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# Application of Fault Detection and Diagnosis Techniques to Automated Functional Testing

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## ABSTRACT

*Extensive research in the field of fault detection and diagnosis has produced useful tools and techniques that have been applied to continuously operating building HVAC systems. A few researchers have applied some of these to commissioning of new buildings. This paper reports on a project that adapted or developed models of air-handling unit components and controls and combined them into an automated functional testing tool. Operation of the tool is demonstrated in testing a real air-handling unit.*

## FAULT DETECTION AND DIAGNOSIS METHODS

Faults in the sensors of a control system can be detected by the addition of redundant sensors, often called *hardware redundancy*. This approach utilizes several sensors to measure the same variable. A fault in one sensor is detected when its reading varies sufficiently from the mean readings of the other sensors. Such redundancy is expensive and can become quite complicated. For some time researchers have been investigating the concept of automated fault detection and diagnosis (FDD) of HVAC systems (Hyvarinen and Karki 1996). In this concept, HVAC systems that have direct digital control (DDC) systems can be programmed to search for, detect, and diagnose problems in the control system itself or in the HVAC system. In FDD, models of the process provide *analytical redundancy* (Patton et al. 1989; Braun and Rossi in Hyvarinen and Karki 1996). Analytical redundancy replaces hardware redundancy with dissimilar sensors measuring different variables, but which are functionally related by the state of the system. The application of FDD to HVAC systems has been studied extensively under the sponsorship of the International Energy Agency (IEA) Annex 25 (Hyvarinen and Karki 1996) and

Annex 34 (Dexter and Pakanen 2001). Norford et al. (2000) tested two types of FDD schemes with both known and unknown faults using the systems at the Iowa Energy Center's Energy Resource Station (IEC ERS), the location of the automated functional tests described in this work.

The fault detection and diagnosis work has been focused on identifying changes in a system as it operates over extended time periods. Thus it can be considered a form of commissioning on a continuous basis. The goal of finding faulty operation is the same, although the types of faults and the methods may differ. Some researchers (Dexter et al. 1993; Haves et al. 1993) have applied portions of the FDD theories to the commissioning process. Salsbury and Diamond (1999) presented the results of an automated commissioning test on a simulated dual-duct air-handling unit. This paper describes another application of the use of models based on first principles to the functional testing of an air-handling unit.

Faults in a system can be detected and diagnosed by comparing the values of output variables against a set of rules that establish the values expected under various combinations of input variables for both correct and faulty operation. This method is relatively easy to develop and operate, but it has the distinct disadvantage that it cannot deal with unexpected conditions or faults that are not anticipated in the rules. Model-based fault detection and diagnosis uses reference models of the system or components to provide analytical redundancy. Values of output variables read from the system are compared with reference values predicted by the models. Differences between the two, termed *innovations* in FDD work but labeled *deviations* in commissioning work, are indicators for detection of faulty operation (Figure 1).

Two broad approaches to model-based FDD have emerged from the research. One uses "black box" models such

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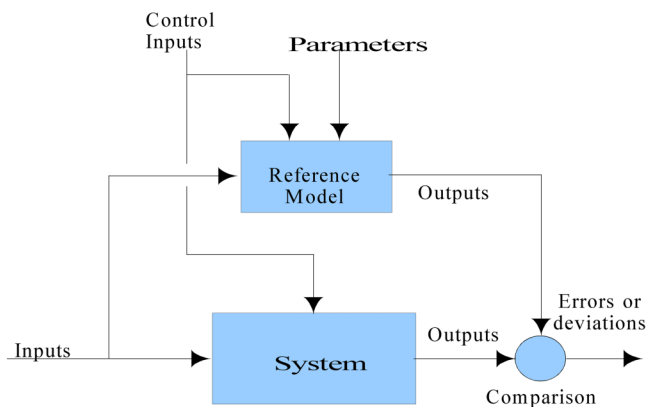
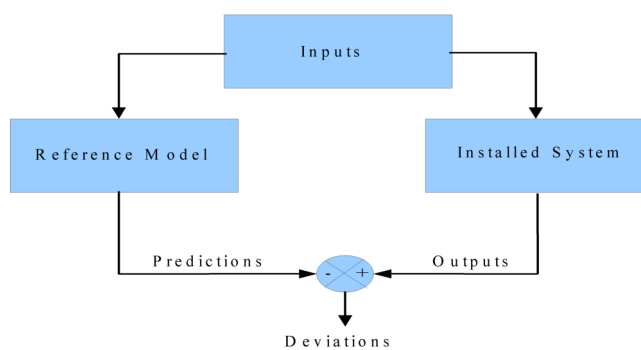**Figure 1**  *Information flow diagram for reference models.*



**Figure 2**  *Detection of faults using first principles models and design intent parameters (Salsbury 1996).*
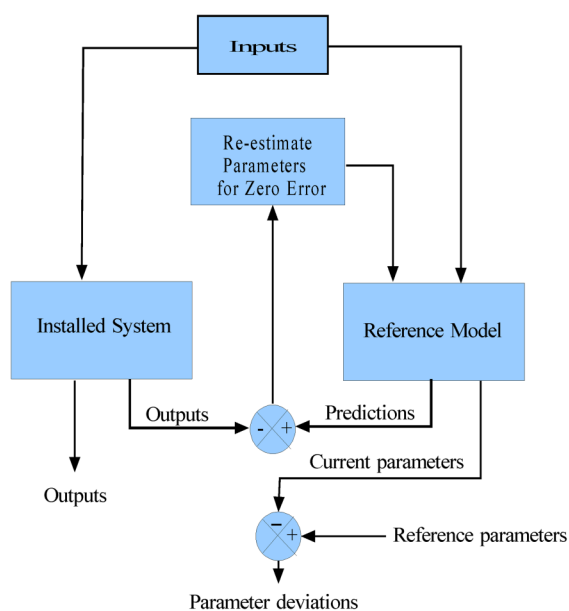


**Figure 3**  *Diagnosis of faults by parameter re-estimation (Salsbury 1996).*



**Figure 4**  *Fault diagnosis by expert rules.*

as neural networks. These models do not require prior knowledge of the physical relationships of the system but do require inputs from a correctly operating system to "train" the model so that subsequent incorrect operation is detectable. The models are only valid over the range of training data and cannot extrapolate outside this region.

The second approach uses mathematical models derived from known physical relationships, or first principles. Parameters for these models, if identified from design information, enable the model to represent the engineering design intent as the correct operation standard. Differences between values of model output variables and system output variables indicate incorrect or faulty operation. Figure 2 is an information flow
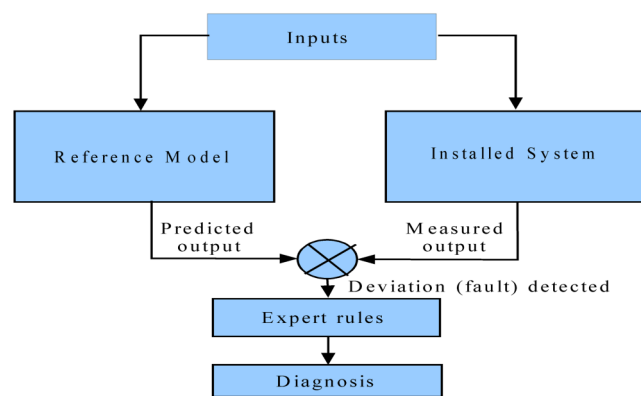
diagram showing the fault detection process used in this report.

Faults detected by the presence of these differences, termed *deviations* herein (because they are initial differences and not changes from initial agreements), can be diagnosed by comparison with a set of expert rules or by optimization of the parameters. Optimization is accomplished by altering the values of the parameters until the modeled outputs match the measured outputs or until the parameter changes are minimized. Differences in the parameter values serve as indicators of the magnitude of faults. Figure 3 shows the method of diagnosis using parameter re-estimation.

Commissioning has the advantage over operational fault detection and diagnosis in that each component can be excited by a series of control inputs selected to expose faults if present. The fault can be isolated to the selected component by testing each component in series while progressing downstream along the air path of the AHU. The expert rules can be less complicated if each component can be tested in turn. Figure 4 diagrams the concept.
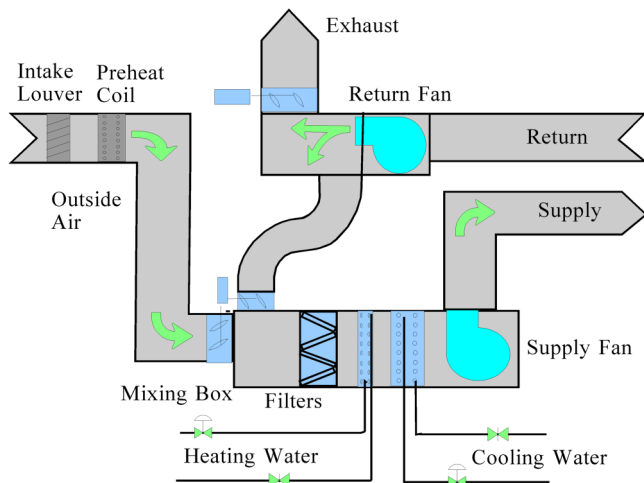
**Figure 5** *Diagram of air-handling unit and system.*



**Figure 6** *Overall plan of commissioning testing procedure.*

A building HVAC system must be tested when the construction schedule indicates, not when the thermal conditions are optimal. The models, then, must be reliable and accurate over a range of operating conditions, not just at full load, and they must be able to extrapolate from the test conditions to design conditions. First principles models are suitable for such extrapolation. Simple but reasonably accurate models that incorporate parameters for control characteristics such as leakage, nonlinearity, and hysteresis are required. Simplicity is desirable for ease of understanding and computer coding as well as for efficient use of computer memory.

These principles of FDD will be applied in functional testing of the assembly of coils, fans, filters, and mixing box commonly identified as an air-handling unit (AHU) (Figure 5). This is one of the most important and common parts of an HVAC system. This assembly is the interface between the water conditioned by the primary plant and the air delivery system. In addition to the previously listed mixing box, filters, heating and cooling coils, and fan, in some cases a return or relief fan is included in the AHU system and is coupled via pressure and flow to the supply fan. Because of its pivotal role in the HVAC system and its widespread use and because it is complicated enough to afford a challenging application of the techniques to be investigated here, the AHU was selected as the first system of the overall HVAC system to be investigated.

## SIMULATING PERFORMANCE WITH FIRST-PRINCIPLES COMPONENT MODELS

The approach to automated functional testing in this work is based on the proposition that a model-based scheme developed from FDD research can be used to commission an air–handling unit. An important part of this approach is the ability to use design information to establish values of parameters
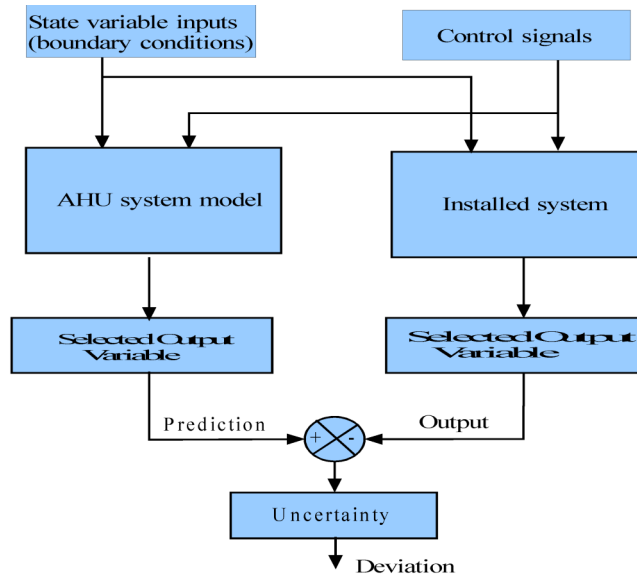
that will enable the models to accurately reproduce the intended performance of the system. Associated with this is the need to develop and test models that accurately portray the performance of the components over their range of operation. Still another significant task is to develop tests that facilitate the detection of likely faults. Figure 6 illustrates the testing procedure developed for automated functional testing.

The starting point is the development of component models and identification of the model parameters from construction document design data. In addition to steady-state thermal models, simple first-order dynamic models and pressure models of the air system have been developed and evaluated. The advantages of these models are in improving detection of faults and reducing the time required for the functional testing process to be evaluated. Figure 7 pictures the flow of information leading to the system model. A companion paper describes the component models in greater detail.

## EXPRESSING DESIGN INTENT WITH MODEL PARAMETERS

Design intent can be interpreted on various levels. Engineering design intent is defined as the construction documents' schedules, manufacturers' schedules, and published performance data. The designer interprets the owner's design intent and writes or approves this information. This is the standard selected as the required performance for the building and specifically for the air-handling unit and system under consideration here.

Air-handling units are custom-built from modular designs that allow a given size of unit to have many options of mixing box, filters, coils, fans, and arrangements. Once the designer has estimated the heating, cooling, and ventilation

**Table 1. Heating Coil Schedule**

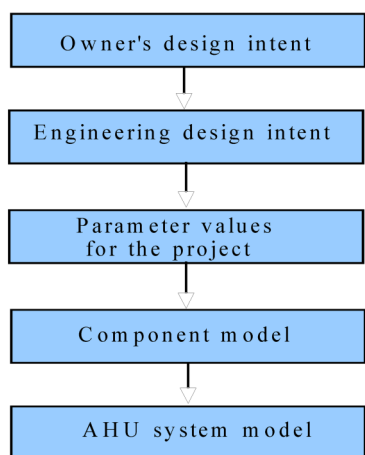| Symbol | Airflow kg/s (cfm) | EDBT °C (°F) | LDBT °C (°F) | EWT °C (°F) | LWT °C (°F) | Duty kW (mBh) | Water flow kg/s (gpm) | Air PD Pa (in. wg) | Water PD kPa (ft wg) |
|---|---|---|---|---|---|---|---|---|---|
| AHU -A | 1.814 (3200) | 4.4 (40) | 37.8 (100) | 82.2 (180) | 71.1 (160) | 60.9 (208) | 1.3 (20) | 62.2 (0.25) | 14.95 (5) |



*Figure 7*    *Information flow in model development.*

requirements at design conditions, the next step is to select the components to deliver these design flow rates. The designer or a representative of the manufacturer, using catalogs with capacity tables or, more commonly now, selection software provided by the manufacturer, makes the selection. The designer communicates the engineering design intent to other participants by including on the drawings a schedule of the principal design performance variables of each air-handling unit. The schedule sets forth the design conditions and characteristic quantities at these conditions. Physical parameters, such as number of rows of tubes in a coil, may be explicitly stated or left to the option of the manufacturer. Competitors bidding on the equipment make their own selections based on the schedule.

There is no universal definition for the design quantities in the schedule. One designer may write into the schedule an estimation of the design loads and interpret them as minimums and require equipment suppliers to meet or exceed the design values. Another may select equipment based on his/her estimate, then write the selected capacities in the schedule and interpret them as approximate targets for other manufacturers. In either case, some uncertainty is built into the selection and conservative selection with excess capacity is the usual result.

Part-load performance of the component is not usually expressed in the schedule. Rather, the designer describes a sequence of actions the control system is to make to regulate the output of the component at less than design conditions.

Frequently the designer includes selection of a specific product. Final modifications of the design intent are sometimes made when submittals for alternative products or materials are approved. The form and content of these various expressions of design intent are critical to the development and application of the commissioning models. The first principles models have parameters that reflect some aspect of the requirements from the previous paragraph and that calibrate the commissioning tool for the specific system under test. Thus, the models must be developed to incorporate this information and to have parameters whose values can be determined from these sources. A discussion of this factor, component by component, follows.

A typical heating coil schedule indicating engineering design intent is given in Table 1.

In this schedule, EDBT represents entering dry-bulb temperature of the airstream and LDBT the leaving temperature. EWT and LWT are entering and leaving water temperatures, duty (or capacity) is total heat transferred, and PD indicates pressure drop. The airflow rate is based on standard air at 1.2 kg/m$^3$ (0.075 lb/ft$^3$). Manufacturers are now publishing coil performance data in the form of computer programs that enable a designer to input some of the performance data from the schedules and to receive as output several choices of coils. Submittal data consist of certified performance tables and drawings of the chosen coil.

The models consist of equations developed from first principles of physics using standard methods such as heat balances. Among the variables in the equations, some are inputs from the test data and are called *state variables* because they describe the state of the system, some are inputs fixed for the duration of the test and are called *parameters*, and the rest are outputs. The parameters describe physical aspects of the components and are selected so that values can be determined from engineering design data presented in the construction documents or from manufacturers' performance data. This is a key aspect of the premise of this study. If data are insufficient or the models cannot reliably predict system performance, the premise will not hold.

The parameters for a heating coil model are width, height, number of rows, number of circuits, tube inside diameter, tube outside diameter, air-side resistance, water-side resistance, metal resistance, UA scale, maximum duty, convergence tolerance, water maximum flow rate, and supply air maximum flow rate. Of these parameters, maximum duty and maximum air and water flow rates are taken directly from the drawing schedule. Width, height, rows, circuits, and tube dimensions

can be found indirectly from the drawings by referring to submittal data and other manufacturers' literature. Air, water, and metal resistance can be found in the technical literature. For a control valve, the parameters are valve authority, valve hysteresis, valve leakage, and valve curvature. Design intent authority can be estimated by calculating branch circuit pressure drop, and curvature can be determined from the manufacturer's valve characteristic. Hysteresis and leakage are fault parameters initially assumed to be zero.

## EXAMPLE OF A COMPONENT MODEL

Models used in this study are described in more detail in a companion paper (Kelso and Wright 2005). The heating coil model was selected as an example to be included here. Heating and cooling coils are cross-counterflow, externally finned heat exchangers. The steady-state heating coil model is developed from the familiar effectiveness-NTU method (Nusselt 1930; Kreith 1958). It uses an overall conductance (UA) of the heat exchanger:

$$Q = UA(T_w - T_a)_{mean} \qquad (1)$$

where $Q$ = heat transfer rate, $T_a$ = air temperature, and $T_w$ = water temperature. The total resistance is found by

$$r_t = r_a \times v_a^{-0.8} + r_m + r_w \times v_w^{-0.8}, \qquad (2)$$

where $r_t$ is overall thermal resistance, $v_a$ is air velocity, $v_w$ is water velocity and $r_a$, $r_w$, and $r_m$ represent air, metal, and water resistance, respectively. $U = 1/r_t$ and $A$ = coil face area times the number of rows. The introduction of the effectiveness term, $\varepsilon$, avoids the trial-and-error solution necessary if the outlet temperature is retained as a variable in the equation. Effectiveness is defined as

$$\varepsilon = \frac{C_h(T_{h_{in}} - T_{h_{out}})}{C_{min}(T_{h_{in}} - T_{c_{in}})} = \frac{C_c(T_{c_{out}} - T_{c_{in}})}{C_{min}(T_{h_{in}} - T_{c_{in}})}, \qquad (3)$$

where $C$ is heat capacity, $mc_p$, and the subscripts $h$, $c$, and $min$ indicate hot, cold, and minimum, respectively. $C_{min}$ is the lesser of the air or water heat capacities and $C_{max}$ in Equation 5 is the greater of the two. The number of heat transfer units, $NTU$, is defined as

$$NTU = \frac{UA}{C_{min}}. \qquad (4)$$

Effectiveness can be calculated from

$$\varepsilon = \frac{1}{1 - \left(\frac{C_{min}}{C_{max}}\right)e^{NTU\left(1 - \frac{C_{min}}{C_{max}}\right)}}. \qquad (5)$$

Finally, the rate of heat transfer can be calculated by

$$Q = \varepsilon C_{min}(T_{w_{in}} - T_{a_{in}}). \qquad (6)$$

## FUNCTIONAL TESTING BY STEP TESTS WITH A CORRECTLY OPERATING SYSTEM

Two tests of the functional testing tool will be described—one with a system free of deliberately introduced faults and assumed to be operating correctly and one with a deliberately introduced fault. The tests were conducted on a real air-handling unit located at the Iowa Energy Center's Energy Resource Station (IEC ERS). Normal operation of the heating coil is for a leaving air temperature sensor, upon sensing a decline in temperature below its setpoint, to signal the hot water control valve to begin to open. In commissioning, instead of waiting for operating conditions to reach the point of calling for heat, the controls are set in open loop mode, supply airflow is set for design conditions, and the water heating system is turned on. The control valve is signaled to move to the fully open position and after a quasi-steady-state condition is achieved, the valve is signaled to close. Expectations are that the leaving air temperature predicted by the model will track the actual measured leaving air temperature within uncertainty limits. Deviations from the predicted temperature will indicate faults. Parameters for the models are taken from engineering design information and manufacturer's performance literature.

The first panel in Figure 8 pictures the leaving air temperature as the heating coil control valve is stepped in open loop control from closed to open and return. Note that the heating coil performance, as indicated by the measured leaving air temperature, exceeds the model predictions when the valve is open. In the figure, the second panel presents the deviation when the measured leaving air temperature varies from the expected (modeled) leaving air temperature. The second panel includes the 95% confidence interval determined from the accumulated precision errors as described by Buswell (2001). The third panel shows a value of 0 when the deviation is below a threshold and 1 when the deviation exceeds the 95% confidence interval. A fault under the normal operating conditions, which means without deliberately introduced faults in this case, would indicate a modeling deficiency or an incorrect parameter. In this case, a fault is indicated when the valve is opened, but the fact that the measured temperature is higher than the modeled temperature is an indication that coil performance exceeds expectations. In an actual commissioning, better-than-expected performance would probably not be considered a fault, but in this investigative study, an explanation for this deviation is given below.

This test is intended to reveal duty, or capacity, faults and gross control faults. Duty is indirectly measured by leaving air temperature, since temperature is easily measured and duty is proportional to temperature change in a heating process. If the modeled leaving air temperature was higher than the measured, the coil would be considered faulty and further investigation would be conducted to diagnose the problem. Diagnosis of this particular fault using the parameter re-estimation technique shows the measured and modeled leaving air temperatures can be brought into close agreement if the
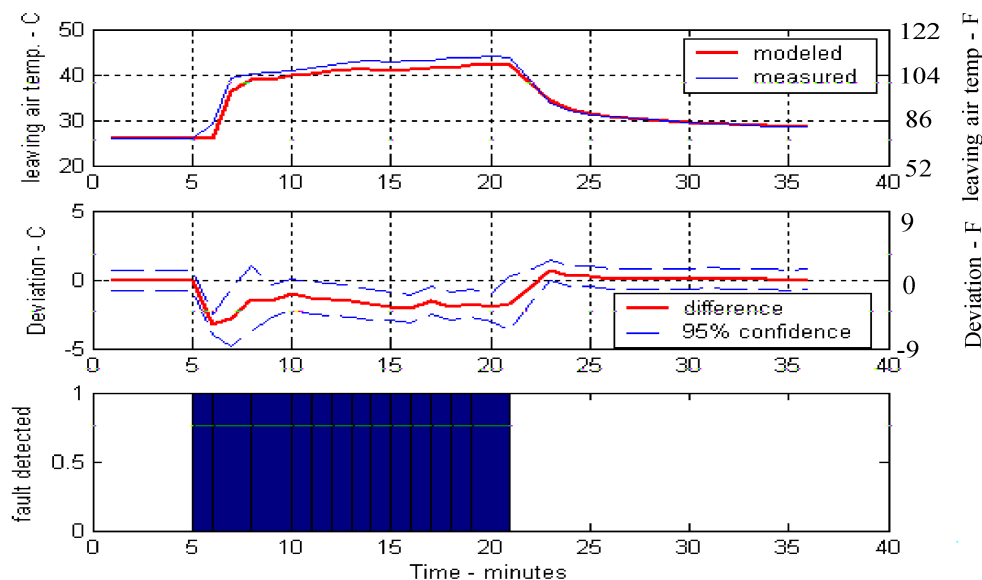
*Figure 8*  *Normal operation step test of heating coil and control valve.*

parameter for number of rows (actually a measure of external surface area) is increased from 2.0 rows based on design data to 2.3 rows.

To clarify these results, the heating coil outperforms its rating expectation. The testing tool using these models has detected this and indicated a deviation. Since the deviation is better than expected, this particular deviation would not be considered a fault, but the tool has worked.

## FUNCTIONAL TESTING A FAULTY SYSTEM

A common problem is a control valve actuator that is set incorrectly so the valve opens when it should be closing and conversely. This simple fault was chosen to demonstrate the tool's performance. Changing the jumpers on the actuator from reverse acting to direct acting simulated this fault. The expected indications that such a fault is present are:

1.  Modeled supply air temperature changes in opposition to measured temperature.

2.  Measured supply air temperature changes in opposition to heating coil control signal.

The heating coil step test is the same as described above, with the supply fan operating at full speed and the return fan tracking the supply fan at 90% of the supply fan flow rate. The VAV terminals were full open and the cooling coil valve closed. The mixing box was set for full outside air. Figure 9 shows the results of the test applied to AHU-B at the IEC ERS.

The reverse-operating valve gives a clear indication of a fault from the beginning of the test. The fault is detected throughout the test. The difference between modeled temperature and measured temperature is large at all conditions. The automated commissioning software incorporating these

models and linking them together with the inputs and outputs successfully detected the reverse-operating control valve in these tests. It also detected a leaking control valve and faults in other components.

## CONCLUSIONS

The principles of automated fault detection and diagnosis developed over the past 10 or 15 years by many researchers can be applied to automated functional testing. The simulation of components by first principles models has been demonstrated. The parameters that configure these models to a particular component can be determined from engineering design intent as expressed in the contract documents and manufacturers' literature. Tests to validate sensors and that exercise particular components to reveal faults have been developed. Physical models require inputs that are well defined or whose uncertainties are estimated in such a way that the uncertainty in the output can be estimated. The input sensors used in this study have precision errors that were used, along with model uncertainties, to evaluate the cumulative uncertainty in the output.

The tool used for these tests has successfully tested correctly operating components (that is, it detected that the coil actually exceeded expectations) and detected a deliberately introduced reversed controller fault.

A follow-up paper describes the models in more detail (Kelso and Wright 2005). The models described herein are thermal models. Pressure and flow models are useful in testing components such as fans and mixing boxes. These models are less mature and deserve additional attention. The tests reported used a real air-handling unit. Expansion of this functional testing to other system components is recommended.
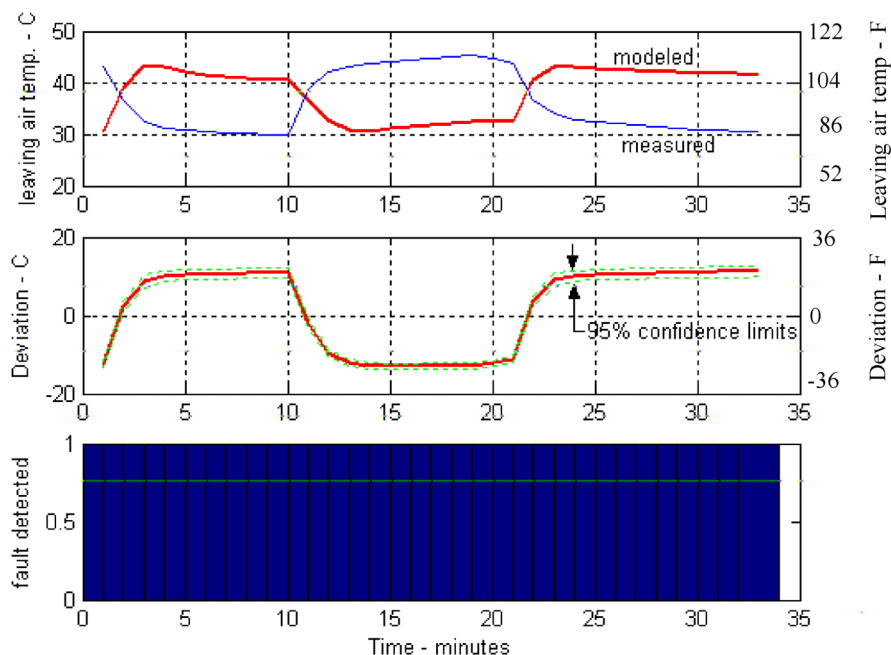
**Figure 9**  *Heating coil step test with control valve incorrectly wired to operate in reverse.*

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