (in this example, seven) are recorded in any 1-h period, a fault report is generated. In this case, the AHU switched between modes 26 times over the 3-h period, satisfying Rule 28 for each of the 3 h. The building operations staff confirmed that the fault was caused by poor tuning of the temperature control PID loop in the AHU controller.

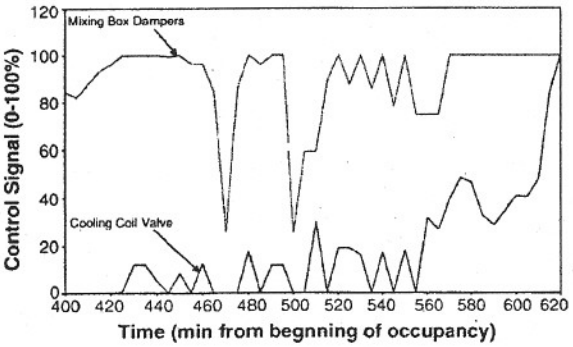

Fig. 5. Field study AHU mode switch fault.

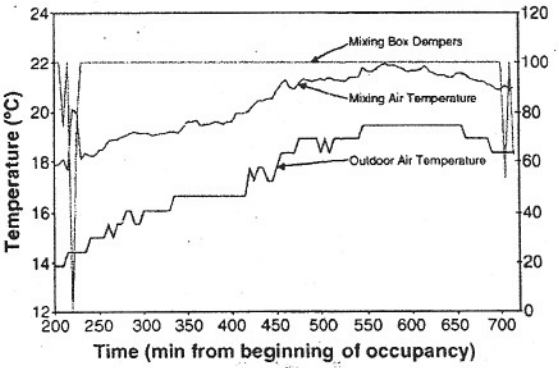

Fig. 7. Field study AHU outdoor air temperature sensor fault.

4.2. Example: AHU supply air temperature setpoint fault

Fig. 6 shows a plot of selected temperature and control signal data from one of the AHUs examined in the study. Based on the control signals (the heating coil valve operation is not shown, but remains fully closed; also the mixing box damper operation is not shown, but remains positioned for minimum ventilation) APAR determines that the AHU is operating in mode 4 (mechanical cooling with minimum outdoor air), then applies the rules for this mode. One of the rules for mode 4 is Rule 19, which states that if the average cooling coil valve control signal is fully open (within a threshold, in this example, 1%) and the difference between supply air temperature and the supply air temperature setpoint is greater than another threshold, in this example 1.7 °C, the cooling coil valve is saturated and a persistent supply air temperature error exists. Fig. 6 shows that the supply air temperature varies from 9 to 13 °C while the supply air temperature setpoint is fixed at 7 °C—an unreasonably low value for this application. Clearly, the supply air temperature error is greater than 1.7 °C, therefore, APAR has detected a fault. Facility personnel confirmed that the fault was the result of inappropriate operator intervention.

4.3. Example: AHU outdoor air temperature sensor fault

Fig. 7 shows a plot of temperatures and control signals from one of the AHUs examined in the study. From 220 min until 700 min after the beginning of the occupied period (approximately an 8 h time span), the mixing box dampers are positioned for 100% outdoor air. The cooling coil valve (not shown) ranges from fully closed to fully open and the heating coil valve (also not shown) remains fully closed. Based on this combination of control signals, APAR places the AHU in mode 3 (mechanical cooling with 100% outdoor air) and evaluates the rules for mode 3. One of these is Rule 10, which states that if the outdoor air and mixed air temperature differ by more than a threshold value, in this example 1.7 °C, a fault has been detected since the outdoor air and mixed air temperature should be the same when the mixing box dampers are positioned for 100% outdoor air. During this time, the mixed air temperature remains approximately 3 °C greater than the outdoor air temperature, satisfying Rule 10. A follow up with facility personnel confirmed the fault and revealed that it was caused by the location of the outdoor air temperature sensor on the roof of the building, remote from the AHU outdoor air plenum.

4.4. Example: AHU simultaneous heating and cooling fault

Fig. 8 shows a plot of the control signals from one of the AHUs examined in the study. During the first 1140 min (19 h) of the day, the heating coil valve varies between 5% and 35% open. Over the same time period, the mixing box dampers vary between 25% and 35% open. This AHU has two separate outdoor air dampers: one allows the minimum amount of outdoor air for ventilation, while the other is for cooling with outdoor air. The mixing box damper position shown in Fig. 8 is

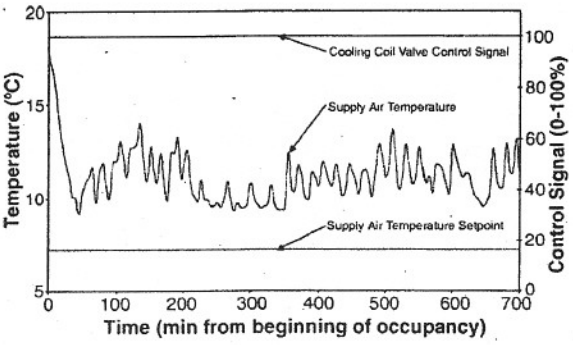

Fig. 6. Field study AHU supply air temperature setpoint fault.

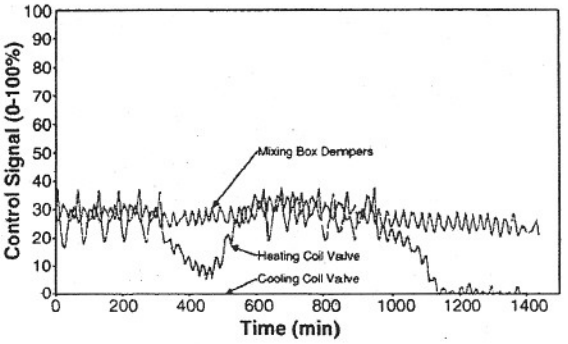

Fig. 8. Field study AHU simultaneous heating and cooling fault.

from the damper for cooling with outdoor air. The cooling coil remains closed throughout the 19 h time period. This combination of control signals is inconsistent with any known mode of operation, so this period of operation is classified as mode 5 (unknown mode of operation) and APAR evaluates the rules associated with mode 5. Rule 23 states that if the average heating coil valve position is greater than a threshold, in this example 1%, and the average mixing box damper position is greater than another threshold, also 1% in this example, then a fault has been detected, since the AHU is simultaneously heating and cooling/economizing. The cause of this fault was a combination of a sequencing logic error and a temperature sensor error related to the specific control strategy implemented in this AHU, in which the cooling coil valve, heating coil valve, and mixing box damper are controlled by independent PID loops, each with independent temperature sensors and setpoints.

5. Conclusions

The increasing performance demands on building automation and control systems, combined with the growing complexity of these systems, has created a need for automated FDD tools. Tools that can be embedded directly in the equipment controllers offer significant advantages over approaches that depend on collecting and analyzing large amounts of trend data. APAR consists of a set of expert rules, derived from mass and energy balances. Control signals are used to determine the AHU's mode of operation, which identifies the subset of the rules to be evaluated. APAR was tested in an emulation study and a field study. Consistent results detecting a variety of common mechanical and control faults show that APAR is effective at detecting these faults and is suitable for embedding in commercial HVAC equipment controllers.

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References

[1] D. Claridge, M. Liu, W.D. Turner, Whole Building Diagnostics, in: Proceedings of the Diagnostics for Commercial Buildings: Research to Practice Workshop, held June 16th & 17th, 1999, Pacific Energy Center, San Francisco, Lawrence Berkeley National Laboratory. Available at: http://poct.lbl.gov/diagworkshop/proceedings/.

[2] M.A. Piette, S. Kinney, P. Haves, Analysis of an information monitoring and diagnostic system to improve building operations, Energy and Buildings 33 (8) (2001) 783–791.

[3] TIAX, Energy Consumption Characteristics of Commercial Building HVAC Systems, vol. III: Energy Savings Potential, Final Report to U.S. Department of Energy, Office of Building Technologies, 2002.

[4] D. Westphalen, K.W. Roth, System and component diagnostics, ASHRAE Journal 45 (4) (2003) 58–59.

[5] J. Hyvärinen, S. Kärki (Eds.), International Energy Agency Building Optimisation and Fault Diagnosis Source Book, Technical Research Centre of Finland, Laboratory of Heating and Ventilation, Espoo, Finland, 1996.

[6] A. Dexter, J. Pakanen (Eds.), International Energy Agency: Demonstrating Automated Fault Detection and Diagnosis in Real Buildings, Technical Research Centre of Finland, Laboratory of Heating and Ventilation, Espoo, Finland, 2001.

[7] J.M. House, H. Vaezi-Nejad, J.M. Whitcomb, An expert rule set for fault detection in air-handling units, ASHRAE Transactions 107 (1) (2001) 858–871.

[8] N.S. Castro, J. Schein, C. Park, M.A. Galler, S.T. Bushby, J.M. House, Results from simulation and laboratory testing of air handling unit and variable air volume box diagnostic tools, NISTIR 6964, National Institute of Standards and Technology, 2002.

[9] S.T. Bushby, N.S. Castro, M.A. Galler, C. Park, J.M. House, Using the Virtual Cybernetic Building Testbed and FDD Test Shell for FDD tool development, NISTIR 6818, National Institute of Standards and Technology, 2001.

[10] J. Schein, S.T. Bushby, J.M. House, Results from laboratory testing of embedded air handling unit and variable air volume box diagnostic tools, NISTIR 7036, National Institute of Standards and Technology, 2003.

[11] J. Schein, S.T. Bushby, N.S. Castro, J.M. House, Results from field testing of air handling unit and variable air volume box diagnostic tools, NISTIR 6994, National Institute of Standards and Technology, 2003.