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Development of Whole-Building Fault Detection Methods

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EXECUTIVE SUMMARY

Building energy systems consume excessive energy due to the use of inefficient control and operational sequences, and the existence of system faults. Theoretical studies and experimental investigations have demonstrated that building energy consumption can often be reduced by 20% and sometimes by up to 50%, and most of the building comfort problems can be solved simultaneously. Optimizing operation of the building energy systems and correcting system control and mechanical faults is one of the most cost effective engineering practices available since the cost of such projects can generally be paid back in less than 3 years from the reduced energy costs.

However, optimizing building system operation and correcting system faults has always been a difficult engineering challenge.

An important step needed to make the optimization of system operation and correction of system faults a business as usual practice is development of cost effective technology to identify system faults and inefficiency at the whole building level, and demonstration of the benefits of these technologies to building owners and engineers. Whole building level fault detection (WBFD) is introduced in this report. This report presents proposed WBFD methods for:

Terminal box reheat valve leakage

Improper minimum terminal box airflow

Improper minimum outside airflow

Poor outside air damper quality

Excessive maximum supply airflow

Improper supply air static pressure

Improper building positive pressure

The report also includes tests of the methods for improper minimum terminal box airflow, improper minimum outside airflow, and poor outside air damper quality. The results of these tests identified significant minimum airflow, outside air intake, and outside air damper faults. With these measured results, building owners and engineers

can see the potential benefits from using WBFD to identify and correct HVAC system faults.

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Introduction

Building energy systems consume excessive energy due to the use of inefficient control and operational sequences [1,2,3], and the existence of system faults [4,5]. Theoretical studies and experimental investigations have demonstrated that building energy consumption can often be reduced by 20% [5,6] and sometimes by up to 50% [7], and most of the building comfort problems can be solved simultaneously [8]. Optimizing operation of the building energy systems and correcting system control and mechanical faults is one of the most cost effective engineering practices available since the cost of such projects can generally be paid back in less than 3 years from the reduced energy costs [10].

However, optimizing building system operation and correcting system faults has always been a difficult engineering challenge. Many investigators have focused on fault detection and development of intelligent optimal control methods for end users [11, 12, 13, 14]. This type of technology holds great potential for the next generation of building automation systems and has found very limited in current building systems since it is still very expensive to implement and subsequently identify the system faults.

An important step needed to make the optimization of system operation and correction of system faults a business as usual practice is development of cost effective technology to identify system faults and inefficiency at the whole building level, and demonstration of the benefits of these technologies to building owners and engineers. This technology will be called whole building level fault detection (WBFD) in this report. This report presents several typical building faults and proposed fault detection methods. It gives implementation procedures and results for selected system faults.

Whole Building Level Faults and Identification

This section presents seven typical HVAC system faults and identification procedures. Two of the seven faults are related to terminal box reheat valves and minimum box airflow. The other five faults treated involve AHU minimum outside airflow, outside air damper quality, maximum supply airflow, static pressure control, and building positive pressure control.

Fault-1: Terminal Box Reheat Valve Leakage

Many of the terminal boxes in buildings are located where they are hard to access and maintain. Reheat coil control valve leakage often causes unnecessary simultaneous heating and cooling energy consumption. For example, 10% water leakage in a reheat coil may increase heating and cooling cost in that zone by 50%. This unwanted heat supplied to the air stream can also cause comfort problems during summer.

To detect this fault, the following procedures are recommended:

- Set room temperature set point to 55ºF using building automation system or manually set room temperature to lowest possible value. This will theoretically shut off all reheat valves since the room temperature is higher than the set point.

- Set the AHU supply air temperature set-point to 55ºF.
- Close all heating coil valves not on terminal reheat coils using the building automation system or manually.
- Follow the procedure below for a two-way valve:
  - Run the hot water pump at 25%, 50%, 75%, and 100% speeds and measure hot water consumption (hot water flow rate and supply and return temperatures)
  - If VFD is not available, run the hot water pump at 100% speed only and measure hot water consumption as above.
- Follow the procedure below for a three-way valve:
  - Control the supply water temperature at 180ºF.
  - Run hot water pump at 100% speed.
  - Measure hot water flow, hot water supply and return temperatures.

For two-way valves, the hot water leakage can be converted into potential annual energy leakage or waste using theoretical models, which may require simulation.

For three way valves, the water leakage through coils can be calculated based on total water flow and supply and return water temperature. Consequently, the energy leakage can be modeled or projected.

Fault-2: Improper Minimum Terminal Box Airflow

The minimum airflow through terminal boxes is a critical parameter affecting indoor air quality, air circulation and energy consumption. If the minimum airflow is higher than required, it often leads to significant simultaneous heating and cooling, in addition to excessive fan power. If minimum flow is less than required, it may cause indoor air quality problems and lack of air circulation. To identify the actual minimum airflow, the following procedures are recommended.

- Set room temperature set point at 85ºF. Theoretically, each box will deliver minimum airflow to the space since the room temperature is higher than the set point. If the minimum heating airflow is different from the minimum cold airflow, this method would not apply. This can be the case in cold climates.
- Close outside air damper

- Control supply air temperature at 55ºF
- Shut off heating water pump
- Run fan at 25%, 50%, 75%, 100%, and the minimum airflow ratio.
- Measure airflow and fan head at each fan speed.

The measured fan airflow can be directly compared with the design value.

The variation of the measured minimum airflow from the design value indicates the terminal box control loop characteristics.

For a pressure dependent terminal box, the test is especially useful to discover excessive airflow under partial load. The benefit of static pressure reset can also be modeled based on the measured data.

Fault-3: Improper Minimum Outside Airflow

Controlling the minimum outside air intake is critical. If it is higher than required, excess energy is used to condition the outside air. If it is too low, IAQ problems appear. When the outside airflow is not monitored and modulated, the outside air intake is dependent on the total airflow. To identify the actual outside air intake, the following procedures are recommended:

- Set room temperature set point at 55ºF so that all terminal boxes should be full open during the experiment.
- Disable the economizer
- Run supply air fan at 25%, 50%, 75%, and 100% and measure
    - Outside air temperature
    - Mixed air temperature
    - Return air temperature
    - Airflow (measure only once)
    - Static pressure at the static pressure sensor location
- Turn off return air fan and repeat last step.

The fan speed can be used represent the percentage of airflow. Based on the temperature measurements, the outside air fraction can be identified at each speed. Using measured airflow, the outside air intake variation with total airflow can be determined.

Fault-4: Poor Outside Air Damper Quality

When an economizer is designed and installed, the outside air dampers often have significant cross sectional area. The air leakage with the damper closed may be higher than the required minimum outside air if poor dampers are used or the mixing chamber has excessive negative pressure. To detect this fault, the following procedures are recommended:

- Set room temperature set point at 55ºF. This will set damper position of terminal boxes at a fixed position during the experiments. Consequently, airflow can be determined based on a one-time measurement and fan speed.
- Close all outside air dampers using BAS
- Run supply air fan at 25%, 50%, 75%, and 100% and measure
    - Outside air temperature
    - Mixed air temperature
    - Return air temperature
    - Airflow
    - Static pressure at the static pressure sensor location
- Turn off return air fan and repeat last step.

The outside air fraction can be determined using the measured temperatures. The outside airflow can be determined from the measured total airflow or the design airflow and the outside air intake fraction.

The worst-case air leakage can be measured by turning off the return air fan.

It should be noted that there must be a significant temperature difference between room air and outside air for this technique to work well.

Fault-5: Excessive Maximum Supply Airflow

For a constant air volume system, excessive maximum airflow often causes the following problems: (1) excessive fan power, (2) excessive cooling and heating, (3) high humidity, and (4) excessive noise.

If the experiments are going to be measured under high building load, the following procedures can be used:

- Measure the zone supply air temperatures
- Estimate the overall system load.
- Measure the room temperature.

If the experiment is not performed at full load conditions, estimate the average zone supply air temperature under full load. The excessive airflow can then be determined based on the average zone supply air temperature and the room temperature based on the following formula:

$$\beta = \frac{T_s - T_c}{T_r - T_c}$$

Where Tr is room temperature, Ts is the measured average supply air temperature under full cooling, and Tc is the design supply air temperature.

In many cases, the actual airflow is higher than the design airflow. To identify the actual airflow, the fan airflow station measurement method [15, 16] may be used:

- Measure the supply air fan speed
- Measure the supply fan head
- Collect the fan curve

The fan curve can be regressed using the following polynomial equation under a selected fan speed.

$$H = a_0 + a_1 Q + a_2 Q^2$$

If the fan is running under partial speed, the fan head is correlated to the airflow using the equation combined with the fan law.

$$H_\omega = \omega^2 (a_0 + a_1 Q/\omega + a_2 (Q/\omega)^2)$$

When both the fan head and the fan speed are given, the fan airflow is deduced as:

$$Q = \frac{\left(-a_1 \pm \sqrt{a_1^2 - 4a_2\left(a_0 - \frac{H_\omega}{\omega^2}\right)}\right)\omega}{2a_2}$$

If the measured fan airflow is higher than the design airflow, the airflow can be adjusted by changing the fan pulley or installing a VFD. This measure can result in significant fan power savings. For example, if the fan airflow is reduced by 20%, the fan power will be reduced by 49%.

Fault-6: Improper Supply Air Static Pressure

For VAV systems, the fan speed is often controlled to maintain the static pressure at the position 2/3 down stream in the main duct at a pre-selected value. This value is often specified by design engineers during the design phase. If this is value is too low, some of the terminal boxes may not be able to provide adequate airflow to the spaces. Therefore, an excessive value is often specified. When excessively high static pressure is used, it creates noise in the terminal boxes, consumes more fan power than necessary, and causes excessive thermal energy use as well. To identify an excessive static pressure set point, the following procedures can be used:

- Measure the static pressure at the sensor location
- Measure the static pressure just before representative remote terminal boxes
- Identify the differential pressure required by the terminal boxes.

If the representative remote box static pressure is higher than the required differential pressure at the terminal box, the static pressure is too high. The potential reduction is the difference between the representative static pressure and the differential pressure required by the box.

To develop the optimal static pressure reset schedule, the required maximum static pressure needs to be identified. The following procedures are recommended.

- Set the room temperature at 55°F. This will force each terminal box to its maximum-open position.
- Measure the static pressure before the representative terminal box
- Measure the static pressure at the sensor location

The maximum static pressure is determined as the difference between the static pressure at the sensor location and the difference between the representative static pressure before the box and the required differential pressure across the terminal box.

Fault-7: Improper Building Positive Pressure

Building positive pressure control is critical for indoor air quality control, moisture damage prevention in humid climates, and building thermal comfort. To identify building positive pressure control problems, the following procedures are recommended:

- Measure the actual building pressure at pre-selected locations under existing operation conditions. Record both supply and return fan speeds.
- Set room temperature at 55°F. This emulates the maximum airflow conditions. Conduct the same measurement.
- Set room temperature to 85°F. This emulates the minimum airflow conditions. Repeat the same measurement.

Experimental Demonstration

To demonstrate the whole building level fault detection procedures, three sets of tests have been conducted using a case study building, including minimum terminal box airflow test, outside air damper quality test and minimum outside airflow test.

The case study building is located in Omaha, Nebraska. It was built in 2001 with a total conditioned floor area of 247,000 square feet (see Figure 1). The major conditioned area is office space. The building is occupied from 8 a.m. to 5 p.m. Monday through Friday. The HVAC systems operate 24 hours per day, seven days a week. The HVAC systems operate in two modes: occupied and unoccupied. The HVAC occupied hours are scheduled from 7:00 a.m. to 5:00 p.m. Other times are defined as unoccupied hours. During system unoccupied hours, the terminal box minimum supply airflow is reduced to zero and the room temperature is maintained at the occupied temperature set point. A total of 223 terminal boxes supply conditioned air to the space.

Figure 1: Case Study Building

The building has two single-duct variable air volume AHUs (MAHUs) for the office areas. Each MAHU has variable frequency drives installed for two supply fans (125hp) and three return air fans (40hp). The supply fan VFD speed is controlled by the duct static pressure set point. Return fan speed is controlled by indirect volume tracking. Each AHU serves both interior and exterior zones. Each MAHU serves half of the building (south and north). The main supply air ducts of the two MAHUs are interlinked in a so-called “donut” shape.

Two centrifugal chillers have been installed (450 ton). Each chiller has one dedicated constant-speed primary chilled water pump (15hp) and one dedicated constant-speed condensing water pump (25hp), respectively. A variable speed drive has been installed on the secondary chilled water pump (40hp).

Ten Gas Fired Pulse Combustion boilers (PHW-1400 size: 1,400,000 Btu/hr) have been installed. A variable speed drive has been installed on the hot water pump (25hp).

Modern DDC control systems have been installed for AHUs, chillers, pumps, and 223 terminal boxes. The boiler has its own control panel, but it can receive global enable/disable commands from the EMCS. The HVAC hourly energy consumption is measured by dedicated meters.

Test I: Minimum terminal box airflow

The minimum terminal box airflow test has been conducted at night (9:00pm) to avoid complaints due to temporary thermal comfort lost. The procedures below have been followed:

- The space temperature is set at 80°F by a global command for 223 terminal boxes.
- Maintain the supply air temperature at 55ºF.
- Keep hot water pump off.
- Minimum flow setting of each box is zero (0) during test
- Override main duct static pressure set point at 0.7 inH_2O and record the total airflow, the duct static pressure and box airflow in one objective box.
- Override main duct static pressure set point at 1.4 inH_2O and record the total airflow, the duct static pressure and one objective box airflow.
- Override main duct static pressure set point at 2.4 inH_2O and record the total airflow, the duct static pressure and one objective box airflow.

Table1: Minimum terminal box airflow test results

AHU1	Fan Speed	Static pressure	Min. Airflow	Observed leakage in one objective box:
	%	inH2O	cfm	Cfm
9:00pm	31.2	0.69	19,731	0
9:18pm	43.4	1.42	27,341	149
9:31pm	56	2.46	34,106	365

Table 1 shows the test results. When the room temperature was reset to 80°F, the terminal box damper returned to minimum position (0% open during unoccupied hour). The total airflow should be zero due to all the terminal box dampers being closed, but the measured results show that the total airflow varies from 19,731cfm to 34,106cfm for the three different duct static pressures used. The test of one leakage box also indicates that the leakage airflow can double when the duct pressure increases from 1.4inH_2O to 2.4 inH_2O. This leads to excessive thermal energy being consumed. Obviously, the minimum airflow is pressure dependent. More thermal energy is used when a higher static pressure set point is used. Based on this result, it is concluded that a significant amount of fan power and thermal energy can be saved if the optimal static pressure reset schedule is used.

Test II: Outside air damper quality

The outside air damper quality test has been conducted on a hot afternoon (4:00pm) to make sure that there is a significant temperature difference between return air and outside air. The procedures below have been followed:

- Close minimum outside air damper and economizer outside air damper using EMCS.
- Override duct static pressure to 0.6inH_2O and record supply fan speed, total airflow, outside air temperature, return air temperature and mixed air temperature.
- Override duct static pressure to 1.3inH_2O and record supply fan speed, total airflow, outside air temperature, return air temperature and mixed air temperature.
- Override duct static pressure to 2.0inH_2O and record supply fan speed, total airflow, outside air temperature, return air temperature and mixed air temperature.
- Calculate the actual outside airflow based on measured data.

Table 2: Outside air damper quality test results

	Fan speed	Static pressure	Airflow	Tr	Toa	Tmix	OA-calculated	% of outside air
	%	inH2O	Cfm	°F	°F	°F	Cfm	
1	27.5	0.52	20013	73.7	99.1	78.50	3,782	19%
2	60.6	1.31	81744	73.5	99.1	77.57	12,985	16%

3	75.5	1.93	117260	73.4	101.0	77.33	16,711	14%

Table 2 shows the test results. The minimum and economizer outside air dampers were both shut off by the EMCS. When the supply fan was running at 27.5% speed, the outside air leakage is about 3,782CFM. When the fan was running at 75% speed, the outside air leakage reached 16,700CFM. The outside air leakage ratio was around 16% for all three measurements, within measurement accuracy. On the day when the test was conducted when the outside air temperature reached 100ºF, the excessive cooling consumption was about 0.96MMbtu/hr at 60% fan speed due to outside air damper leakage. The outside air leakage is more than the design specified minimum outside air requirement.

Test III: Minimum outside airflow

The minimum outside airflow test was also conducted during the outside air damper quality test. The minimum outside air damper is set at 50% open for each supply fan speed. Table 3 shows the test results. With the fixed minimum outside air damper position (50%), the actual outside airflow rate varies from 5,752 CFM to 25,916 CFM for the three supply fan speeds tested. When the fan speed is high, the outside air intake is twice as high as the design specified minimum outside air requirement. Therefore, improved outside air control (and damper repair) will be able to reduce outside air intake by half during summer. Consequently, a significant amount of cooling energy can be saved.

Table3: Minimum outside airflow test results

	Fan speed	Static pressure	Airflow	Tr	Toa	Tmix	MOA	Outside air
	%	inH2O	Cfm	F	F	F	cfm	%
1	27.5	0.52	20013	73.7	99.1	81.00	5,752	29%
2	55.00	1.35	81744	73.5	99.1	79.00	17,562	21%
3	75.5	1.93	117260	73.4	101	79.50	25,916	22%

Conclusions

Seven whole building level fault detection procedures have been proposed. These procedures can potentially identify major system faults, which cause excessive energy consumption and building comfort problems.

Experiments have been conducted to demonstrate three of these fault detection methods. The experiments identified significant minimum airflow, outside air intake, and outside air damper faults. With these measured results, both building owners and engineers can see the potential benefits of optimizing the system control and operation and correcting these faults.

This is a preliminary investigation. The detailed physical and mathematical models for potential project savings and optimal set points need to be developed.

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