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Feasible Tool Development for Fault Detection and Diagnosis on Chiller Operations in Thailand

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Abstract

Commercial buildings are one of the most energy-intensive sectors. A chiller system is the most significant machine in this building type consuming around 30% of the total power. However, degradation faults on chillers caused by unsuitable design, improper routine operations and commissioning lead to wasted energy up to 30% in average. Without proper and well-serviced maintenances in time, the faults will become failures causing high cost services and system shutdown. To minimize these happenings, automated fault detection and diagnosis (FDD) has been developed and embedded into on-board controllers of heating, ventilation and air-conditioning (HVAC) equipment (e.g., rooftop unit) used in developed counties such as the U.S. and U.K. With AFDD implementation, the machine controllers can automate the process of continuous commissioning and endow the building energy systems with intelligence so that they can self-diagnose problems and even self-execute correcting actions for non-optimal operations to provide recommendation reports for building operators. AFDD has been growing well in the industrial countries because they have testing facilities and machine laboratories to efficiently develop and test FDD algorithms. However, these testing elements are cost-prohibitive in developing countries like Thailand. To overcome these limitations, this paper feasibly proposes the tool development for FDD applied in water-cooled chillers. First of all, the benchmark method and tool under the research project 1043-RP sponsored by the American Society of Heating, Refrigerating, and Air-Conditioning Engineers (ASHRAE) are investigated to determine the possible trend of typical faulty operations occurring in the chiller; this project is used as the guideline to limit the scope of considered faults. Next, American and Thai manufacturer's data are compared and used to construct fault-free models for generating more non-fault models for Thailand chillers. At last, the obtained information from the first two steps are compared and discussed as the feasible benchmark chiller evaluation tool. To evaluate the Thai benchmark method, chiller field data obtained from two commercial buildings are conducted. The proposed benchmark method can be used as an effective tool to further detect and diagnose faults, and it should be further tested for enhancing tool reliability and potential.

Keywords: Benchmark Laboratory Data, Chiller, Degradation Fault, Fault Detection and Diagnosis, Manufacturing Data

1. Introduction

Smart building solutions are perspective technologies to efficiently improve building energy systems in modern building industry via locally advanced controllers or centralized control in terms of building automation system (BAS). Although these advanced controllers can be used to enhance the system efficiency, degradation faults can develop during system installations, routine operations or scheduled preventive maintenances and can result in excessive energy waste. In a survey of UK buildings, the data showed 25–50% of energy wasted from faults in heating, ventilation and air-conditioning (HVAC) systems. This waste range could be reduced below 15% whenever those faults could be detected and identified early in the premature stage before unacceptable damages occur [1]. These issues significantly challenge the current status of energy efficiency in buildings.

For now in developed counties, automated fault detection and diagnosis (AFDD) algorithms have been mainly developed for minimizing system performance degradation, product deterioration, and equipment damage while improving human comfort and safety, and assisting in the improved planning of the maintenance program. Especially, a chiller consumes 28 – 30% of the total power consumptions of a building [2]. American Society of Heating, Refrigerating, and Air-Conditioning Engineers (ASHRAE) had funded the three on-going projects composing of: ASHRAE RP-1043 [3], ASHRAE RP-1275 [2] and ASHRAE RP-1486 [4] for successfully developing on-line and benchmarking AFDD on water-cooled chillers. For successful cases, with well-designed and efficient AFDD implementations in RTUs, enabling AFDD can eliminate waste energy caused by faults and non-optimal operations in HVAC systems up to 30% in average [5] and enhance productivity and reduce maintenance costs by 70% of yearly preventative maintenance [6].

However, fault-free data from a laboratory are cost-prohibitive in developing countries, and HVAC machine is not standardized leading obstructing in

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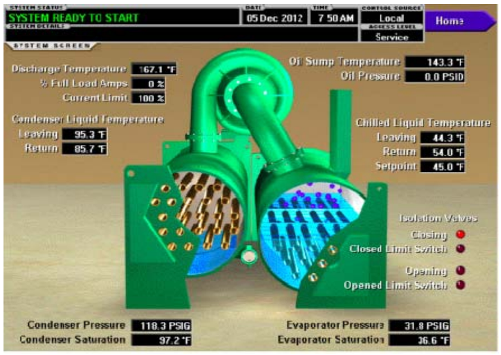
AFDD development for HVAC areas. To penetrate these barriers, this paper feasibly proposes tool development to construct FDD standard for water-cooled chillers in Thailand. First of all, the benchmark data of ASHRAE RP-1043 are investigated for water-side and refrigerant-side compared to imported American chiller brand. After that, manufacturers' data are further surveyed since they can be used to develop virtual sensors [7] instead of unavailable physical sensors embedded on the chiller. In addition, ASHRAE RP-1275 is used to study simplified chiller models based on the available parameters in chiller case studies. Lastly, two water-cooled chillers are utilized to evaluate the feasible tools as effective tools for Thailand standard in near future.

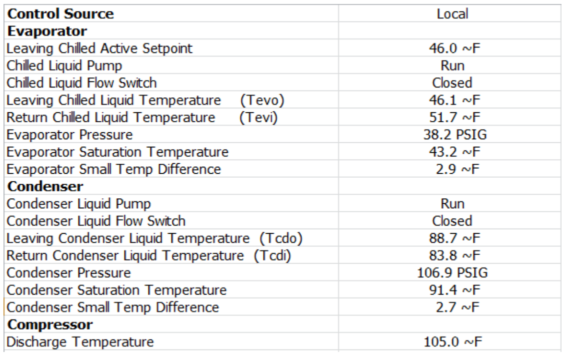
2. Backgrounds

Based on ASHRAE RP-1043, all parameters recorded are compared to one of the American modern chiller brands. As shown in Fig. 1.



SYSTEM READY TO START
05 Dec 2012
7 50 AM
Control Source: Local
Access Level: Service
Discharge Temperature 167.1 °F
% Full Load Amps 0 %
Current Limit 100 %
Condenser Liquid Temperature
Leaving 95.3 °F
Return 85.7 °F
Oil Sump Temperature 143.3 °F
Oil Pressure 0.0 PSID
Chilled Liquid Temperature
Leaving 44.3 °F
Return 54.0 °F
Setpoint 45.0 °F
Condenser Pressure 118.3 PSIG
Condenser Saturation 97.2 °F
Evaporator Pressure 31.8 PSIG
Evaporator Saturation 36.6 °F

Fig. 1 Example of modern chiller monitoring



Control Source	Local
Evaporator	
Leaving Chilled Active Setpoint	46.0 ~F
Chilled Liquid Pump	Run
Chilled Liquid Flow Switch	Closed
Leaving Chilled Liquid Temperature (Tevo)	46.1 ~F
Return Chilled Liquid Temperature (Tevi)	51.7 ~F
Evaporator Pressure	38.2 PSIG
Evaporator Saturation Temperature	43.2 ~F
Evaporator Small Temp Difference	2.9 ~F
Condenser	
Condenser Liquid Pump	Run
Condenser Liquid Flow Switch	Closed
Leaving Condenser Liquid Temperature (Tcdo)	88.7 ~F
Return Condenser Liquid Temperature (Tcdi)	83.8 ~F
Condenser Pressure	106.9 PSIG
Condenser Saturation Temperature	91.4 ~F
Condenser Small Temp Difference	2.7 ~F
Compressor	
Discharge Temperature	105.0 ~F

Fig. 2 Available raw data from on-board controller

2.1 Parameter Measurement Analysis

The chiller monitoring is a graphical user interface (GUI) which can be coded by any commercial visual computer programming software via a board controller. Thus, all embedded sensors in the chiller can be downloaded via the chiller manager software as depicted in Fig. 2. Meanwhile, all significant parameters (water-side and refrigerant-side) are illustrated in Fig. 3 and are summarized in Table1.

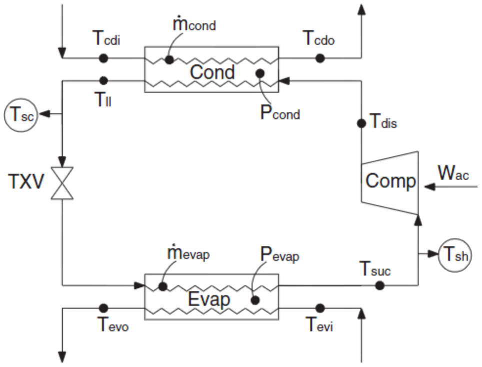


Fig. 3 Required parameters on water-cooled chiller system [4]

Table1 Recorded Data Summary of Chiller Monitoring in Thailand Building Examples

System	Recorded parameters				
Evaporator	Tevo	Tevi	Pevap	Tevaps	Tsh
System	Recorded parameters				
Condenser	Tcdo	Tcdi	Pcond	Tconds	Tsc
System	Recorded parameters				
Compressor	Tdis		Tsuc		Wac
Others	% Chiller Load and kWh				

For the evaporator, Tevi and Tevo are return and supply chilled water temperature, whereas Pevaps stands for evaporator pressure and. Tsh is superheat temperature.

For the condenser, Tcdo and Tcdi are leaving and entering condenser water temperature; Tconds is condenser saturation temperature; Pcond is condenser pressure; and Tsc is sub-cooling temperature.

For the compressor, Tdis and Tsuc are discharge and suction temperature, whereas Wac refers input compressor power.

With the comparisons to ASHRAE RP-1043, water flow rate sensors are not available in condenser and evaporator. Also, discharge superheat is not measured, but it can be replaced by the difference between Tdis and Tc, whereas refrigerant-line temperature (T_{ll}) can be computed from the difference between Tc and Tsc. Even through most of chiller parameters are downloaded, but they are not fault-free data. Thus, any analysis method is degraded by unexpected fault levels of the current system performance.

2.2 Typical Chiller Faults

Based on the considered data in last section, they are adequate to diagnose typical faults leading to chiller performance degradation called “degradation faults”. They are as follows:

Fault (F) 1: Reduced condenser water flow is examined to identify lower condenser water flow rate causing higher condenser temperature and pressure, thereby leading the compressor to work harder and draw more power.

F2. Similar to F1, reduced evaporator water flow refers evaporator fouling and lower heat absorption efficiency.

F3: Low refrigerant charge is one of service faults leading to lower heat transfer efficiency.

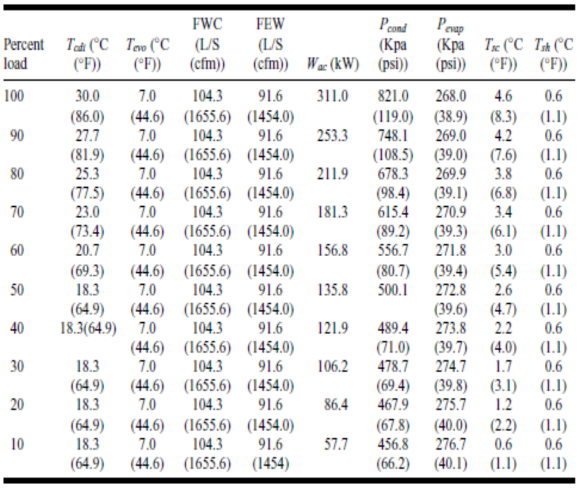
F4: Refrigerant overcharge is caused by service causing high pressure and higher compressor work.

F5: Non-condensable gas in the refrigerant tends to accumulate in the condenser due to incomplete refrigerant cycle; its primary effect is to increase heat transfer resistance, resulting in high condenser pressure and temperature.

F6: Condenser fouling typically accumulates gradually in the condenser tubes without water treatment processes in water-cooled chillers.

These faults cause overall chiller system degradation. Energy savings in terms of recovering near-design chiller performance can be conducted if these degradation faults are diagnosed in time. However, without physical repairs, they could be severe when the faults can gradually develop to sudden faults and failures. The diagnostics will be potentially accurate and reliable if fault-free data are available.

2.3 Fault-free Model from Manufacturers’ data



Percent load	T_{cdi} (°C (°F))	T_{evo} (°C (°F))	FWC (L/S (cfm))	FEW (L/S (cfm))	W_{ac} (kW)	P_{cond} (Kpa (psi))	P_{evap} (Kpa (psi))	T_{sc} (°C (°F))	T_{sh} (°C (°F))
100	30.0 (86.0)	7.0 (44.6)	104.3 (1655.6)	91.6 (1454.0)	311.0	821.0 (119.0)	268.0 (38.9)	4.6 (8.3)	0.6 (1.1)
90	27.7 (81.9)	7.0 (44.6)	104.3 (1655.6)	91.6 (1454.0)	253.3	748.1 (108.5)	269.0 (39.0)	4.2 (7.6)	0.6 (1.1)
80	25.3 (77.5)	7.0 (44.6)	104.3 (1655.6)	91.6 (1454.0)	211.9	678.3 (98.4)	269.9 (39.1)	3.8 (6.8)	0.6 (1.1)
70	23.0 (73.4)	7.0 (44.6)	104.3 (1655.6)	91.6 (1454.0)	181.3	615.4 (89.2)	270.9 (39.3)	3.4 (6.1)	0.6 (1.1)
60	20.7 (69.3)	7.0 (44.6)	104.3 (1655.6)	91.6 (1454.0)	156.8	556.7 (80.7)	271.8 (39.4)	3.0 (5.4)	0.6 (1.1)
50	18.3 (64.9)	7.0 (44.6)	104.3 (1655.6)	91.6 (1454.0)	135.8	500.1	272.8 (39.6)	2.6 (4.7)	0.6 (1.1)
40	18.3(64.9)	7.0 (44.6)	104.3 (1655.6)	91.6 (1454.0)	121.9	489.4 (71.0)	273.8 (39.7)	2.2 (4.0)	0.6 (1.1)
30	18.3 (64.9)	7.0 (44.6)	104.3 (1655.6)	91.6 (1454.0)	106.2	478.7 (69.4)	274.7 (39.8)	1.7 (3.1)	0.6 (1.1)
20	18.3 (64.9)	7.0 (44.6)	104.3 (1655.6)	91.6 (1454.0)	86.4	467.9 (67.8)	275.7 (40.0)	1.2 (2.2)	0.6 (1.1)
10	18.3 (64.9)	7.0 (44.6)	104.3 (1655.6)	91.6 (1454)	57.7	456.8 (66.2)	276.7 (40.1)	0.6 (1.1)	0.6 (1.1)

FWC: Condenser water flow rate; FWE: evaporator water flow rate.

Fig. 4 US Manufacturers’ data example [4]

Due to the limitations to obtain non-fault data from a chiller testing laboratory, some fault-free data can be compensated by manufacturers’ data. The US manufacturers’ data example is depicted in Fig. 4 in which Pcond and Pevap are provided at different load conditions. These pressure values can be indirectly used to approximate fault-free conditions of Tcond and Tevap by multiple linear relations (MLR) [4]. More importantly, fault-free operations of Tsh and Tsc given are utilized as normal or non-fault conditions of refrigerant status. However, Tcdo and Tevi are not in this example then temperature differences of condenser and evaporator can be determined at normal conditions.

2.4 Simplified Fault-free Chiller Model

Using fault-free data and fault simulations of ASHARE RP - 1043 for off-line FDD analysis in ongoing ASHRAE RP – 1275 project, 27 different conditions were run to collect normal data conditions. The 12 benchmark data sets recommended in RP 1043 were selected to develop the benchmark MLR equation as simplified fault-free models in RP 1275 (Eq. 1).

$$y = a_1 T_{evo} + a_2 T_{cdi} + a_3 Q_{ch} + a_4 T_{evo} Q_{ch} + a_5 T_{cdi} Q_{ch} + a_6 Q_{ch} Q_{ch} + a_0 \qquad (1)$$

, where y consisted of the following quantities: power use in kW, Pevap, Pcond, Tsc, Tsh, evaporator water temperature difference (CQ1), condenser water and temperature difference (CQ2). Meanwhile, a_0 to a_6 are MLR coefficients obtained from empirical or manufacturers’ data. Using the fault-free or quality data, Eq. 1 can be applied in FDD and model prediction of chiller optimization.

3. Modified Tools for Thailand Applications

The surveyed data and methods in section 2 are modified in this section for Thailand applications. With the direct data communication through a controller port, all parameters in Table 1 can be downloaded from imported US chillers in Thailand.

3.1 Chiller Interaction Development

According to Eq. 1 and MLR principle, independent variables used in MLR are dominant to the dependent variable (y). If kW is selected as y with consistent sampling time, kWh can be used instead of kW. Consequently, Tcdi, Tevo and Qch significantly relate to kWh of chiller. 100 % load refers to the design condition at peak load operation. Thus, this proposed rule can be used to initially examine chiller operations.

In case of the correlated value in terms of Pearson’s correlation (R), if some independent parameters do not influence kWh, it means other effects cause kWh instead of these low R values. Using chiller characteristics versus each parameter, chiller interaction conditions can be designed as tabulated in Table 2.

Table2 Chiller interaction

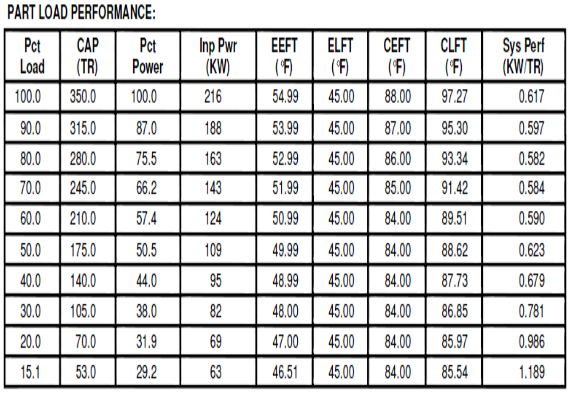
Parameters	Pearson’s correlation level (R) between kWh and the parameters with interaction description
Tcdi	Medium level

Tcdi is return water temperature from a cooling tower used in condenser for heat transfer process. High entering Tcdi cause high pressure operations and excessive power.	
Tevo	Medium level (-, negative relation direction)
Tevo is directly used to supply chilled water temperature for air-handing units (AHU). High Tevo results in lower chiller load or chiller power.	
Load	High level
Qch refer to chiller load; high load operations result in high kWh.	

Note: Low level (0-0.50), Medium level (0.51-0.89) and high level (0.9-1.0) [8, 9]

The application of this chiller interaction can be applied to initially investigate acceptable routine chiller operations of Thailand building operation and maintenance (O&M) operators.

4.2 Fault-free Model of Manufacturers' Data



PART LOAD PERFORMANCE:

Pct Load	CAP (TR)	Pct Power	Inp Pwr (KW)	EEFT (°F)	ELFT (°F)	CEFT (°F)	CLFT (°F)	Sys Perf (KW/TR)
100.0	350.0	100.0	216	54.99	45.00	88.00	97.27	0.617
90.0	315.0	87.0	188	53.99	45.00	87.00	95.30	0.597
80.0	280.0	75.5	163	52.99	45.00	86.00	93.34	0.582
70.0	245.0	66.2	143	51.99	45.00	85.00	91.42	0.584
60.0	210.0	57.4	124	50.99	45.00	84.00	89.51	0.590
50.0	175.0	50.5	109	49.99	45.00	84.00	88.62	0.623
40.0	140.0	44.0	95	48.99	45.00	84.00	87.73	0.679
30.0	105.0	38.0	82	48.00	45.00	84.00	86.85	0.781
20.0	70.0	31.9	69	47.00	45.00	84.00	85.97	0.986
15.1	53.0	29.2	63	46.51	45.00	84.00	85.54	1.189

Fig. 5 Imported US Manufacturers' data example

Comparing Fig. 5 to Fig. 4, it can be noticed that the figure provides the leaving and entering water temperature of the condenser and evaporator. Therefore, the differences between EEFT (Tevi) and ELFT (Tevo) are CQ1 values. Similar to CQ1, designed operations of the CQ2 values are the differences between CEFT (Tcdi) and CLFT (Tcdo) at distinguishable chiller loads. By applying the benchmark MLR model in Eq. 1 by selecting y equaling CQ1 and CQ2, the water temperature difference equations can be rearranged by simple linear regression (SLR) since Tevi is set constantly at 45 °F and Tcdi does not contribute much higher prediction performance that why the predicted SLR is potential enough as follow:

$$CQ_i = a_1 Q_{ch} + a_0 \qquad (2)$$

, where i is subscribed for 1 and 2 and Qch can be used for chiller load or chiller power. The example of Eq.2 is applied to construct the black linear line in Fig. 6 for CQ2 which is plotted versus the measured CQ2 of any red points from a chiller operation monitoring system.

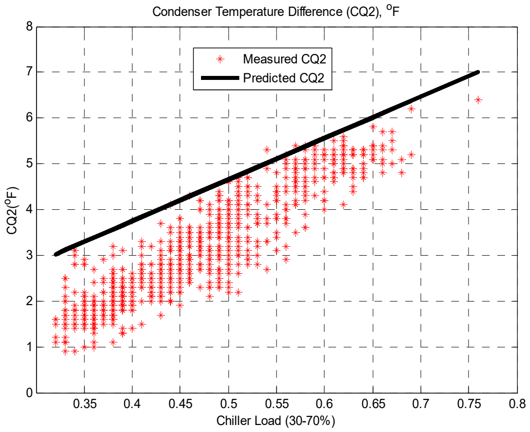


Fig. 6 Normal and measured CQ2 versus chiller load

4. Method Evaluation for Thailand Applications

For the tool evaluations, two chiller data from two commercial buildings in Thailand are applied to evaluate the proposed techniques.

4.1 Performance Investigation via Interaction

To firstly calculate R values of each chiller versus the three significant independent parameters, the computed values are compared to the expected interaction performance criteria in Table 2. The primary inspections are resulted in Table 3.

Table 5 Chiller interaction analysis

R value	Chiller Interaction		
	Tcdi	Tevo	Load
Chiller A	0.34 (fault)	-0.07 (fault)	-0.11 (fault)
Chiller B	0.78 (normal)	-0.51 (normal)	0.96 (normal)

In Table 5, all investigations are faulty for chiller A; it can be concluded that kWh of chiller A are consumed by other factors such as faulty commisioning or routine operations (unbalanced water stsrem). In contrast, the operations of chiller B are normal or accetable because the R values are in the criteria ranges; however, Tevo vs. kWh is almost faulty for chiller B; it can imply that Tevo set-points are not properly set cooresponding to the building conditioned spcae.

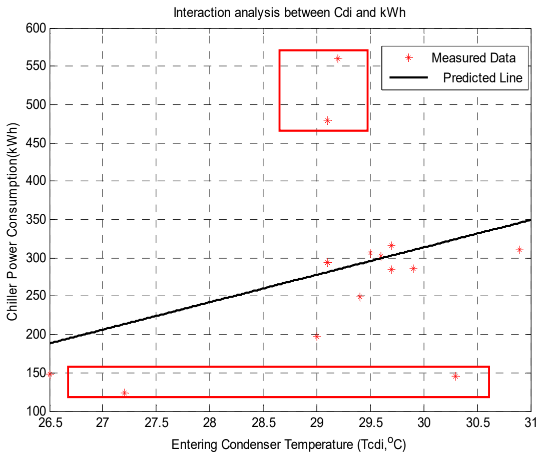


Fig. 7 Faulty relation between Tcdi and kWh for chiller A

Fig. 7 depicted the relation between Tcdi and chiller A performance (kWh) for two weeks. At least two data areas are skew from the expected linear line. It confirms the conclusions that the operations are affected by other system parameters. With investigations at the building, at least two significant points were founded: 1) the supply and return valves of AHUs are unbalanced. When zone temperatures cannot be controlled by the temperature set-points, technicians adjust the balanced valves manually and 2) some temperature sensors used for controlling zone temperatures were not calibrated; they always read wrongly at 24 °C, even the operating percentages of automatic control valves are reduced by BAS monitor. All these problem examples cause unstandardized routine operations leading to excessive power consumptions.

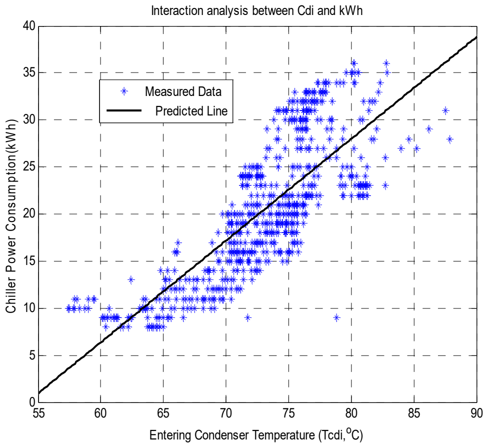


Fig. 8 Normal relation between Tcdi and kWh for chiller B

In opposite to chiller A, chiller B performance is illustrated in Fig. 8.

4.2 FDD for Reduced Water Flow rate

From section 4.2, Eq.2 is applied in quantifying indirect water flow rate in terms of CQ1 and CQ2 for evaporator and condenser in Fig. 9 and 6, respectively.

In Fig. 9, by comparing the predicted model and measured data for water temperature differences at evaporator (CQ1), the steady-state heat balance equations in Eq. 3 can be used to explain the water flow effect to temperature difference.

$$Q_{evap} = m_{evap} c_p CQ_1 \tag{3}$$

$$Q_{cond} = m_{cond} c_p CQ_2 \tag{4}$$

, where Q_{evap} and Q_{cond} are heat transfer at evaporator and condenser; m_{evap} and m_{cond} are water flow rate at at evaporator and condenser, whereas C_p is constant heat transfer capacity.

Meanwhile, Eq. 4 is used to explain the correlation between condenser water flow rate and CQ2. These two relations are similar in opposite heat transfer process. If CQ_1 or CQ_2 is higher than the predicted model obtained from the manufacturers' data or fault-free data from RP-1043 (e.g. normal 2data set), reduced water flow rate results in lower heat transfer efficiency and excessive power consumptions in the chiller compressors as depicted in Fig. 9 that normal 2 data set of CQ1 vs. kW is plotted to compare with the performance line of the F1 data set at level 4 (40% reduced flow rate).

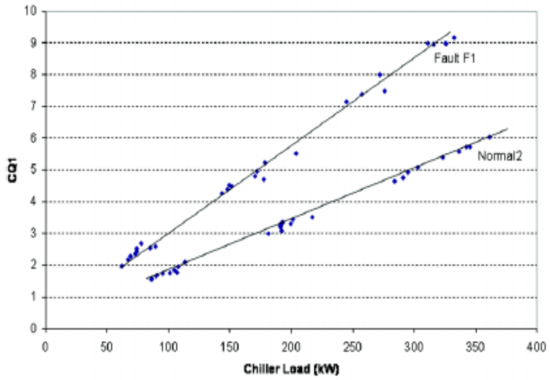


Fig. 9 Normal 2 data and F1 at fault level 4 of CQ1 versus chiller load (kW) [2]

However, in practice such as the operations of chiller B in Fig. 10, the measured CQ1 values are all lower than the normal data from the manufacturers' data leading to higher evaporator water flow rate corresponding to the principle in Eq. 3 called "low delta T syndrome" or low evaporator temperature difference; this syndrome practically occurs due to selecting oversizing control valves or unbalanced water flow causing frequent compressor and primary water pumps cycles. As a result, equipment life cycle is shorter and waste energy is very high. .

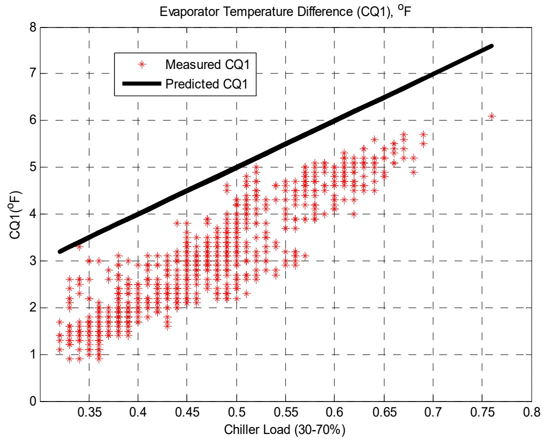


Fig. 10 Normal and measured CQ1 versus chiller load in building B

4.3 Simplified Model Prediction

According to section 2.4, the benchmark equation can be modified for model predictions for FDD and optimization applications. However, due to non-linear terms may lead to divergence or unstable solutions for optimization applications. With the testing, reduction in non-linear effect in Eq.5 seldom affects the model prediction performance

$$kW = 0.5T_{cdi} - 1.94T_{evo} + 286.8Load + 3.16 \qquad (5)$$

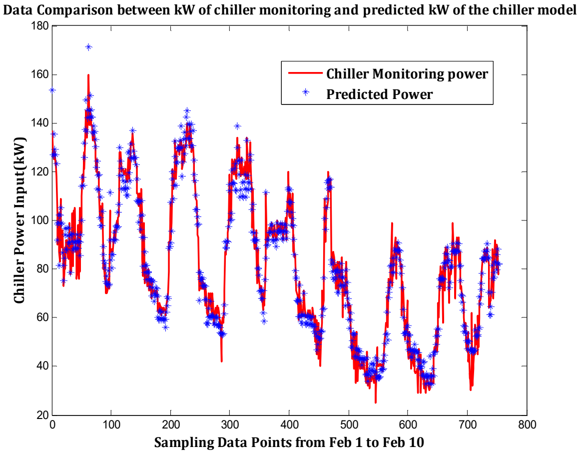


Fig. 11 Predicted and monitoring kW of chiller B

Using regression tool, the accuracy of Eq. 5 is 96.67 % in terms of R^2 (coefficient of determination) as shown in Fig. 11. With this model performance, other chiller parameters can be also predicted potentially and can be further to develop user-friendly chiller manager based on simple tool such as Solver function in Excel instead of commercial chiller manager in graphical user interface (GUI).

5. Conclusion and Contribution

Due to ineffective HVAC routine operations and building commissioning without standard, AFDD is a self-diagnose tool to identify fault locations for building operators to provide physical repairs in time. With this protection, HVAC equipment can be recovered to near-design efficiency resulting energy savings and productivity. However, development of AFDD in developing countries like Thailand has limitations due to cost-prohibitive issues. This paper feasibly develops FDD tool for compensating faulty-free data from chiller lab testing. The developed tool consists of: 1) chiller benchmark data RP-1043; 2) chiller benchmark model RP-1275 and 3) fault-free physical measurement from manufacturers' data. Using all the three information, chiller interaction, simplified chiller model and model prediction can be developed for Thailand chiller applications. With the testing in building A and B, some common chiller faults can be diagnosed without investment and original system retrofitting (invasive).

6. Acknowledgement

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7. References

[1] Cibse, GH. (2000). Building control systems, Butterworth-Heinemann, Oxford, 2000.

[2] Reddy, TA. (2006). Evaluation and assessment of fault detection and diagnostic methods for centrifugal chillers—Phase II, Final project report of ASHRAE Research Project (RP-1275), 2006.

[3] Bendapudi, S. and Bruan, JE. (2002). Development and validation of a mechanistic dynamic model for a vapor compression centrifugal liquid chiller. ASHRAE Research Project (1043-RP). 2002.

[4 Zhao, X., Yang, M. and Li, H. (2011). Decoupling features for fault detection and diagnosis on centrifugal chillers (1486-RP): *HVAC&R Research* 2011; Vol 17(1): 86-106.

[5] Katipamula, S., Brambley, M.R. (2005). Methods for fault detection, diagnostics and prognostics for building Systems: A review. Part I. *HVAC&R Research* 2005; Vol 11 (1): 3-25.

[6] Li, H., Braun, J.E. (2004). An economic evaluation of automated fault detection and diagnosis for rooftop air conditioners. International Refrigeration and Air Conditioning Conference. 2004.

[7] Yu, Y., Woradechjumroen,. D and Yu, D. (2014). A review of fault detection and diagnosis methodologies on air-handling Units. *Energy and Buildings 2014*; Vol 82: 550-562.