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Diagnostics for Outdoor Air Ventilation and Economizers

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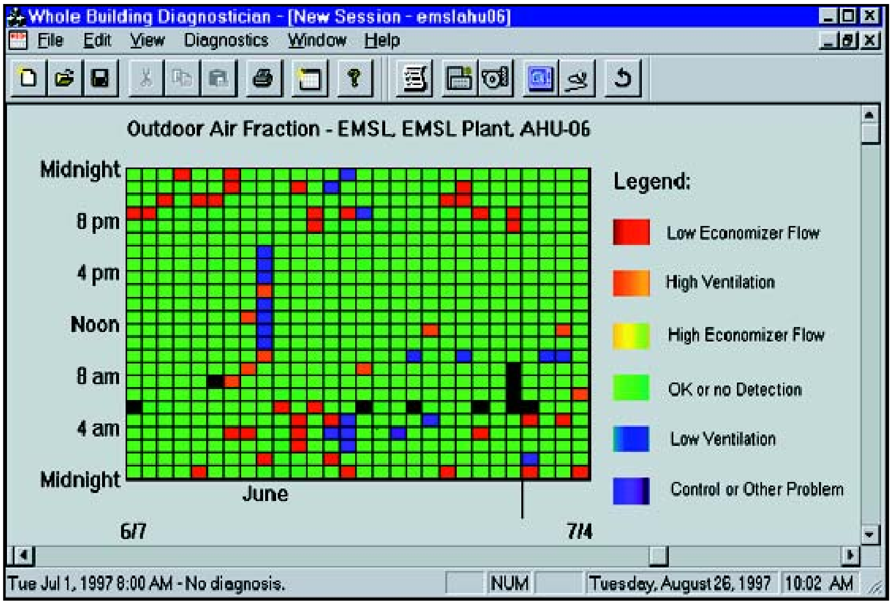

Figure 1: User interface of the outdoor air/economizer diagnostician showing hours of proper operation (green squares) and faulty operation (other colors).

Today, most problems with building systems are detected as a result of occupant complaints or alarms provided by building automation systems (BAS). Building operators often respond by checking space temperatures or adjusting setpoints (or thermostat settings). The root causes of operation problems are often not diagnosed, so problems reoccur and the operator responds by making another adjustment.

When the operator diagnoses problems more carefully by inspecting equipment, controls or control algorithms, it is time consuming and often is based on rudimentary physical reasoning and rules of thumb built on personal experience. Many times a properly operating automatic control is overridden or turned off, when it appears incorrect and possibly the cause of a problem. Moreover, some problems do not manifest themselves in conditions that directly affect occupants in obvious ways and, as a result, go undetected. These problems may, however, affect energy costs or indoor air quality. Furthermore, as performance contracting for services becomes more prevalent, the need for tools to ensure good performance will increase.

With the increased use of building automation and the prevalence of personal computers in the workplace, the computing infrastructure already exists for deploying new automated tools for building operation. The underlying methods for detecting and diagnosing faults in building systems are emerging from research and development efforts. The BACnet™ standard (ANSI/ASHRAE Standard 135-1995, *BACnet™—A Data Communication Protocol for Building Automation and Control Networks*) will contribute to easier implementation by providing a standard mechanism for communication between diagnostic software and devices. The stage is set for practical applications of fault detection and diagnosis to emerge within commercial products to help facility staff detect and solve operation problems and ensure comfortable, healthy, indoor environments, while reducing costs and providing building staff greater job satisfaction.

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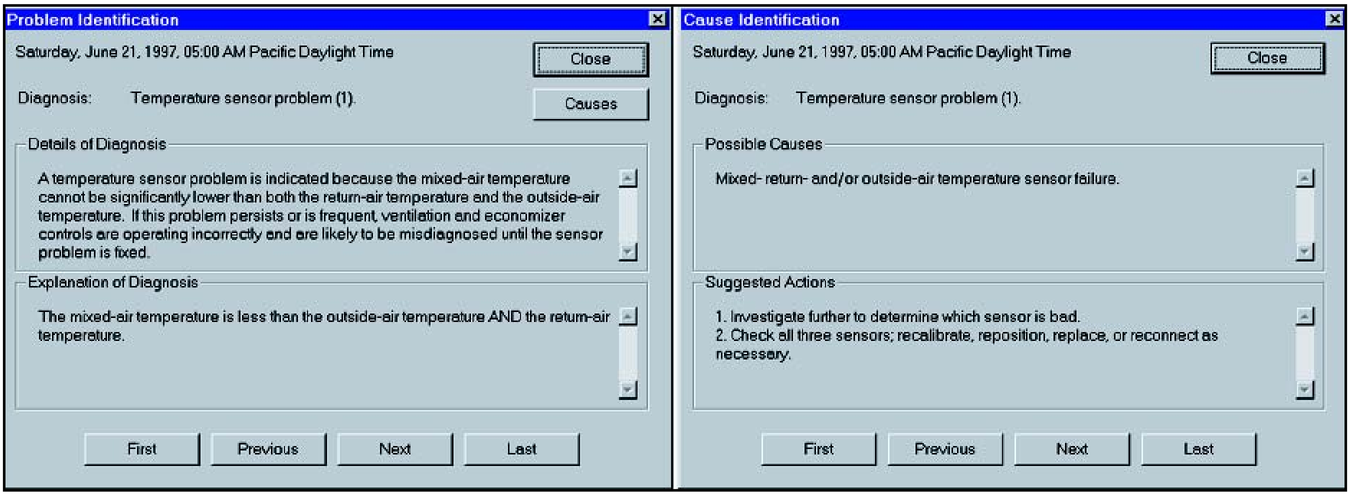

Figure 2: Windows show a description of a problem, a potential cause of the problem and suggested corrective actions.

Early work in diagnostics for building operation focused on the use of expert systems and data visualization for identifying building performance problems.[1, 2, 3, 7] More recently, work in this field has focused on exploring other techniques for automating fault detection and diagnosis[4, 5, 6, 8, 9, 11] and on laboratory testing.[10] These technologies are beginning to move into field testing and should begin to appear in commercially available building automation systems and software for building management in the next few years.

Outdoor Air/Economizer Diagnostician

As part of its mission in commercial building research and development, the U.S. Department of Energy (DOE) in collaboration with industry is developing a tool that automates detection and diagnosis of problems associated with outdoor-air ventilation and economizer operation. The tool, known as the outdoor air/economizer (OAE) diagnostician, monitors the performance of air-handling units (AHUs) and detects problems with outside air control and economizer operation, using sensors that are commonly installed for control purposes.

The current prototype of the OAE diagnostician works on constant-volume systems and variable-air-volume (VAV) systems that do not use volume compensation (i.e., outside-air intake is a constant fraction of the supply-airflow rate). Although still prevalent in the field, uncompensated VAV systems do not satisfy Standard 62-1989 under some conditions; therefore, the OAE diagnostician will provide a warning during set up for such systems. The AHUs may or may not use economizer control. For systems without economizers, the diagnostician detects only ventilation problems, based on ventilation requirements established by ANSI/ASHRAE Standard 62-1989, *Ventilation for Acceptable Indoor Air Quality* or specified by the user during set up. For systems with economizers, it detects both ventilation and economizer operational problems.

The diagnostician currently supports integrated economizer operation, where simultaneous use of the economizer and mechanical cooling is permitted. Economizer control may be based on a dry-bulb temperature differential, an enthalpy differential, a high limit dry-bulb temperature or a high limit enthalpy.

The tool diagnoses the operating conditions of AHUs using rules derived from engineering models of proper and improper air-handler performance. These rules are implemented in a decision tree structure in software. The diagnostician uses data collected periodically (e.g., from a BAS) to navigate the decision tree and reach conclusions regarding the operating state of the AHU. At each point in the tree, a rule is evaluated based on the data, and the result determines which branch the diagnosis follows. A conclusion is reached regarding the current condition of the AHU when the end of a branch is reached.

The building operator or installer of the diagnostician enters data during setup that characterizes each AHU and its control. These data are entered only once, when the diagnostician is configured for the AHU. During operation, the diagnostician uses data collected periodically (e.g., hourly) to detect and diagnose problems with the air handler's performance. The periodically collected data can originate from a BAS, datalogger or other data collection system. All data are stored in a database. As a result, the diagnostician can operate in batch mode, processing many hours or days of data at once, or in (near) real-time, processing data as they are collected.

All data are filtered through a high-low range-checking routine before they are passed on to the diagnostic module. If any variable that is critical for diagnostics is found to be out of range, no diagnosis is provided for the time step. In addition, tolerances are specified for each measured and derived variable. These can be adjusted to increase the detection sensitivity or to decrease the false-alarm rate associated with noise in the measured data.

When the outdoor air, return air and mixed air temperatures are close to each other, the outdoor air fraction cannot be accurately calculated; therefore, no diagnostics are provided when such conditions occur. From the perspective of energy savings, this is not a problem. When outdoor air and return air temperatures are nearly equal, problems associated with the economizer operation are less critical because the energy penalty (or benefit) of using a greater amount of air from one source rather than the other is small. However, problems associated with outdoor air ventilation are still critical under these conditions and can be diagnosed only if the position of the outdoor air damper is measured.

The current prototype detects about 20 different basic operation problems. These problems are associated with:

- Inadequate outside air to meet ventilation requirements, potentially resulting in poor indoor air quality.
- Too much outside air resulting in wasted energy to heat or cool it.
- Economizer operating when it should not or at an outside air intake rate that is too high.
- Economizer not operating when it should or at an outside air intake rate that is too low.
- Control or sensor problems, such as mechanical cooling operating when the economizer is 100% open and the outdoor air conditions are sufficient to satisfy the cooling load without mechanical cooling.
- Incorrect setup of the diagnostician.

The diagnostician uses color coding to alert the building operator when problems occur and then provides assistance in identifying the causes of the problems and in correcting them (see *Figure 1*). The system also provides an explanation of each diagnosis. In some cases the diagnostician can isolate a single cause of the problem. In other cases, it identifies multiple potential causes. When this occurs, the building operation and maintenance staff must distinguish among the causes by inspecting the air-handling unit.

For example, if the diagnostician finds that too much warm outside air is brought in for ventilation, it might identify two potential causes: 1) the outside air damper is stuck open and 2) an air temperature sensor has failed and is causing poor damper control. The diagnostician alerts staff to the problem and directs them to the most likely causes, but the operation staff must still distinguish between these causes by inspection. As a result, a problem that might have gone undetected is found and repair efforts are targeted to the most likely causes. Time is saved, but some intervention by an operator is required. The next version of the OAE diagnostician will isolate the cause of a problem to the one most likely, providing even greater benefits.

As an example, *Figure 2* shows pop-up windows providing a description of a

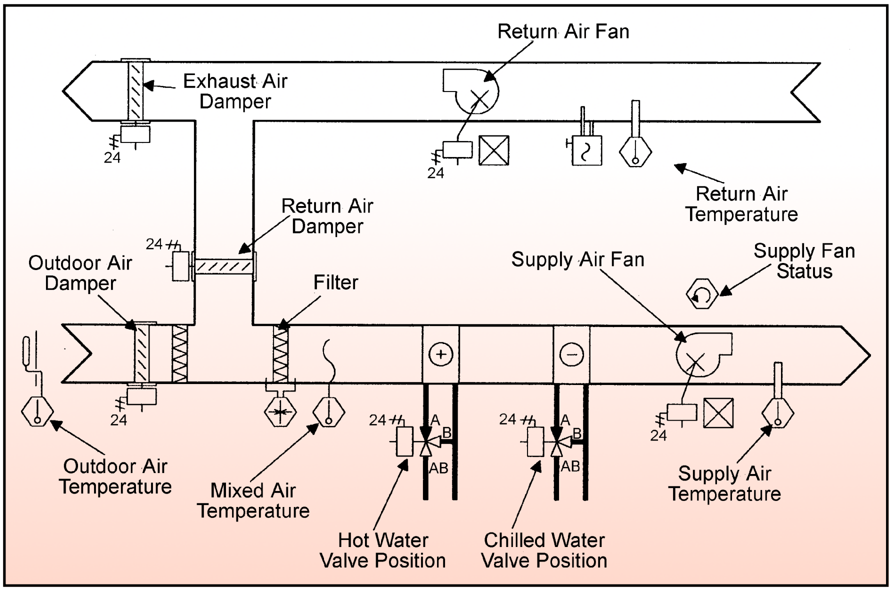

Figure 3: Schematic of an AHU showing the location of measured sensor points.

problem, a potential cause and suggested corrective actions for the purple cell for 5:00 a.m. on June 21, 1997 in *Figure 1*. These windows are accessed by clicking the mouse on the cell and then clicking on the "Causes" button. If other potential causes exist, they can be revealed by clicking on the "Next" button.

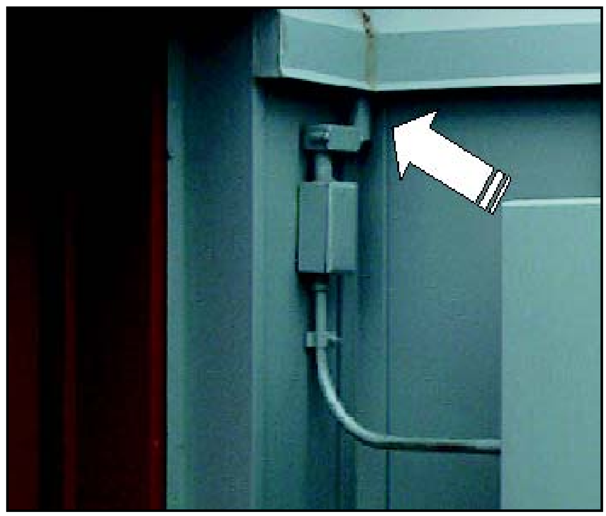

Figure 4: Location of the "failed" sensor.

Building Tests

The OAE diagnostician is presently installed and operating on AHUs in two buildings. The first is the newly constructed and occupied DOE William R. Wiley Environmental Molecular Sciences Laboratory (EMSL) in Richland, Wash. The 200,000-ft² (18,580-m²) building houses laboratories, offices, conference rooms and computer facilities. A commercial BAS provides monitoring and control of the facility using 3,421 sensor points. This building is more highly instrumented than most commercial buildings of similar size, but the data used by the diagnostician are commonly found in buildings with BASs. The diagnostician currently monitors three AHUs in this building. All AHUs are approximately 20-ton (70-kW) cooling capacity.

The second building is the Technical Management Center, also located on the Richland campus of Pacific Northwest National Laboratory. This 72,700-ft² (6754-m²) office building constructed in 1973 has four central AHUs with economizers. A commercial BAS provides monitoring and control of the facility using 420 sensor points. The diagnostician monitors all four AHUs in this building.

For each AHU, data are recorded hourly from BAS sensors for outside air temperature, return air temperature, mixed air temperature, supply air temperature, on/off status of the supply fan, and open/closed status of the chilled water and hot water valves (see *Figure 3*). To minimize problems associated with stratification, the mixed air temperatures for all AHUs are average values of temperatures measured across the cross-section of the duct. No sensors were installed specifically for the diagnostician; all of these data points are used by the BAS for control purposes.

The data are automatically transferred each hour from the BAS to the diagnostician's database, using a dynamic data exchange (DDE) connection. The diagnostician then periodically processes the new data producing diagnostic results that can be viewed on the user interface.

Test Results

Of the seven air handlers monitored, four were found to have problems shortly after initial processing of data. The problems found included a sensor malfunction, return air dampers not closing fully, a mixed air sensor problem, and a chilled-water controller problem. All problems have been confirmed by inspection of the AHUs.

Figures 1 and *2* show some results for AHU-06 in the EMSL building, as an example. This AHU operates continuously 24 hours-a-day. The diagnostician detected a problem with the outdoor air sensor and identified one of the potential causes as a failed temperature sensor. Inspection of the air handler and its sensors revealed that a problem with the outside air sensor did indeed exist. Rather than a failure of the sensor itself, however, the location and installation of the sensor caused it to read incorrect air temperatures. *Figure 4* shows the sensor location. It was located in a non-aspirated tube with the top of the tube sealed and mounted in a corner under an overhang. This arrangement did not allow the air to circulate adequately. When the walls adjacent to the tube were heated by sunlight, the sensor indicated a temperature closer to the wall temperature than the air temperature.

This is shown in *Figure 5*, where the outdoor air temperature indicated by this sensor (O/A AHU-06) reads significantly higher in the morning when it is exposed to direct sunlight, than the outdoor air temperature from a nearby air handler (O/A AHU-10). Because each AHU in this building has its own outside air sensor, this problem can be corrected by simply mapping one of the other outside air sensors to this variable in the BAS.

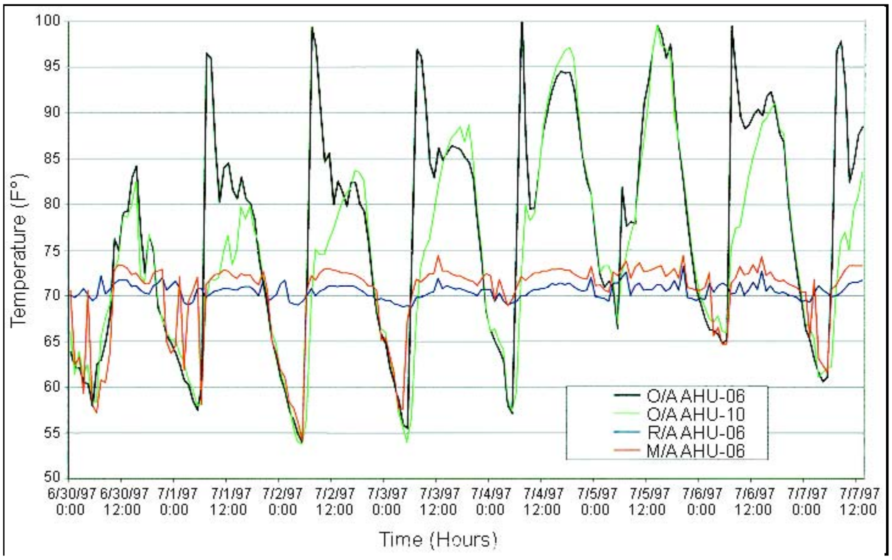

Figure 5: Outdoor air (O/A), return air (R/A), and mixed air (M/A) for AHU-06 and outdoor air temperature of AHU-10.

Figure 6 shows the diagnostician screen for another example, AHU-02 at the Technology Management Center. This AHU also operates continuously (24-hours-a-day). The diagnostician detected that cooling energy was being wasted because the economizer was operating partly closed even when the outside air conditions were favorable for economizing. Inspection of the AHU revealed that the return air damper was not closing completely when the economizer called for 100% outside air. The diagnostician provided this as one of the suggested causes.

Figure 6 also illustrates that the diagnostic results depend on outside and operating conditions. These conditions determine the mode in which the AHU operates and, therefore, whether a problem can be observed or not. For example, when the outside air condition is not favorable for economizing, the damper problem is not apparent, and the cells are green. In some cases, an underlying cause may also manifest as different problems at different times. On Friday, June 27, for instance, the diagnostician identifies (red cells in *Figure 6*) that the economizer should not be at part flow from midnight to 3 a.m. At 4 a.m., the diagnosis changes to purple, in this case indicating that mechanical cooling should not be off (although it is). This apparent problem persists until 9 a.m., when the cells become red again. Later in the day, the cells are green (starting at noon), when conditions are such that a problem is not apparent.

The underlying cause, which is the leaky damper described earlier, has not changed, but the apparent problem that the diagnostician identifies has changed because outside air conditions and occupancy changed. In each case, the underlying problem was one of several identified as possible by the diagnostician (details are not shown in the figure). By observing the diagnostic results over several hours, the operator can infer the most likely cause of the problem. The ability to automatically consider trends to refine the diagnosis, as done manually for this problem, is currently under development.

Discussion and Conclusions

The OAE diagnostician has proven effective in identifying installation and operation problems in AHUs during initial field testing. Furthermore, the small sample of air handlers monitored have confirmed our suspicion in selecting outdoor-air intake control for as our focus—improper installation, control, and operation are common. Four of the first seven AHUs monitored had some type of problem. The results indicate that automated diagnostic technology promises to help identify and eliminate these common problems.

The current version of the OAE diag-

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nostician is a prototype intended to demonstrate the potential for this technology and provide a methodology that ultimately is deployed in different ways. For example, the OAE diagnostician could serve as a tool to support commissioning, routine building operation, or equipment servicing. During commissioning, the diagnostician could help ensure that air handlers are installed and operating properly. It would process data and identify problems, which would be eliminated as part of the commissioning process.

To extend its application to support routine building operation, control system installers or manufacturers could deploy the OAE diagnostician as an embedded part of a control system, BAS, or supervisory software. In this form, the diagnostician would provide on-demand support to building operators or facility managers. Operations staff could access diagnostic results as often as desired to support operation of their facilities.

By monitoring air handler performance and diagnosing problems continuously, the diagnostician would ensure that equipment is maintained and operated properly, providing the equivalent of continuous commissioning. If used at a central location by a manager of several properties or a campus, the diagnostician could process data from several different buildings. This would reduce the frequency of site visits, improve operation and maintenance of air handlers and lower operating costs.

The OAE diagnostician represents only one application of automated diagnostics to building equipment and systems. Diagnostic technology could be used to detect and diagnose problems with many other HVAC components and systems—boilers, chillers, variable-air-volume (VAV) boxes, and thermal energy storage systems, to name a few. Deployment of automated diagnostics and the continuous commissioning that it could provide should help improve building operation, potentially bringing improved comfort, air quality, longer equipment life, and lower costs.

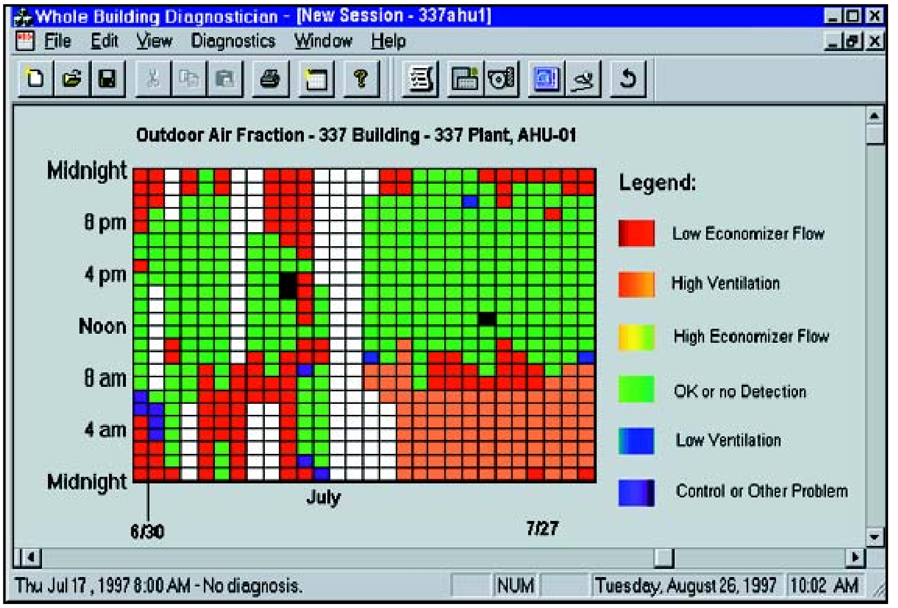

Figure 6: User interface screen for Air Handler 1 in the Technology Management Center, which had a return air damper problem.

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