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A Model-Based Fault Detection and Diagnosis Methodology for Cooling Tower

Byung Cheon Ahn*

Key words: Characteristic parameters, Tower approach, Tower effectiveness, Performance degradation, Diagnostic rules

Abstract

This paper presents a model-based method for detecting and diagnosing some faults in the cooling tower of heating, ventilating, and air-conditioning systems. A simple model for the cooling tower is employed. Faults in cooling tower operation are detected through the deviations in the values of system characteristic parameters such as the heat transfer coefficient-area product, the tower approach, the tower effectiveness, and fan power. Three distinct faults are considered: cooling tower inlet water temperature sensor fault, cooling tower pump fault, and cooling tower fan fault. As a result, most values of the system characteristic parameter variations due to a fault are much higher or lower than the values without faults. This allows the faults in a cooling tower to be detected easily using above methods. The diagnostic rules for the faults were also developed through investigating the changes in the different parameter due to each faults.

Nomenclature

APPROACH : cooling tower approach
h : enthalpy
LMHD : log mean enthalpy difference
Load : cooling load
Ma : cooling tower fan air flow rate
Mw : cooling tower pump water flow rate
Q : heat rejection for cooling tower cell
SHR : sensible heat ratio
T : temperature
UA : cooling tower heat transfer coefficient area product

Greek symbols

ε : cooling tower effectiveness

Subscripts

a : air
in : inlet

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* Department of Building System Engineering, Kyungwon Univ., Seongnam 461-701, Korea

out : outlet
w : water
wb : wet bulb

1. Introduction

Fault detection and diagnosis for heating, ventilating, and air-conditioning systems is important in reducing energy and maintenance costs and improving comfort and reliability. A fault in a building can cause degradation in technical performance and availability of the building. The faults may result in inefficient energy use and an uncomfortable working environment. Kao(1) showed that sensor errors in the air handling unit of HVAC system increase the annual energy requirement up to 50%. A fault, in the context of HVAC applications, may be defined as an unsatisfactory or unacceptable condition in the operation of a system or subsystem. A condition is unacceptable if it is a failure or if it causes one directly or indirectly through a series of other faults. There are various types of faults, some of which are more difficult to detect and diagnose than others.

Fault detection and diagnosis are the initial steps in taking corrective or preventative measures in HVAC system. Fault detection involves the determination that a fault truly exists based on the deviation of an observable quantity that exceeds some predetermined threshold or criterion. Fault diagnosis is the subsequent step that then isolates the cause of the fault. Sometimes this diagnostic step does not immediately locate the root cause of the fault initially detected but may involve a series of steps which eventually converges on the course at some later point in the diagnosis.

Fault detection and diagnosis in a chiller subsystem and/or its components have been previously investigated. Pape et al.(2) developed a methodology for fault detection in HVAC systems based on optimal control. To detect a fault the deviation from optimal performance is sensed by comparing the simulated system power with the power predicted for the optimal strategy. Detection required significant deviations because of the uncertainty in the power prediction. A study on a method for automated detection and diagnosis of faults in vapor compression air conditioners that only requires temperatures measurements and one humidity measurement has been carried out by Rossi and Braun.(3) The diagnostic approach is based on generic rules and does not require equipment specific experimentation. Thresholds for both fault detection and diagnosis are based upon statistical analysis of on-line measurements.

This paper describes a model-based method for detecting and diagnosing faults in a cooling tower as a component of air conditioning system. The three distinct faults considered were in the condenser outlet water temperature (cooling tower inlet water temperature) sensor, the cooling tower pump, and the cooling tower fan. Values of the system characteristic parameters, such as the cooling tower heat transfer coefficient-area product UA, the approach, and the cooling tower effectiveness are compared to baseline values for fault-free operation. Faults are detected through the deviations in the values of these system characteristic parameters from those expected. Diagnostic rules for the faults are developed based on the changes in all parameters.

The Transient Simulation Program, TRNSYS Version 14.2,(4) was used to model the chiller, cooling tower, cooling coil, and auxiliary components. A least squares regression technique was used to obtain the predicted characteristic quantity of the system with respect to load and ambient conditions. The methodology can be implemented in real life buildings by either incorporating it into an Energy Management and Control System (EMCS) or into a standalone PC based supervisor.

2. Characteristic parameters for fault detection and diagnosis

In general, there are two types of faults: complete failures and performance degradation. Complete failures are severe and abrupt faults but performance degradation is due to gradually evolving faults. This paper suggested the simple method to detect faults such as performance degradation of temperature sensor, fan, and pump by using system parameters and power consumption without expensive pressure or flow rate sensors, etc. The tendency of characteristic parameter variations due to faults in cooling tower and also the possibility of detecting faults by the rules developed from the tendency were studied. To illustrate the fault detection and diagnosis methodology, three faults in the cooling tower as a component of HVAC system were introduced as given in Table 1. These represent situations in which a temperature sensor, a fan or a pump are not operating properly, or the temperature indicated by a sensor deviates from the actual temperature by an error, or the maximum air and water flow rates are reduced because of fan or pump fouling. Temperature sensor errors of 2℃ and 4℃ were considered. The degradation for the pump and fan was assumed to produce a 10% and 20% reduction of the maximum flow rate.

Table 1 Fault type of cooling tower

Faults	Fault type	Fault simulation
Temperature sensor fault	◦ Sensor bias/drift ◦ Electrical noise ◦ Improper location ◦ Poor resolution/ accuracy	Inaccurate sensing
Cooling tower pump	◦ Performance degradation ◦ Mechanical damage	Reducing mass flow rate
Cooling tower fan	◦ Dirtiness ◦ Leakage ◦ Abnormal electrical power	

The system model studied in this paper is based on the system used by Pape(2) and the models of Braun(5) included in TRNSYS program were used as system components. The supervisory control and local PID control algorithms are based on the system researched by Ahn.(6)

The chracteristic quantities of cooling tower used to identify these faults are the *UA* (cooling tower heat transfer coefficient-area product), the *APPROACH* (cooling tower approach), and the tower effectiveness. The cooling tower heat transfer coefficient-area product was computed from the simulated values as using the following equation:

$$UA = \frac{Q}{LMHD} \tag{1}$$

where

$$LMHD = \frac{(h_{w,out} - h_{a,in}) - (h_{w,in} - h_{a,out})}{\ln\left(\dfrac{h_{w,out} - h_{a,in}}{h_{w,in} - h_{a,out}}\right)}$$

where Q and $LMHD$ are the heat rejection for cooling tower cell and log mean enthalpy difference.(7) The UA is a function of the heat rejection, air and water flow rates, and ambient wet bulb temperature. Measurements of flow rates and temperature are needed to obtain the UA in equation (1).

A method for predicting the product UA is required for on-line fault detection and diagnosis system. In this study, the baseline values for the conductance area products as a linear function of cooling load ($Load$), wet bulb temperature (T_{wb}) and sensible heat ratio (SHR).

$$UA = H(Load,\ T_{wb},\ SHR) \qquad (2)$$

A least square regression technique$^{(8)}$ was used to obtain the coefficients of the baseline *UA* equation. With no faults present, the values of *UA* from equation (2) and from equation (1) agree well with the standard deviation $S = 2652$ (about 2%) and coefficient of determination $R = 99.1\%$. The values calculated using equation (2) were used as baseline for fault-free operation. Values were then calculated using equation (1) during operation with faults. A comparison of baseline and calculated values was used to detect faults.

The *APPROACH* of the heat exchanger device is the temperature difference between the leaving treated fluid and the entering working fluid. The cooling tower *APPROACH* which is the difference between the temperature of the water leaving the tower ($T_{w,out}$) and the entering ambient wet bulb temperature was used as a characteristic quantity.

The *APPROACH* is defined as

$$APPROACH = T_{w,out} - T_{wb} \qquad (3)$$

The cooling tower effectiveness is defined also as a function of temperatures only as using the following equation:

$$\varepsilon = \frac{T_{w,in} - T_{w,out}}{T_{w,in} - T_{wb}} \qquad (4)$$

3. Results and discussion

The heat transfer coefficient-area product for the cooling tower without faults and with some faults is presented as a function of the load (Figure 1), as a function of the ambient wet bulb temperature (Figure 2), and as a function of the sensible heat ratio (Figure 3), respectively. For fault operation a temperature sensor deviation of −2℃ and −4℃, and a 10% and 20% reduction of the maximum flow rate for the pump and fan were simulated.

In Figure 1, the ambient wet bulb temperature ($T_{wb} = 18$℃) and sensible heat ratio ($SHR = 0.8$) are fixed. As shown in Figure 1, the heat transfer coefficient-area product increases

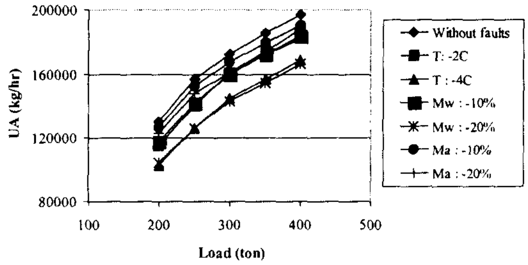

Fig. 1 The *UA* as a function of cooling load for $T_{wb} = 18$℃ and $SHR = 0.8$.

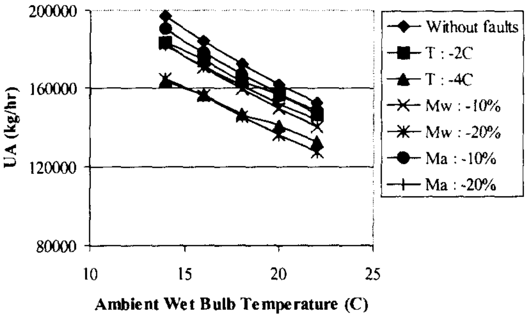

Fig. 2 The *UA* as a function of ambient wet bulb temperature for $Load = 300$ tons and $SHR = 0.8$.

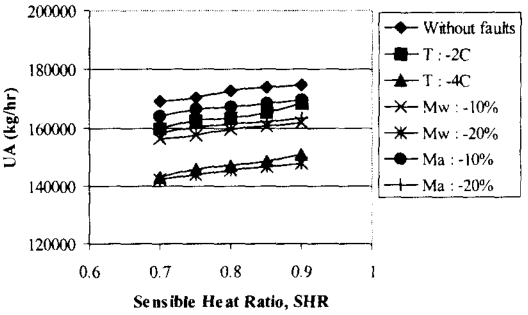

Fig. 3 The *UA* as a function of *SHR* for $Load = 300$ tons and $T_{wb} = 18$℃.

with increasing load. In the system with faults such as temperature sensor fault, pump and fan degradation, all values of the heat transfer coefficient-area product decrease more than the 3% from the value without faults. The greater the value of fault is, the more the value decreases.

Figure 2 shows that the values of the heat transfer coefficient-area product decrease with increasing ambient wet bulb temperature at a fixed load of 300 tons and sensible heat ratio of 0.8. All values of heat transfer coefficient-area product with faults decrease in similar fashion to that shown in Figure 1. In Figure 3, the load of 300 tons and the ambient wet bulb temperature is 18℃. The values of the heat transfer coefficient-area product increase with increasing sensible heat ratio. All values of heat transfer coefficient-area product with faults also decrease similar to that shown in Figure 1.

Figures 4 to 6 compare the *APPROACH* in cooling tower without any faults and with some faults as a function of the load (Figure 4), as a function of the ambient wet bulb temperature (Figure 5), and as a function of the sensible heat ratio (Figure 6), respectively. As shown in Figure 4, most values of the *APPROACH* decrease for lower loads and increase for higher loads. The *APPROACH* with the pump fault of a water flow rate reduction decreases and the *APPROACH* with the temperature sensor and fan faults increase over the no-fault value. The *APPROACH* with faults differs more than 8% from the no-fault value.

Figure 5 shows that most values of the *APPROACH* decrease with increasing ambient wet bulb temperature. The *APPROACH* values with faults differ approximately 11% from the no-fault values. Figure 6 shows that most values of the *APPROACH* increase with increasing ambient wet bulb temperature. The *APPROACH* with faults differs approximately 13% from the no-fault values.

Figures 7 to 9 compare the tower effectiveness without any faults and with some faults

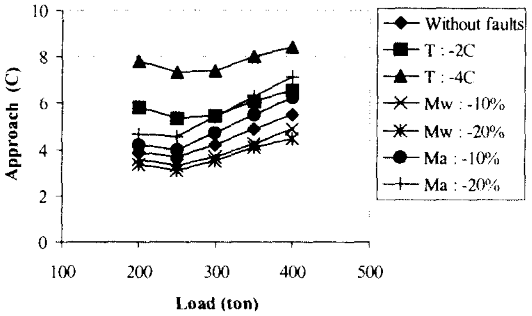

Fig. 4 The *APPROACH* as a function of cooling loads for $T_{wb}=18℃$ and $SHR=0.8$.

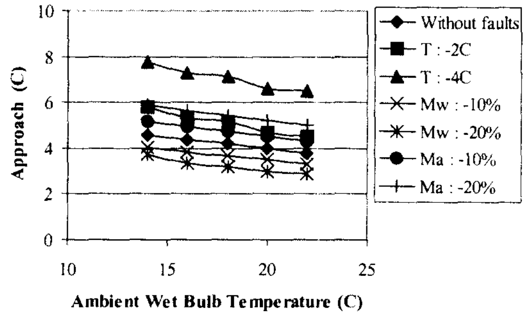

Fig. 5 The *APPROACH* as a function of ambient wet bulb temperature for $Load=300$ tons and $SHR=0.8$.

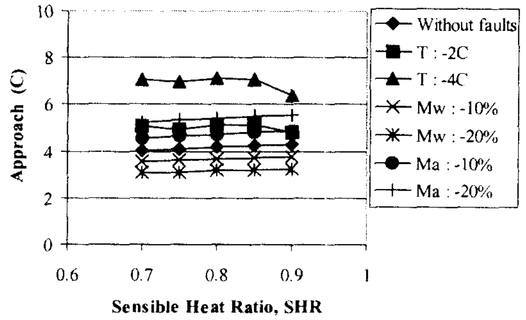

Fig. 6 The *APPROACH* as a function of *SHR* for $Load=300$ tons and $T_{wb}=18℃$.

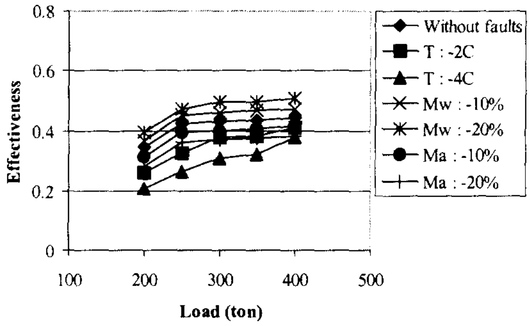

Fig. 7 The Effectiveness as a function of cooling loads for $T_{wb}=18℃$ and $SHR=0.8$.

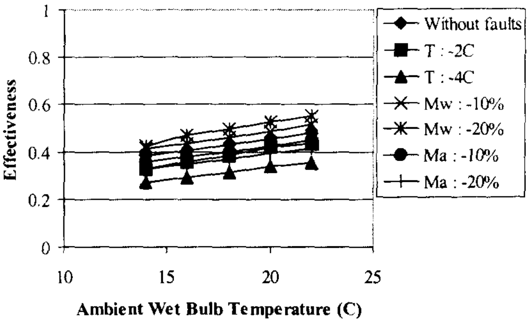

Fig. 8 The Effectiveness as a function of ambient wet bulb temperature for *Load*=300 tons and $SHR=0.8$.

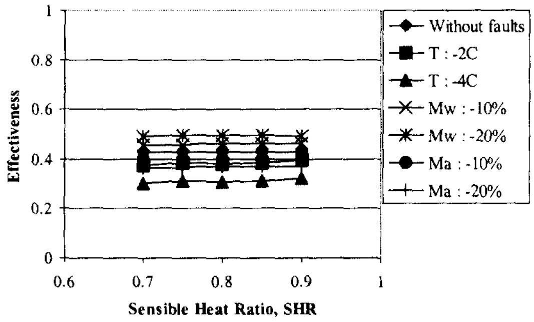

Fig. 9 The Effectiveness as a function of *SHR* for *Load*=300 tons and $T_{wb}=18℃$.

as a function of the load (Figure 7), as a function of the ambient wet bulb temperature (Figure 8), and as a function of the sensible heat ratio (Figure 9), respectively. As shown in Figure 7, most values of the tower effectiveness increase much for lower loads and increase a little for higher loads. The tower effectiveness with the pump fault of a water flow rate reduction increases and the tower effectiveness with the temperature sensor and fan faults decrease over the no-fault values. The tower effectiveness with faults differs more than 5% from the no-fault values. Figure 8 shows that most values of the tower effectiveness increase with increasing ambient wet bulb temperature. The values with faults change in similar fashion to that shown in Figure 7 and the tower effectiveness with faults differ approximately more than 7% from the no-fault values. Figure 9 shows that tower effectiveness is approximately constant with increasing the sensible heat ratio, and that the variation of the sen-

Table 2 The system characteristic parameter variation with or without faults in condenser outlet water temperature sensor

Fault	*UA*	*APPROACH*	Effectiveness
−4℃	102500(−21.6%)	7.793(+102.2%)	0.209(−39.2%)
−2℃	115500(−12.0%)	5.818(+51.0%)	0.259(−24.7%)
−1℃	123000(−5.9%)	4.835(+25.5%)	0.302(−12.2%)
Without faults	130700(0%)	3.854(0%)	0.344(0%)
+1℃	135100(+3.4%)	3.417(−11.3%)	0.385(−11.9%)
+2℃	139000(+6.4%)	2.819(−26.9%)	0.416(−20.9%)
+4℃	139000(+6.4%)	2.819(−26.9%)	0.416(−20.9%)

Load=200 tons, $T_{wb}=18℃$, $SHR=0.8$

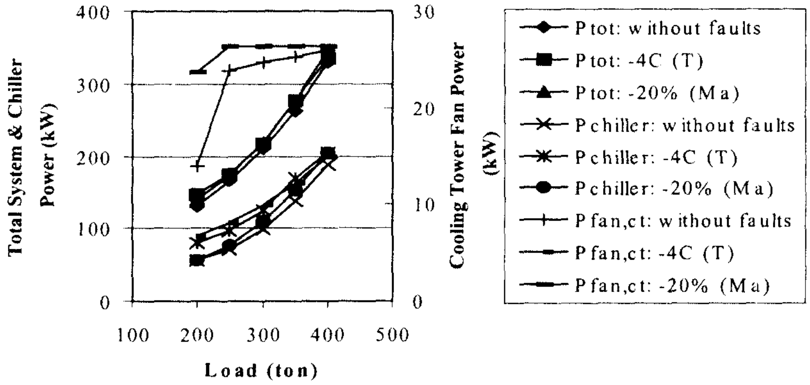

Fig. 10 Total system and component powers as a function of cooling loads for $T_{wb}=18℃$ and $SHR=0.8$.

sible heat ratio has no influence on effectiveness. The values with faults change in similar fashion to that shown in Figure 7 or Figure 8 and the tower effectiveness with faults differs approximately more than 7% from the no-fault values.

Table 2 shows system characteristic parameter variations with or without faults in condenser outlet water temperature sensor. The parameter values with ±1℃, ±2℃ and ±4℃ sensor errors are compared to those without sensor error. The parameter values with plus sensor errors are in the opposite direction of the ones with minus sensor errors.

The parameter variations with plus temperature sensor errors under most of the conditions (load and ambient conditions) considered in this study are near to or the same as the values without faults.

Figure 10 shows total system power, chiller power, and cooling tower fan power without any faults and with some faults as a function of the load. The total system power and chiller powers with faults increase over the no-fault values. However, in the cooling tower fan power with temperature sensor error decrease below the no-fault values and the power with fan fault increase over the no-fault values.

Table 3 Rules for diagnosing faults in cooling tower

Faults type		*UA*	*APPROACH*	Effectiveness	Cooling tower fan power	Sensitivity
Temperature sensor fault	−	↓	↑	↓	↓	1st : *APPROACH* 2nd : Effectiveness 3rd : *UA* 4th : Fan power
	+	↑	↓	↑	↑	
Pump fault		↓	↓	↑		1st : *UA* 2nd : *APPROACH* 3rd : Effectiveness
Fan fault		↓	↑	↓	↑	1st : *APPROACH* 2nd : Effectiveness 3rd : *UA* 4th : Fan power

↑ : increase, ↓ : decrease

Table 3 gives the diagnostic rules for the faults considered in this study. This rule was developed through simulation and investigating the results of Figures 1 to 10 and Table 2. With minus temperature sensor error, both of the *UA* and the effectiveness decrease, the *APPROACH* increases, and the cooling fan power decreases. The values of three characteristic quantities (the *UA*, the *APPROACH* and the effectiveness) and cooling fan power with plus temperature sensor error are in the opposite direction of the ones with minus temperature error. Both of the *UA* and the *APPROACH* with pump fault decrease, the effectiveness increases. In cooling tower with fan fault, three characteristic quantities vary similar to those with minus temperature sensor error, but the power increases. Therefore, the plus temperature sensor error or pump fault can be diagnosed by using the characteristic quantities. Diagnosing minus temperature sensor error or fan fault can be done by using the values of cooling tower fan power and the three characteristic quantities. A rank of 1 to 3 with 1 being the most sensitive to faults in those three quantities was also shown in Table 3. Cooling tower fan power gives an idea for diagnosing the difference between minus temperature sensor error and fan fault. The system control can be overriden locally due to some constraints. However, the system presents same tendency even though absolute values of characteristic parameter differs within uncontrollable region due to constraints.

Model-based fault detection and diagnosis in this study is based on the values of the characteristic quantities and power in the system to be operated under optimal control. In the system which is not optimally controlled, the magnitudes of the characteristic quantities and power are different from those under optimal control, but both of the systems under non-optimal or optimal control have the same tendency (increase or decrease).

4. Conclusions

A simple model-based method for detecting and diagnosing some faults in the cooling tower of air-conditioning system was developed and evaluated by simulation. Three distinct faults were considered: cooling tower inlet water temperature sensor fault, cooling tower pump fault, and cooling tower fan fault. The faults in cooling tower were detected and diagnosed through the deviations in the values of fan power and three system characteristic parameters: the cooling tower heat transfer coefficient-area product *UA*, the tower *APPROACH*, and the tower effectiveness.

With faults, most of the system characteristic parameter variations, the *UA*, the tower *APPROACH*, and the tower effectiveness with faults increase or decrease highly over or below the no-fault values. From the diagnostic rules for the faults developed in this study, the plus temperature sensor error or pump fault can be diagnosed by using the three characteristic quantities (the *UA*, the *APPROACH*, and the tower effectiveness), and diagnosing minus temperature sensor error or fan fault can be done by using the values of cooling tower fan power and the three characteristic quantities.

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