Simple Fault Detection and Diagnosis Methods for Packaged Air Conditioners

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Automatic fault detection and diagnosis (FDD) in HVAC systems has the potential to ensure the comfort of building occupants and decrease energy consumption. Disadvantages of current FDD methods include the high costs of engineering specific FDD systems for individual equipment, expensive sensor and microprocessor requirements, and poor performance. This paper presents two easy-to-implement FDD methods in rooftop air conditioners that require relatively few temperature sensors. The two methods were tested by laboratory experiments for different fault types and fault levels and found to have good performance and low hardware and software requirements.

Introduction

Due to decreasing costs of microprocessors, fault detection and diagnosis technology (FDD), which previously has been used in critical applications such as aircrafts, has become possible in more appliances, including HVAC systems. FDD in HVAC systems has the potential to reduce energy and maintenance costs, improve occupant comfort and advance the reliability of equipment.

A variety of different approaches have been investigated for FDD applied to HVAC [1-21]. Although many of the methods exhibit good performance under given situations and for given equipment, most of them have some of the following disadvantages: relatively high development costs (experiments), high initial costs (sensors and microprocessor), and poor performance under certain operating conditions. A commercial FDD system should be easy to engineer for a specified unit (require a small number of experimental tests and be easy to implement), use a small number of inexpensive sensors, and have good performance under a variety of operating conditions.

This paper presents two easy-to-implement methods for detecting and diagnosing faults in rooftop air conditioner units. The first method, termed the "Sensitivity Ratio Method", uses measurements and model predictions of temperatures for normal operation to compute ratios that are uniquely sensitive to individual faults. The second FDD method, termed the "Simple Rule-Based Method", does not require any on-line model. This method uses performance indices computed from raw measurements that are relatively independent of operating conditions but are sensitive to faults. The two methods were tested using experimental data for different fault types and fault levels at different operating conditions. They have good performance and low hardware and software requirements.

Test unit and fault simulation

Experiments and FDD method development were carried out on a 5-ton rooftop unit. The unit has a constant speed, hermetically sealed scroll compressor and uses a TXV as the expansion device. The condenser fan moves air through the condenser with a nominal flowrate of 4500 cfm. The nominal flowrate of air through the evaporator is 2000 cfm. The unit was installed in the psychrometric rooms at Purdue University and instrumented with sufficient sensors to both develop and evaluate the FDD methods. The cooling and dehumidification for the rooms are provided by a direct expansion vapor compression system powered by a variable capacity screw compressor capable of offsetting a heat addition of over 120,000 BTU/hr. The reheat is closely controlled with a combination of discrete and continuous control. Figure 1 presents the test unit instrumentation. Figure 2 shows the installation inside the psychrometric rooms.

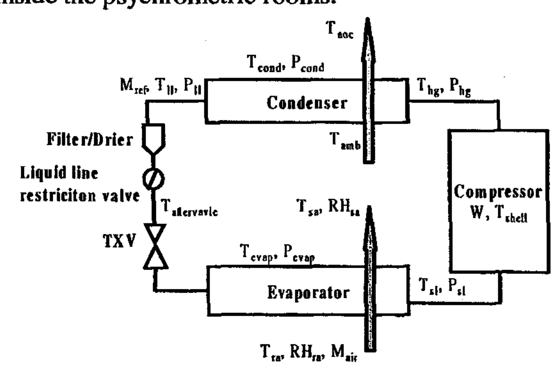

Figure 1 Test unit instrumentation

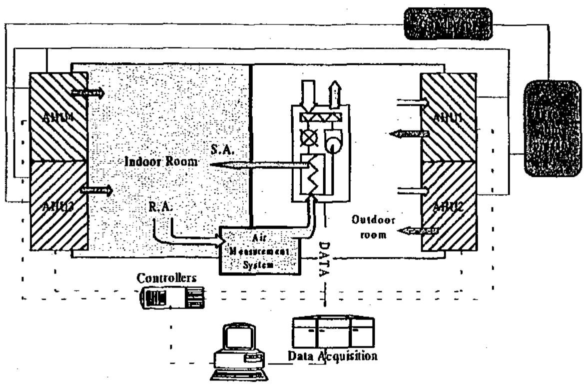

Figure 2 Psychrometric rooms and test unit

Since rooftop units commonly operate at transient or quasi-transient states in the field while the FDD methods work only at steady states, both steady and transient state operations were simulated. Steady-state tests were designed to analyze the fault characteristics and develop the fault diagnosis methods including the steady-state model while the transient state tests were used to analyze the transition from transient to steady state and evaluate the developed FDD methods in 'real' circumstances. Transient tests were performed at the three load levels (low, medium, and full) shown in Table 1. The tests for all the load levels used an operating cycle of 20 minutes. At the low indoor load level (40% of full load) the indoor temperature decreased 2 F in 8 minutes with the rooftop unit turned ON and increased 2 F in 12 minutes with the unit OFF. At the medium indoor load level (70% of full load), it took 14 minutes to cool down and 6 minutes to heat up within the same temperature dead band. When the indoor load level was 100% of the design load, the rooftop unit operated at all times. For all the tests, the indoor dry bulb temperature was controlled to vary linearly between 74 F and 76 F with the relative humidity held constant at 40%. This indoor condition is within the central region of the ASHRAE comfort zone.

Load level	Ambient temperature (F)
40%	90
70%	96
100%	105

Table 1 Load levels simulated and corresponding ambient conditions

Seven typical faults in rooftop air conditioners were studied, which are:

- Evaporator air blockage (filter fouling or fan malfunction; identified as 'evapfoul')
- Condenser air blockage (fouling or fan malfunction; 'condfoul')
- Liquid line restriction (stuck filter/drier; 'llrestr')
- Compressor wear (leakage among the chambers of a scroll compressor or through the valves of a reciprocate compressor; 'compnv')
- Refrigerant leakage ('refleak')
- Refrigerant overcharge ('refover')
- Non-condensable gas ('gas')

Table 2 lists the fault simulation method, fault level characterization, and fault levels simulated. All types of faults were tested at all three load levels except the fault of non-condensable gas, which was tested only at the full load level.

Fault type	Simulation method	Fault level characterization	Fault level simulated				
			1	2	3	4	5
Condenser fouling	Block the condenser coil with paper	% Reduction of the surface area of the condenser coil	0.00%	10.00%	20.00%	30.00%	40.00%
Evaporator fouling	Adjust the air flowrate through the evaporator coils	% Reduction of the air flow rate	0.00%	6.82%	13.64%	20.46%	27.28%
Liquid line restriction	Close partially a needle valve installed in the liquid line	% of the pressure drop from high pressure side to low side	0.00%	4.75%	10.86%	13.07%	18.66%
Compressor wear	Open a bypass valve installed the discharge line and suction line	% Reduction of the volumetric efficiency	0.00%	10.00%	20.00%	30.00%	40.00%
Refrigerant leakage	Discharge some of the refrigerant from the system	% Reduction of the total charge in the system	0.00%	5.00%	10.00%	20.00%	30.00%
Refrigerant overcharge	Overcharge some refrigerant into the system	% Addition of the total charge in the system	0.00%	5.00%	10.00%	20.00%	30.00%
Non-condensable gas	Charge controlled amount of N_2 into the system	% Total refrigerant mass	0.00%	0.03%	0.09%	0.13%	0.17%

Table 2 Method of implementing the faults and levels simulated

Fault effect analysis

Breuker and Braun [1998] studied the fault characteristics of a rooftop air conditioner with a fixed orifice as the expansion device, whereas this paper focuses on a rooftop air conditioner with a thermal expansion valve as its expansion device. The TXV, together with its sensing bulb and the evaporator, work as a feedback control system inside the refrigeration loop and compensate for the system disturbances (either the shifting of operating conditions or the occurrence of faults). Therefore, it is much more difficult to perform FDD on a system with a TXV than for a system with a fixed orifice. For example, a restriction in the liquid line initially leads to an increased pressure drop and decreased refrigerant flow rate. However, an increased refrigerant superheat exiting the evaporator causes to an increase in the opening of the TXV causing the refrigerant flow to remain relatively constant. This occurs until the restriction is severe enough so that the TXV is fully open and the refrigerant flow rate decreases, resulting in the increased suction superheat and discharge temperature. One approach to early detection of this fault involves measurement of the temperature change within the liquid line. As the pressure drop increases, liquid vaporization occurs and the temperature drop increases significantly.

Table 3 presents the influences of faults on the unit temperature measurements (evaporation, suction line superheat, compressor discharge, condensation, liquid line subcooling, condenser air difference, evaporator air difference, liquid line difference) that were found for the test unit. In Table 4, '=' indicates there was not a noticeable change for the measurement with the corresponding fault, '++' means a significant increase while '+' means a fairly moderate increase from its normal value. Similarly, '--' means a significant decrease while '-' means a fairly moderate decrease. Noticeably many measurements for this system were insensitive to the faults. Stronger effects would be expected for a system with a fixed orifice.

Figure 3 presents the cooling capacity change for the seven fault types considered. Some faults did not have very significant impacts on the system capacity at moderate to medium fault levels. In particular, condenser fouling had a very small impact on the capacity. Within 20% of nominal refrigerant charge, refrigerant overcharge actually increased the system capacity. Compressor wear, refrigerant leakage and non-condensable gas are the three types of faults with most considerable impacts on the system capacity. Too much non-condensable gas inside the system made the readings of the refrigerant flow meter unstable and thus no capacity value is given for 'gas' at fault level 5 in Figure 3.

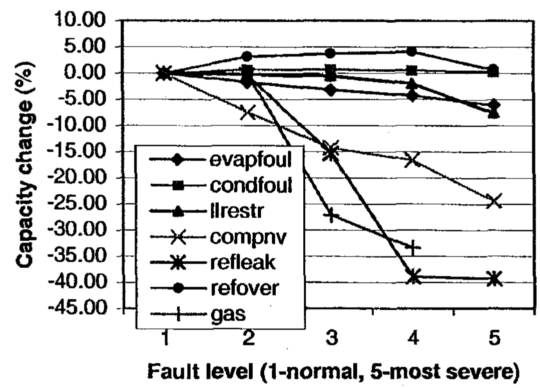

Figure 3 Impacts of faults on cooling capacity

Fault types	Tevap	Tsh	Thg	Tcond	Tsc	dTca	dTea	dTll
Condenser fouling	=	=	++	++	++	++	=	=
Liquid line restriction	=	=	=	=	=	=	=	++
compressor wear	++	=	++	--	-	--	--	=
Refrigerant leakage	= (- at leakage >=30%)	= (++ at leakage >=20%)	= (++ at leakage >=20%)	= (-- at leakage >=20%)	--	= (-- at leakage >=20%)	= (-- at leakage >= 20%)	= (+ at leakage >=30%)
Refrigerant overcharge	=	=	+	+	++	+	=	=
Evaporator fouling	--	=	=	-(significant only at severe fault levels)	=	-	++	=
non condensable gas	= (+ at higher fault levels)	= (+ at higher fault levels)	+ and reaches steady state quicker	+	++	+	= (- at higher fault levels)	=

Table 3 Fault characteristic of a rooftop air condition unit with a TXV as the expansion device

Sensitivity Ratio Method

The basic idea of the Sensitivity Ratio Method is to use a unique pair of measurements for each fault type where one is fault sensitive and the other is not. Fault sensitivity ratios are computed as

$$R_i = \frac{|r_{insens,i}|}{|r_{sens,i}|}$$

where for fault type i: R_i is the fault sensitivity ratio,

$r_{insens,i}$ is the residual of insensitive measurement,

and $r_{sens,i}$ is the residual of sensitive measurement.

The residual of a given temperature measurement T is defined as

$$r_T = T_{actual} - T_{pred}$$

where T_{actual} is the measurement and T_{pred} is the model prediction for normal operation.

For example, the ratio for liquid line restriction is expressed as R_{ll}. In this case, the temperature difference across the liquid line increases is chosen as the sensitive measurement, while the evaporation temperature does not change significantly and is chosen as the insensitive measurement.

When a fault develops, the sensitivity ratio for that fault decreases. As soon as the value is below the pre-set threshold, an alarm for that fault can be given.

Pre-processors

1. *Steady State Detector*

Most of the measurements used in Sensitivity Ratio Method are very responsive to the variation of operating conditions after the first few minutes of a start-up transient. The slowest measurement used is the liquid line subcooling and its variance was chosen as the steady state detector for the evaluation in this paper. When the variance of the sub-cooling temperature was lower than $0.030F^2$ within a measurement window, it was assumed that the unit was operating at steady state.

2. *Steady State Model*

The on-line steady-state model for normal operating states should have the following two conflicting properties: low estimation error and easy to train. No-fault steady-state tests were performed at different combinations of the conditions inside the ASHRAE comfort zone and ambient situations. First-order polynomial models, expressed in terms of the return air dry-bulb temperature (T_{ra}), relative humidity (RH_{ra}), and ambient dry-bulb temperature (T_{amb}) were found to have good accuracy. The model was trained using 40 data points (combinations of eight indoor conditions and five ambient conditions). The model accuracy was tested using another 70 data points. Table 4 gives the root mean square (RMS) of the error in predicting the test data. T_{evap}, T_{cond}, T_{sc} and ΔT_{ll} have the best model accuracy and are used in the FDD methods.

T_{evap}	T_{sh}	T_{hg}	T_{cond}	Tsc	ΔT_{ca}	ΔT_{ea}	ΔT_{ll}
0.55	2.21	2.62	0.23	0.52	1.54	1.19	0.27

Table 4 Steady state model RMS (F)

3. *Noise Filter*

With experimental noise and/or modeling error, a sensitivity ratio could be very small at no-fault situations when both residuals are small. This problem was solved by incorporating a filter to ignore small differences between measurements and model expectations. If a residual is smaller than a pre-set threshold, the residual is reset as a very small value. The threshold should be dictated by the desired method sensitivity and error tolerance determined by the user. For the evaluation in this paper, 2 F was used as the threshold. If a residual was less than 2 F, the difference was ignored and the residual was reset to 0.1 F.

4. *Measurement Window*

A moving measurement window was used to evaluate steady-state operation and to determine average sensitivity ratios for diagnostic purposes. In the experiments, the sampling rate was about eight to nine seconds per test point. A 10-testing-points moving window, which takes about one and a half minutes, was used for the evaluation in this paper. Decisions were made only if all the sensitivity ratios within the moving window would give consistent results, i.e., all were larger than or all were smaller than 1.

Algorithm

In order to identify a fault, at least one of the fault sensitivity ratios must be less than 1 (Table 5). Under normal operating conditions, it is expected that all the sensitive and insensitive measurement residuals would be less than the noise threshold (2 F). In this case, the residuals are set to 0.1F and the compute sensitivity ratios are 1. As a fault develops, at least one of the fault sensitive residuals should increase beyond the noise threshold and the corresponding sensitivity ratio should decrease. An alarm for fault type i is given if and only if $R_i < 1$.

Figure 4 lists the steps associated with executing the method. The method is implemented as a series of steps where the rules of Table 5 are applied. Additional criterions are necessary for several of the faults. The method does not distinguish between refrigerant overcharge and the presence of non-condensable gas. However, a service technician could easily identify the presence of non-condensables by measuring the pressure in the evaporator when the unit is off and comparing it to saturation pressure associated with the return air temperature. Large deviations would indicate the presence of non-condensables.

Ratio	$R_{ll}=\|r_{Tevap}\|/\|r_{Tll}\|$	$R_{compnvlevapfoul}=\|r_{Tll}\|/\|r_{Tevap}\|$	$R_{condfoul}=\|r_{Tevap}\|/\|r_{Tcond}\|$	$R_{refleaklrefoverlgas}=\|r_{Tll}\|/\|r_{Tsc}\|$
Liquid line restriction	<1			
Compressor wear	>=1	<1, $r_{Tevap}>0$		
Evaporator fouling	>=1	<1, $r_{Tevap}<0$		
Condenser fouling	>=1	>=1	<1	
Refrigerant leakage	>=1	>=1	>=1	<1, $r_{Tsc}<0$
Refrigerant overcharge	>=1	>=1	>=1	<1, $r_{Tsc}>0$
non-condensable gas	>=1	>=1	>=1	<1, $r_{Tsc}>0$

Table 5 Sensitivity Ratio Method algorithm

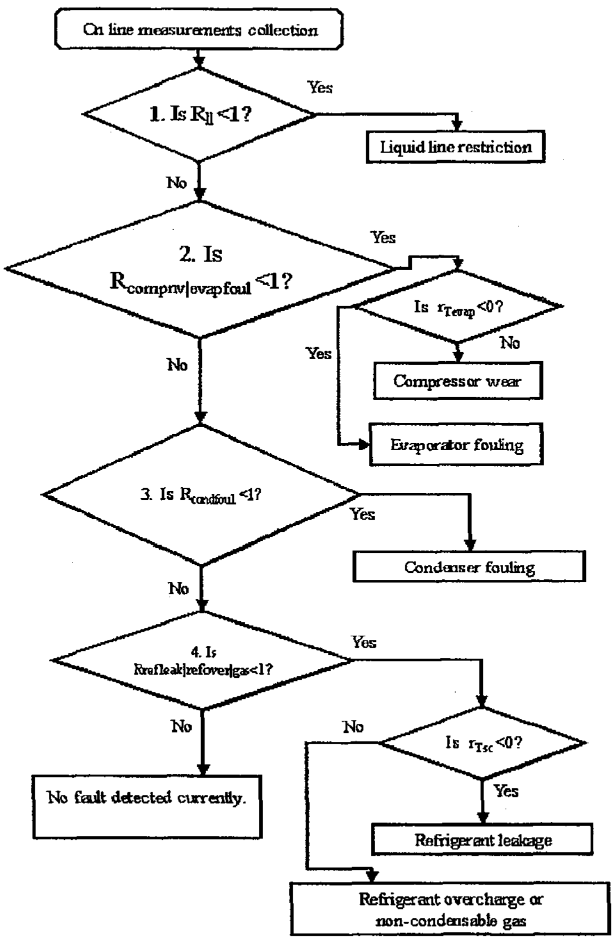

Figure 4 Sensitivity Ratio Method flowchart

Evaluation

The transient test data with medium indoor load level (T_{amb}=96F) are initially presented as an example. The fault levels and their indices are given in Table 1. The method sensitivity and correctness were assessed in the evaluation. The method sensitivity means the minimum fault level that could be detected. The method correctness is its ability to the correct fault diagnosis.

According to Figure 4, when given a set of on-line measurements,

$$R_{ll} = \frac{|r_{T_{evap}}|}{|r_{T_{ll}}|}$$

is evaluated first to detect a liquid line restriction. Table 6 shows values of R_{ll} determined from experimental data for the medium load level tests for all of the faults at all fault levels. These results indicate that this ratio is less than 1 for a liquid line restriction with fault level equal to or greater than level 3, i.e., pressure drop through the liquid line is equal to or greater than 10.86% of the pressure drop from the condenser to the evaporator. No wrong diagnoses (in terms of fault type) were found (i.e., R_{ll} is not less than unity for any other fault).

		R_{ll} value				
		Fault levels				
		1(normal)	2	3	4	5
Actual fault type	Liquid line restriction	1.00	1.00	0.03	0.01	0.52
	Compressor wear	1.00	1.00	37.86	62.97	90.88
	Evaporator fouling	1.00	1.00	9.97	29.32	39.97
	Condenser fouling	1.00	1.00	1.00	1.00	1.00
	Refrigerant leakage	1.00	1.00	1.00	1.00	28.90
	Refrigerant overcharge	1.00	1.00	1.00	1.00	1.00
	non-condensable gas	1.00	1.00	1.00	1.00	1.00

Table 6 R_{ll} with different fault types and levels

If R_{ll} is not less than 1, then

$$R_{compnv|evapfoul} = \frac{|r_{T_{ll}}|}{|r_{T_{evap}}|}$$

will be calculated. $R_{compnv|evapfoul}$ is the reciprocal of R_{ll}. Therefore, Table 6 also shows that $R_{compnv|evapfoul}$ will be less than 1 for a compressor wear or an evaporator fouling with fault level equal to or greater than level 3. Although $R_{compnv|evapfoul}$ is also less than 1 at the severest refrigerant leakage (i.e., 30% leakage), a refrigerant leakage can be detected at least at 10% leakage by the Sensitive Ratio Method (Figure 5) and therefore it will not cause a wrong diagnosis decision.

Figure 5 presents the overall sensitivities of the Sensitivity Ratio Method for the three load levels tested. The results are presented in terms of the first fault level where an alarm was set for each fault type. The method was able to correctly diagnose faults at all three load levels with reasonable sensitivity. As previously noted, non-condensables were only simulated at the full load conditions.

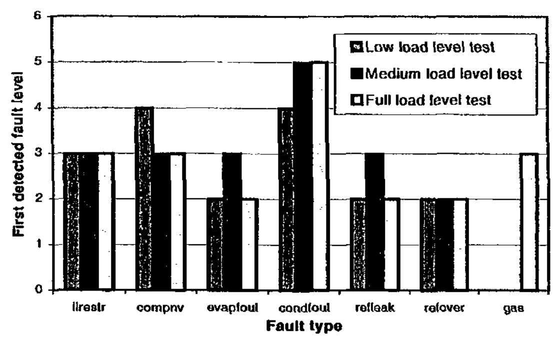

Figure 5 Sensitivity Ratio Method performance

Simple Rule-Based Method

Most of the FDD methods described in the literature use on-line models for expected behavior under normal operation. However, the process of obtaining a model for a specific unit is costly. Extensive experiments are usually needed for each type and size of air conditioner. Furthermore, the models require measurements of the inputs to the models, which typically add to the total number of on-line sensors. This section presents a Simple Rule-Based Method that eliminates the requirement of an on-line model and can greatly decrease the number of necessary lab experiments.

Approach

The Simple Rule-Based Method compares performance indices determined from raw measurements with preset thresholds to detect and diagnosis faults. There were two important issues associated with developing this method. First, it was critical to find performance indices that are sensitive to faults but insensitive to operating conditions. The following measurements were found to have such characteristics:

- Liquid line subcooling (T_{sc}).
- Difference between return air dry-bulb temperature and evaporating temperature ($T_{ra} - T_{evap}$)
- Difference between condensing temperature and the ambient temperature ($T_{cond} - T_{amb}$)
- Temperature difference across the liquid line restriction valve (ΔT_{ll}).

Secondly, there should be a unique pattern of the changes in the performance indices for each type of fault. $(T_{ra} - T_{evap})$ will increase when the evaporator fouls or there is malfunction in the evaporator blower (i.e., the heat exchanger is effectively smaller and a larger temperature difference is necessary to give the required heat rejection). Compressor wear reduces cooling capacity and leads to a smaller $(T_{ra} - T_{evap})$. Similarly, $(T_{cond} - T_{amb})$ will increase when the condenser fouls or there is malfunction in the condenser fan. ΔT_{ll} will increase when the filter/drier gets clogged such that the pressure drop through the liquid line is abnormally high. Subcooling is sensitive to some system-level faults. It will be unusually low when the refrigerant charge is low and unusually high when refrigerant is overcharged or air is trapped inside the system. Although the later two faults cannot be distinguished by T_{sc} alone, a service person could distinguish these faults through an additional pressure measurement when the unit is off.

As with the Sensitivity Ratio Method, the Simple Rule-Based Method only works at steady-state conditions and a steady-state detector is required.

Table 7 lists the measurements and thresholds used in the Simple Rule-Based Method for the evaluation of this paper. Each threshold is a normal range for the performance indices. Since the indices do not vary significantly with respect to the operating conditions, it is much easier to identify their normal ranges than to train a model for each unit.

Evaluation example

Figure 6 and 7 show the effect of evaporator fouling on $(T_{ra} - T_{evap})$ for two different ambient temperatures (90 F (40% indoor load) and 105 F (full indoor load)). In comparing these two figures, it is apparent that $(T_{ra} - T_{evap})$ is nearly the same for the no-fault tests at the two operating conditions. However, evaporator fouling has a significant effect on this performance index. From these data, it was concluded that the normal evaporating temperature should be between 31 F and 33 F. Any deviation above 34 F was regarded as an indication of a fault. As can be expected, a single measurement, such as T_{evap}, does not have this characteristic. When the ambient temperature increases from 90 F (Figure 6) to 105 F (Figure 7), the evaporating temperature for the no-fault case increases from around 41 F to 44 F.

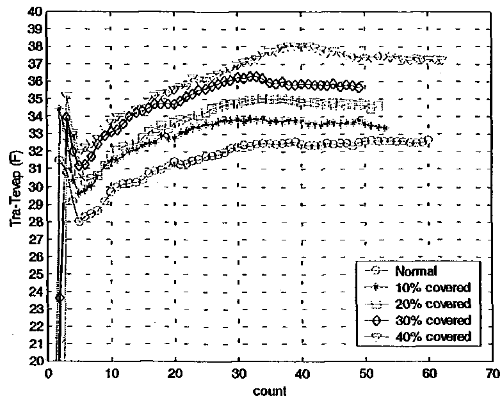

Figure 6 Evaporator fouling at Tamb=90F

Figure 8 presents the overall sensitivities of the Simple Rule-Based Method for the three load levels tested. The results are presented in terms of the first fault level where an alarm was set for each fault type. In comparing Figure 5 and Figure 8, it can be seen that the Simple Rule-Based Method and Sensitivity Ratio Method have similar performance.

Conclusions

Two on-line fault detection and diagnosis methods for rooftop air conditioners were presented and evaluated experimentally. In the 'Sensitivity Ratio Method', ratios of two measurement residuals are computed that are uniquely sensitive to each of the faults. The "sensitivity ratios" are compared to preset thresholds. If the ratio for a fault type is smaller than its threshold, the fault can be detected. In the 'Simple Rule-Based Method', several performance indices that are insensitive to operating conditions but sensitive to faults are used in place of on-line models. Given that the method does not use a model (normally developed on a specified unit), it is more general and could significantly reduce the cost of engineering FDD systems for specific units. Both methods are fairly easy to implement compared to other FDD methods. The Sensitivity Ratio Method requires six temperature measurements and one relative humidity sensor. The Simple Rule-Based Method only requires six temperature measurements. This is a big advantage considering the high cost and low accuracy of humidity sensors. Both methods had reasonably good sensitivity in detecting the seven fault types studied.

Acknowledgements

This research is supported by National Institute of Standard Technology (NIST) and Johnson Controls, Inc.

Fault type	Performance Indice	sensors and locations	no fault range	fault range
evaporator fouling	(Tra-Tevap) will be abnormally high	Tevap, Tra	32-33 F	>34F
condenser fouling	(Tcond-Tamb) will be abnormally high	Tcond, Tamb	19-20F	>21F
liquid line restriction	dTll will be abnormally high	Tll,in, Tll,out	1-2F	>3F
refrigerant leakage	Tsc will be abnormally low			<12F
refrigerant overcharge	Tsc will be abnormally high	Tsc	13-14F	>15F
non condensable gas	Tsc will be abnormally high			>15F
compressor leakage	(Tra-Tevap) will be abnormally low	Tevap, Tra	32-33F	<31F

Table 7 Simple Rule-Based Method

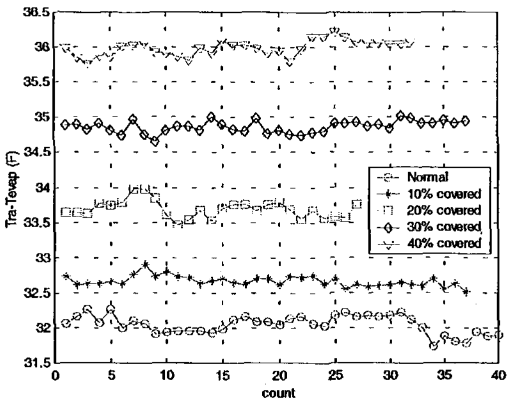

Figure 7 Evaporator fouling at Tamb=105F

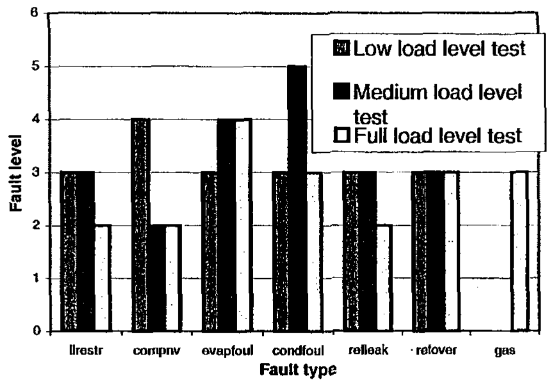

Figure 8 Simple Rule-Based Method performance

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