RULE-BASED DIAGNOSTIC METHOD FOR HVAC FAULT DETECTION

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ABSTRACT

In a typical computer-based building energy management system (BEMS) for HVAC applications, pertinent variables such as pressure, temperature, fluid flow rate, valve and damper positions and the open/close status of the flow control devices, are measured for control and energy monitoring purposes. In addition to these primary functions, the data from the measurements can also be used to detect the abnormal performance of the HVAC system and possible equipment malfunction.

This paper describes the development of a prototype computerized diagnostic method for the detection of faulty equipment in an HVAC air handling unit (AHU) using sensor data from the BEMS as input. The method uses a computer model of the AHU to compute a set of optimum performance parameters for the AHU under normal operating conditions and compares the parameters with actual values calculated from the measured sensor data. Deviations between the two sets of parameters are an indication of either an out-of-tune system or malfunction of certain equipment. The program will point out to the building operator the source of the fault and the possible cause in a timely fashion. The modeling part of the program is computation intensive and is written in the FORTRAN language. The diagnostic part is rulebased and is written in the symbolic language Prolog for its inference capability. Example case runs are presented to illustrate the proposed method.

INTRODUCTION

Over the past decade, due to the reduction in cost and the greatly increased capability of microcomputers, the application of computer-based building energy management systems (BEMS) to control HVAC systems has increased rapidly. In a BEMS installation, sensors for pertinent variables such as pressure, temperature, water and air flow rate, open/close status of dampers and valves and their positions,etc., are installed at strategic locations throughout the HVAC system and connected to the BEMS. Computer software is used to continuously monitor and control the operation of the HVAC equipment and system through the BEMS based on the inputs from these sensors.

In addition to their function of providing input to the BEMS for the control and operation of the HVAC system,the sensors also provide information to the building engineer and operator on possible malfunctions of HVAC equipment, such as damper or valve sticking, pneumatic actuator air leakage,and setpoint drifting. However, the amount of information provided by the sensors can be considerable, and it is very easy for the operator to overlook information indicating a malfunction. This can cause a delay in discovering the faulty operation in a timely fashion which can result in a degradation of performance due to an out-of-tune control system, or even damage to some related equipment.

This paper describes the development of a prototype computerized diagnostic method for the detection of faulty equipment in a HVAC air handling unit (AHU). The data input to the program are from the sensors used by the BEMS for controls and energy monitoring. The method is divided into two parts. The first part uses the environmental data from the sensors of the BEMS as input to a computer model of the AHU. The model computes the optimum performance parameters of the AHU in terms of the mixed air temperature, supply air temperature, open/close status of the air dampers and steam and chilled water valves and their positions, etc. The second part of the method compare the optimum performance parameters with the actual ones calculated directly from the measured sensor data. The deviation of the actual parameters from the optimum values beyond a specified limit will indicate either an out-of-tune system or a malfunction of certain equipment. The program will point out to the operator the source of the fault and the possible cause of the malfunction. The model part of the program is computation intensive and is therefore written in the FORTRAN 77 language. The diagnostic part of the program is rule-based and is written in the symbolic language Prolog. Prolog was developed for artificial intelligence applications and is well suited for rule-based program.

BACKGROUND OF KNOWLEDGE-BASED SYSTEM

In recent years, knowledge-based expert systems initially developed by the artificial intelligence community, have been applied to a wide range of problems such as medical diagnosis, chemistry, computers and electronics, geology, and business. Expert systems are designed to assist the users with domain specific problems requiring expert knowledge for solution. A knowledge-based program is concerned with the logical relationship among facts. It combines stored knowledge (facts and rules) with an inference procedure to solve a particular problem. By applying deductive reasoning to relevant rules about the relationships among facts and using pattern-matching techniques, a specific goal is satisfied and a solution obtained. Unlike conventional programming languages such as FORTRAN, BASIC, or Pascal, where an algorithm of step-by-step instructions is used to solve a problem,a knowledge-based program declares a number of facts and rules describing the relationship among the facts and asks the computer to find one or all possible solutions to the problem by using the language's deductive reasoning (inference)capability. A review article on the various expert systems developed for different problem areas such as medical diagnosis, chemistry, etc. was given by Buchanan [1],and a brief review of expert systems for applications involving building and HVAC systems was given by Haberl [2]. A recent paper [3] described the development of an expert system for building energy analysis, and another paper [4] described the knowledge acquisition process in the development of an expert system for building energy auditing.

An expert system is generally defined as a system whose knowledge base contains rules that are used by a human expert to solve a problem in his special field of expertise. Some of the rules are supposed to be heuristic in nature, that is, they either do not have a well-understood theoretical basis, or the underlying principle has not been discovered. However, inclusion of heuristic rules is not required for the knowledge-based programming technique to be used for problem solving. If the problem involves mostly the checking of the IF-THEN type rules, a knowledge-based programming approach often results in an easier way to construct and check out rules on an incremental basis, and a shorter program.

Knowledge-based computer programs are commonly developed in a symbolic programming language such as Prolog, Lisp, or OPS5. There are also a number of software programs called expert system shells which facilitate the development of expert systems. A discussion on the merits of each of the language or software is beyond the scope of this paper. For the present work, the Prolog language was used and a commercially available Prolog language compiler for microcomputers was chosen.

AIR HANDLING UNIT MODEL

The AHU model for the prototype program is a single deck, single zone, terminal reheat air handling unit with a dry bulb economizer cycle. The model was developed previously as part of a building emulation computer program for the testing of building energy management systems [5]. The air handling unit consists of a steam preheat valve and coil, a chilled water valve and coil, outdoor, mixed air and exhaust air dampers,and supply and return air fans. Figure 1 shows a schematic of the AHU. The operation of the dampers and the preheat and chilled water valves are controlled by the algorithm for the economizer cycle. The control action of the BEMS that provides input to the AHU are starting and stopping the AHU, closing,opening or modulating the outside air damper, opening and closing of the steam and chilled water valves, and the supply air temperature reset schedule for summer or winter operation. The model uses steady state air enthalpy calculations to determine the amount of energy required for cooling and heating

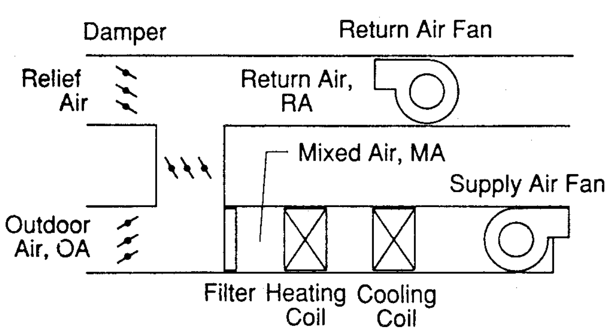

Fig 1. Single-zone air handling unit

by the coils to bring the supply air temperature to the setpoint called for by the resetschedule. The terminal reheat unit brings the zone air temperature to the setpoint of the zone.

Two types of data are required as input to the AHU model. The first type is the characteristic parameters for the unit. These include the supply fan air flow rate, power rating of the fans, minimum outside air requirement, the minimum temperature and the change-over temperature of the economizer cycle, and the capacities of the heating and cooling coils. The parameters are constant for a specific AHU. The other type of data is the time dependent weather data and zone air temperature from the sensors and the seasonal data such as the supply air reset temperature schedules.

The Fortran program used in this work follows the building emulation computer program developed by May and Park [5]. After reading in the sensor data from the BEMS sensor data file at the user specified starting date and time, actual performance of the air handling unit is calculated in terms of the mixed air and supply air temperatures and humidity ratios, flow rates of the outdoor fresh air, return air and supply air, fluid flow rates through the preheat valve and the chilled water valve, heating or cooling energy supplied to the coils, and the position of the dampers and valves. The calculated values are averaged over a ten-minute interval to smooth out any transient spikes in the data. Next, the performance of the AHU when operated at normal and optimal conditions is determined under the same measured outside air and zone air tempera- tures. The opening, closing or modulating status of the outside air damper is determined on the basis of the outside air temperature, the setpoint of the supply air temperature, and the minimum and change-over temperature of the dry-bulb economizer cycle. In essence, if the outside air temperature is below the economizer cycle minimum temperature,the outside air damper is closed or at its minimum outside air position and the preheat valve is opened to bring the supply air temperature to the setpoint of the reset schedule. If the outside air is between the minimum temperature and the setpoint, the outside air damper is to modulate its opening to bring the mixed temperature of the outside air and return air to the setpoint. If the outside air is above the setpoint temperature but below the economizer cycle change-over temperature, the outside air damper is fully opened and the chilled water valve is also opened to bring the supply air temperature to the setpoint. If the outside air is above the change-over temperature, the outside air damper is closed or at its minimum outside air position and the chilled water valve is opened to bring the supply air temperature to the setpoint. As stated in the last paragraph,steady state air enthalpy calculation is used to determine the heating or cooling energy requirement of the coils. The position of the outside air damper is assumed to vary linearly with the percentage of the fresh air through the damper. The position of the valve is assumed to vary linearly with the ratio of the energy requirement to the rated capacity of the coil. Figure 2 shows a schematic of the calculation sequence. Detailed calculation procedure and the equations employed are described in the report by May and Park [5].

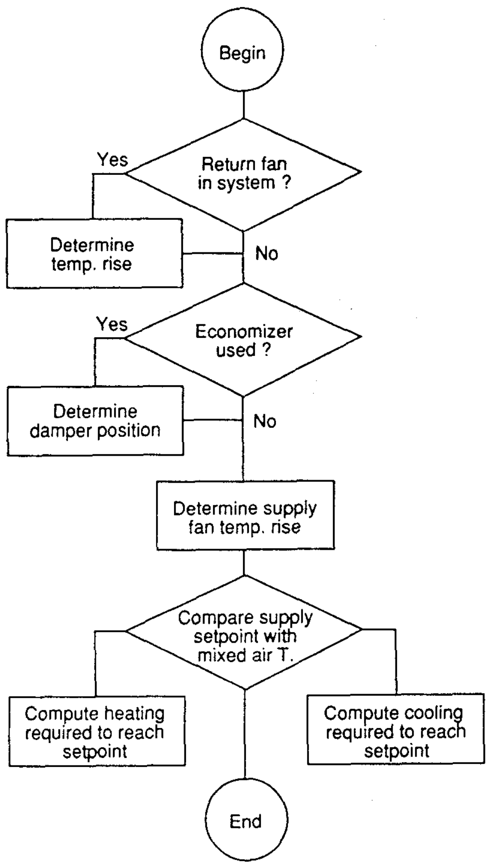

Fig 2. Air handling unit model calculation sequence

Briefly, the procedure to generate the diagnostic data file containing the measured performance parameters and the calculated optimum parameters (through the model) for the AHU is as follows:

1. At the user specified starting date and time, average the sensor data (over a predetermined time period) from the data file produced by the BEMS which monitors and stores data at regular time intervals.

2. Determine the actual performance of the AHU in terms of the mixed air temperature, return air temperature, supply air temperature, supply air flow rate, status of the outside air damper (closed, fully open or modulating) and damper position, status of the preheat valve and position, status of the chilled water valve and position, and steam or hot water flow rate and chilled water flow rate, if sensors for the flow measurement are installed in the BEMS.

3. Based on the measured outside air temperature and zone air temperature and the supply air temperature reset schedule, calculate the optimum mixed air temperature, the amount of outside air flow, the supply air temperature, the status of the outside air damper (closed, fully open or modulating) and damper position, the status of the preheat valve or the chilled water valve and position, and the heating or cooling energy of the coils required by the supply air temperature reset schedule.

4. Output the results from steps 2 and 3 to a database file to be read by the diagnostic program written in the Prolog language as described in the next section. The database file contains set of data for the actual performance parameters at ten minutes intervals based on ten-minute averaged sensor data as well as set of the optimal performance parameters at the same ten minutes intervals.

THE RULE-BASED DIAGNOSTIC PROGRAM

The diagnostic part of the program was written in the Prolog language and consists of IF-THEN type rules. The rules are applied to the two sets of performance parameters (actual and optimum) produced by the FORTRAN program to check the deviation of the actual system from the model. The main quantities checked cover the following items:

1. Operational condition of the fans.

2. Operation and sequencing problems of the outdoor damper, preheat valve, and chilled water valve caused by pneumatic leakage or sticking damper or valves.

3. The mixed air temperature under economizer cycle operation, and any deviation from the optimum value caused by the out-of-tune or out-of-sequence outside air damper.

4. Deviation of the supply air temperature from the reset schedule caused by the out-of-tune or out-of-sequence operation of the outside air damper, the preheat valve, or the chilled water valve.

5. Deviation of the zone temperature from the generally accepted comfort range.

Fan Operation

The operation of the fans are checked by comparing the actual supply air flow rate with the normal air flow rate of the air handling unit. A deviation beyond a certain limit indicates a clogged air filter assembly or a faulty fan motor. The normal supply air flow rate should be obtained during the operation of the system under well-tuned condition, for example, after the air filter is replaced.

Device Sequencing

The sequencing of the devices (outside air damper, the preheat valve and the chilled water valve) is determined by the outside air temperature and the minimum and the change-over temperatures of the economizer cycle. For this paper, the actual control of the devices was assumed to be pneumatic. During normal operation, the opening or closing of each of the devices is at a different range of the actuation air pressure to prevent out-of-sequence operation. For example, the preheat valve may move from fully open to fully closed position as the pressure varies from 6.89 kPa (1 psig) to 41.37 kPa (6 psig), the outside air damper may move from fully closed to fully open position as the pressure ranges from 48.26 kPa (7 psig) to 68.98 k Pa(10 psig), and the chilled water valve may move from fully closed to fully open as the pressure increases from 68.98 kPa (10 psig) to 103.42 kPa (15 psig). The sequence of these devices may be scheduled as shown in the following table:

preheat valve	outside air damper	chilled water valve
open	closed	closed
closed	modulating	closed
closed	fully open	open
closed	closed	open

During abnormal condition, there could be either air leakage into or out of the pneumatic actuator/system, or bending or sticking of the damper or valve stem, resulting in out-of-sequence operation of the devices or an error in the open/close status of the devices. In this program, the method of diagnosing abnormal operation of the devices is to compare the normal statuses (open/close) of the devices as predicted by the model with that of the actual measured statuses. Any deviation from the normal status will trigger one of the rules in the program's knowledge-base. The rule will decide the kind of malfunction and point out the possible source as well as consequence of the malfunction on the equipment.

Figure 3 shows an example of the way the rules check for the operation of the outdoor air damper and the preheat and chilled water valves, when the normal (optimum) position of the outside air damper is supposed to be closed. The closing of the outside air damper during normal operation indicates two possibilities, that is, the ambient temperature is either below the minimum temperature or higher than the change-over temperature of the economizer cycle. The diagnosis is started by looking at the status of the actual outside air damper position. The status can either agree or disagree with the normal status. If the two agree, the next item, the status of the preheat valve, is examined. The normal status can be either open (heating case) or close (cooling case). If the actual status agrees with the normal one, the third item, the status of the chilled water valve, is examined. Again the normal status can be either close (heating case) or open (cooling case). If the actual status agrees with the normal one, it can be concluded that the sequencing of the devices operates correctly, and a message to the operator can state as such. Otherwise, the deviation can be at one of the three levels or devices (outside air damper, preheat valve, or chilled water valve). The first level is that the actual outside air damper is open. There are two possible cases depending on whether the normal operation of the AHU is in heating or cooling mode. Each case is described below:

1. For the heating case, the status of the actual preheat valve is examined to see if it agrees with the 'open' status of the valve under normal operation. If it does, a message is given to the operator that the outside air damper is stuck open and unnecessary heating of cold outside air is happening. If the status of the actual preheat valve does not agree with the normal status and is closed, the outside air temperature is then examined to see if it is below the coil freeing temperature, and a corresponding message is given to warn the operator of either a sticking outside air damper as well as a sticking preheat valve, or additionally, the possibility of coil freezing. The latter is more serious and requires immediate attention from the operator.

2. For the cooling case, the normal status of the preheat valve should be 'close' and that of the chilled water valve should be 'open'. If the actual status of the preheat valve disagrees with the normal, a message is given to indicate a stuck open outside air damper, a stuck open preheat valve and unnecessary heating under cooling mode. If the actual status of the preheat agrees with the normal, then the actual status of the chilled water valve is examined. If it is open, a message is given for a stuck open outside air damper and unnecessary cooling of excess hot outside air. If the actual chilled water valve is closed, a message is given to indicate that a stuck open outside air damper and a stuck closed chilled water valve will result in a zone air temperature above the comfort range. The zone air temperature is examined and the value is shown to the operator.

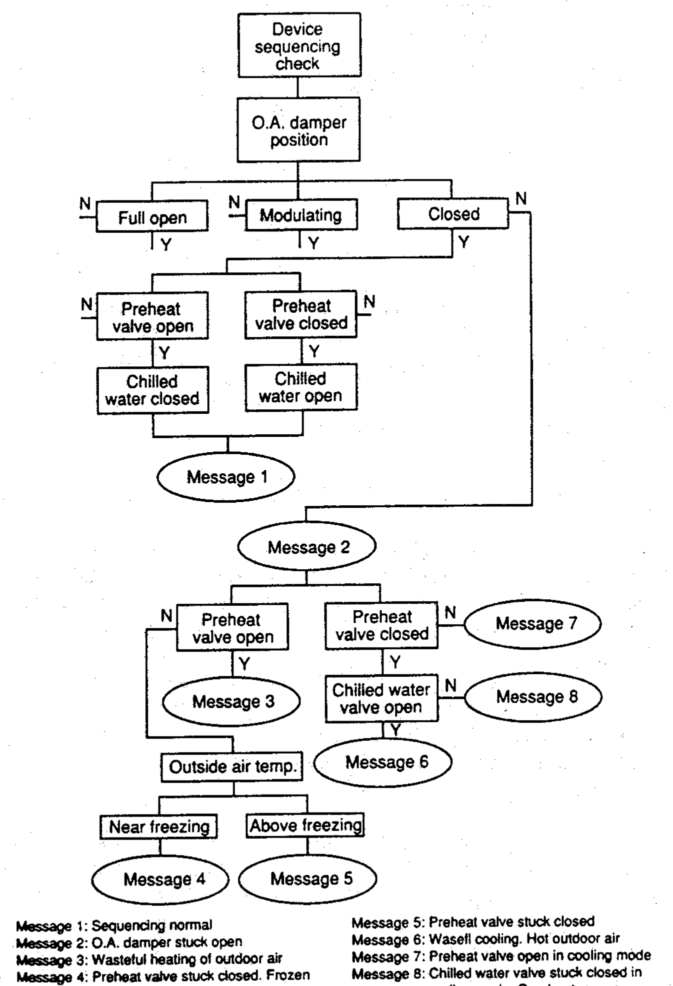

Fig 3. Diagnostic device sequencing check when O.A. damper should be closed under normal operation

In the Prolog language, the above description for Fig. 3 is coded as the following rules in the knowledge-base:

```
check_sequence(_,Odm,0,Hvm,Hvn,Cvm,0) if
  Odm<=0.05,Hvm>0,Hvn>0,Cvm<=0.05,
  write("Heating mode - sequencing normal").
check_sequence(_,Odm,0,Hvm,0,Cvm,Cvn) if
  Odm<=0.05,Hvm<=0.05,Cvm>0,Cvn>0,
  write("Cooling mode - sequencing normal").
```

```
check_sequence(_,Odm,0,Hvm,Hvn,_,_) if
  Odm>0.05,Hvm>0,Hvn>0,
  write("O.A.damper stuck open - heating of cold
  outside air").
check_sequence(Toa,Odm,0,Hvm,Hvn,_,_) if
  Odm>0.05,Hvn>0,Hvm<=0.05,
  write("O.A.damper stuck open and preheat valve
  stuck closed"),
check_freeze(Toa).
check_sequence(_,Odm,0,Hvm,0,_,Cwn) if
  Odm>0.05,Hvm>0.05,Cwn>0,
  write("Cooling mode - both O.A.damper, preheat
  valve stuck open").
check_sequence(_,Odm,0,Hvm,0,_Cwn) if
  Odm>0.05,Hvm<=0.05,Cwn>0,
  write("O.A.damper stuck open - cooling of hot
  outside air").
check_sequence(_,Odm,0,Hvm,0,Cwm,Cwn) if
  Odm>0.05,Hvm<=0.05,Cwn>0,Cwm<=0.05,
  write("O.A.damper stuck open. C.W.valve stuck
  closed.- Overheat of zone air possible").
check_freeze(Toa) if Toa>34.
check_freeze(Toa) if
  Toa<=34, write("Outside temp.below 34 F - possible
  frozen coil").
```

In this example, 'check_sequence' is the predicate for the rules to check the proper open or close status of the outside air damper and the valves. The arguments in the parenthesis represent the outside air temperature and the status of the devices (O.A. damper, pre-Heat valve, and chilled water valve) for both the actual system and the optimum status under normal operation. A 0 (zero) indicates 'close' and a 1 (one) indicates 'fully open', with values between 0 and 1 indicating 'partial open'. For the actual system, anywhere less than 5% (0.05) opening is taken as closed. The messages are self-explanatory. The predicate 'check_freeze' is for the rules to check the outside air temperature for the possibility of freezing of coil. The symbol '_' in place of an argument indicates a dummy argument.

From the above example, it is seen that it is fairly easy in the Prolog language to code the rules which branch out in a tree type structure. The sequential placement of the rules is not required but is convenient for debugging and for checking of missing rules. Any rule that governs a special situation can be added or deleted without disturbing the rest of the rules. The rules for checking the sequencing of the devices under the other two top branches in Fig. 3 are added and coded in the same fashion and are not shown. If some special combination of the faulty status may never happen in practice, it need not be coded. For example,if the chance of all three devices getting stuck in the wrong status at the same time is remote, then that rule is not included.

Mixed Air Temperature

In an AHU with economizer cycle, the mixed air temperature is determined by the percent opening of the outside air damper. Correct opening of the damper will give the maximum possible free cooling of the supply air under the algorithm for the economizer cycle. To check the operation of the outside air damper, the value of the actual mixed air temperature is compared with the optimal computed value from the model. Since the model uses the actual outdoor and zone air temperatures to arrive at the optimal value, a deviation of the actual and computed value beyond a specific tolerance indicates an improperly operating outdoor air damper. If the damper is operating out of sequence, a rule in the knowledge-base will confirm the abnormal operation by printing out value of the actual deviation.

Supply Air Temperature

In the AHU, the supply air temperature is determined by the supply air reset schedule and is dependent on the outside air temperature or the zone air temperature. In the model, the same reset schedule is used to compute the supply air temperature. Therefore, a deviation of the actual supply air temperature from the computed value beyond a specific tolerance indicates an out-of-tune preheat or chilled water valve. The diagnostic program will send a message to the operator on the amount of the deviation, which, when combined with the message from the device sequencing check, points out to the operator the device that causes the abnormal operation.

Zone Air Temperature

For a HVAC system with terminal zone reheat as used for the prototype diagnostic system described in this paper, the zone air temperature is usually determined by the reheat unit when the system is in the heating mode. If the zone air temperature is above or below the comfort range and the supply air temperature does not indicate abnormal deviation from the reset value, and the system is in the heating mode, the reheat unit is usually at fault. Also, if the system is in the cooling mode and the supply air temperature shows no abnormal deviation and yet the zone air temperature is above the comfort limit, the reheat unit is providing heating unnecessarily. However, if the system is in cooling mode, the zone air temperature is above the comfort range and the supply air temperature is above the specific tolerance of the reset schedule, the chilled water supply temperature and the percent opening of the chilled water valve are compared with the normal values to determine the possible source of the zone overheating.

In all the diagnostic checks discussed above,some of the data required may not be included in a particular BEMS installation. For example, if the chilled water temperature or the chilled water flow rate is not instrumented in the BEMS, the exact cause of the zone overheating during cooling mode with the supply air temperature above a specific tolerance would not be ascertained, and the message to the operator would be 'possible chilled water valve or terminal reheat unit malfunction'. In general, the more sensor data from the BEMS, the more specific are the rules that can be put into the knowledge-base to pinpoint the trouble area in the AHU.

It should be pointed out that all the rules in this prototype development are for the detection of fault only. No rules for the repair of the faulty equipment were developed. Knowledge from service manuals for the specific equipment as well as expert knowledge from repair technicians are required to develop those rules. However, if those rules were developed, they could easily be included in the above developed knowledge-base to extend the program into a diagnostic and repair program.

EXAMPLE CASES

Several example cases were run to evaluate the fault detection method presented in this paper. In each case, abnormal operation or abnormal deviation in temperature or device sequencing was imposed on the AHU in order to test the ability of the program to diagnose the faulty condition. The results of the example case runs are shown in Figure 4.

Case 1 shows an example of the AHU in summer operation with the outside air damper stuck in the open position when the outside temperature was above the change-over temperature of the economizer cycle. In addition, the chilled water valve was out of tune as indicated by the below normal supply air temperature. Case 2 shows an example of an out-of-tune chilled water valve causing overheating as indicated by the zone air temperature being out of the comfort range. Cases 3 and 4 show examples of winter heating season problems with outside air damper malfunction causing possible coil freezing.

From the above examples, it is seen that the diagnostic method is able to detect the planted faults in an AHU with messages easily understandable to the operator. The only requirement is that the pertinent sensors and transmitters be in place in the BEMS. Modification to the model would make the program applicable to other types of air handling unit such as dual duct,VAV, controlled humidity, etc.

Example case 1:

Supply fan operating.
O.A. damper stuck open w/outside temp. at 72 F.
Supply air 52 F - more than 3 F below setpoint.
---The actual difference is 8 F below setpoint.
Zone temp. 78 F - within comfort range.

Example case 2:

Supply fan operating.
Supply air 50 F - more than 3 F above setpoint.
---The actual difference is 5 F above setpoint.
Zone temp. 85 F - above the 82 F comfort limit.
Chilled water valve opening smaller than normal.
---Possible air leak in pneumatic control.

Example case 3:

Supply fan operating.
Preheat on - O.A. damper should be closed but was stuck in open position.
Supply air within 3 F of the 73 F setpoint temp.
Zone temp. 68 F - within comfort range.

Example case 4:

Supply fan operating.
Preheat valve should be open but is stuck closed.
---With outside air 33 F, frozen coil possible.
Supply air 33 F - more than 3 F below setpoint.
---The actual difference is 42 F below setpoint.

Fig 4. Example diagnostic case runs

CONCLUSIONS

A computerized method for fault detection in an AHU using a combination of the programming language FORTRAN and the knowledge-based programming language Prolog has been presented. By using the existing sensor and transmitter data from the building energy management system, two sets of parameters relating to the performance and operational status of the various flow control devices in the AHU are derived in the FORTRAN program. One set of the parameters is derived through a model of the AHU operating under normal and optimal conditions, and the other set is calculated from the actual sensor data. By comparing the actual performance parameters with those computed by the model, using a set of rules in the knowledge-based Prolog program, the method is able to diagnose out-of-tune operation of the AHU and the out-of-sequence operations of the flow control devices. By using the FORTRAN program to calculate and reduce the sensor data into pertinent parameters and the knowledge-based Prolog program to analyze the performance, the advantages of the computational ability of the FORTRAN language and the inference ability of the Prolog language in selecting appropriate rules are both utilized.

The method is applicable to any HVAC system that has built-in sensors and transmitters for monitoring or control purpose. The program developed in this paper is for the detection of faults only. However, additional knowledge and rules on the repair of faulty equipment when obtained from the service manuals and expert service technicians could be coded into the Prolog program to make the programs a combined diagnostic and repair expert system.

ACKNOWLEDGMENT

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