Evaluation of a Decoupling-Based Fault Detection and Diagnostic Technique – Part II: Field Evaluation and Application

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Abstract: Existing methods addressing automated fault detection and diagnosis (FDD) for vapor compression air conditioning system have good performance for faults that occur individually, but they have difficulty in handling multiple-simultaneous faults. The decoupling-based (DB) FDD method explicitly addresses diagnostics for multiple-simultaneous faults for the first time. This paper is the second part of a two-part evaluation of the decoupling-based (DB) fault detection and diagnosis (FDD) technique whose intent is to validate the DB FDD performance and demonstrate its applications. The first part focuses on sensitivity and robustness evaluation through controlled field emulation testing. In this paper, the technique is applied to a number of field sites in California. Detailed results are given for a single site and summary results are given for the other sites. In sum, about 70% of the investigated systems are impacted by faults and about 40% have more than one fault. Service is justified for about 40% of the units. Most of the diagnosed faults are verified through field visits.

Key words: fault detection and diagnostics; air conditioning; decoupling; multiple faults

1 INTRODUCTION

This paper is the second part of a two-part evaluation of the decoupling-based (DB) fault detection and diagnosis (FDD) technique developed by Li and Braun [1]. The first part [2] focuses on sensitivity and robustness evaluation through controlled field emulation testing. Sensitivity tests with artificially introduced faults show that individual faults can be identified before they cause a 5% of degradation in cooling capacity, EER and sensible heat ratio. Robustness tests for forty-one multiple-simultaneous-fault combinations demonstrate that no wrong diagnosis occurred with only two false alarms and sensitivity losses for a liquid-line restriction.

To further demonstrate the performance of the DB FDD method under real field conditions, the method is applied to a number of different field sites in California. Detailed results are given for a single site and summary results are given for the other sites.

2 DESCRIPTION OF FIELD SITES

All the field sites in California are small commercial buildings that utilize packaged air conditioning and heating equipment. The criteria used for selecting the field-sites included: 1) building occupancy types and sizes; 2) HVAC system types installed, and 3) climate regions (see Tab. 1).

The types of building utilized for this study include modular schoolrooms, children's play areas located in fast food restaurants and retail stores of a major pharmacy chain. The HVAC systems installed include different rooftop and wall mounted units with different capacities and from different manufacturers. The climates include two different macroclimate types: coastal and inland. The restaurant and school sites are located in Sacramento and the San Francisco Bay area in northern California, while the retail stores are located near Los Angeles and Rialto in southern California.

The HVAC systems are instrumented to provide the following measurements: high and low-side pressures, suction and discharge line temperatures, evaporating and condensing temperatures, liquid line temperatures before and after filter/driers, condenser inlet and outlet air temperatures, return and outdoor and supply air temperatures, return and outdoor air humidities, and current and voltage and power consumption of the compressor. Cooling capacity is estimated using measurements and the virtual sensor for refrigerant mass flow rate [3]. In all, eighteen different packaged air conditioners are monitored.

Tab. 1 California field sites' information

Occupancy Type	Climate Location	Model	Cap (Tons)	Stage No.	Exp. Device	VM No.	Good Data	RTU/COMP Model No.
Schoolroom	Inland Woodland	Bard HP	3.5	1	FXO	1	A.M.	WH421-A CopelandRecip. CR42K6-PFV
						2		
	Coastal Oakland					3	P.M.	
						4		
McDonalds	Inland Sacramento	York	10	2	FXO	Watt Ave	P.M.	D3CG120N20025MKD Bristol Inertia H25A56QDBLA
			6	1		Brad-shaw	A.M.	D1CG072N07925ECC CopelandScroll ZR72KC-TF5
	Coastal Oakland					Milpitas	P.M.	D1CG072N09925C CopelandScroll ZR72KC-TF5-250
			12	2		Castro	P.M.	D4CG150N16525MDB Bristol Inertia H26A720QDBLA
Walgreens	Inland Rialto	Trane HP Voyage r	6.25	1	FXO for Cooling TXV for Heating	3	P.M.	WCD075C30BBC Comp: GP813-NN3-GA
			7.5			1	A.M.	WFD090C30BBC Comp:CRHH075J0H00
						5	A.M.	
						2	A.M.	
						4	A.M.	
	Coastal Anaheim		5	1		2	P.M.	WSCO60A3R0A01H0A Comp: SSR061A3RPA
			6.25			1	P.M.	RTU:WCD075C30CBC Comp: GP813-NN3-GA
						5	P.M.	
			7.5			4	P.M.	RTU: WCD090C30CBC Comp: CRHH075J0H00
						3	P.M.	

Tab. 1 also tabulates other information about the sites and equipment, including expansion device information, system model number, compressor model number and solar radiation information. FXO and TXV denote fixed-orifice and thermal expansion valve respectively. Entries in the 'Good Data' column indicate when the ambient air temperature sensor is not exposed to direct solar radiation, in the morning (A.M.) or afternoon (P.M.).

3. CASE STUDY RESULTS FOR A FASTFOOD PLAY AREA

This site is located in Oakland, California. A single 6-ton rooftop unit is installed for the play area of this fastfood restaurant and uses a scroll compressor and a TXV. Data collected from April to October in 2002 were used to perform FDD. After filtering the transient data using a steady-state detector and removing the bad data corrupted by the acquisition equipment, 1119 data points (one data point every five minutes) were retained. Since the RTU was installed for several years, faults have developed. Statistical results are presented in terms of histogram bar plots.

Fig. 1, 2, 3, 4 and 5 show normalized fault indicators for the five different faults considered in this study. Fig. 1 gives normalized fault indicators for a liquid-line restriction fault. All the steady-state data points are located at the right of the red dotted FDD threshold line and the mean value is around 0.8. That is, all steady-state points indicate that the liquid-line was restricted. Most likely the filter or drier is clogged with debris. If this fault happened individually, it would result in about a 16% cooling capacity degradation.

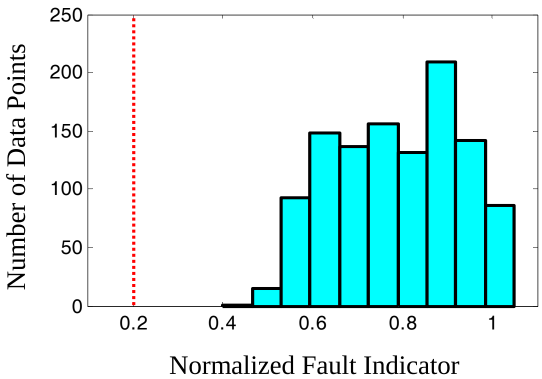

Fig. 1 Liquid-line restriction indicator distribution

Fig. 2 plots the normalized fault indicator for refrigerant charge faults. Similar to Fig. 1, all of the steady-state data points are located to the right of the FDD threshold and the mean value is about 1.6, which means that the system charge is very low. If this fault happened individually, it would result in about a 32% cooling capacity degradation.

Fig. 3 plots the normalized fault indicator for a condenser fouling fault. Most of the steady-state data points (>95%) are to the right of the FDD threshold and the mean value is about 0.5, which indicates that the condenser is a little dirty. If this fault happened individually, it would result in about 10% cooling capacity degradation.

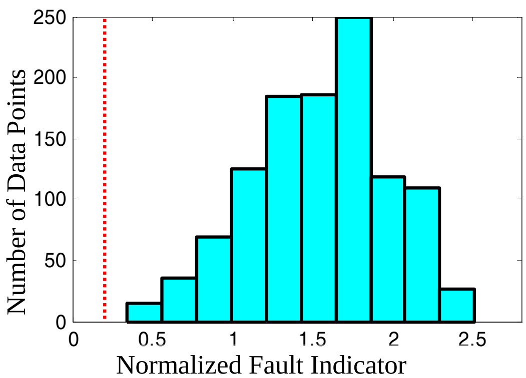

Fig. 2 Refrigerant low charge indicator distribution

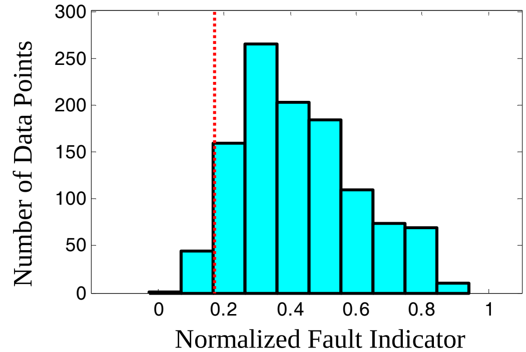

Fig. 3 Condenser fouling indicator distribution

Fig. 4 plots the normalized fault indicator for a compressor valve leakage fault. All the steady-state data points are to the left of the FDD threshold and the mean value is about -0.7, which indicates that the compressor is working properly and the compressor has about 15% heat loss. However, according to heat transfer analysis and our experience with laboratory data, compressors installed in packaged RTUs have very small heat loss, less than 5% of the power input and even gain some heat at some operating conditions. The explanation for this discrepancy is probably that the discharge line temperature is not measured accurately using the RTD temperature sensor. Li [4] investigated the RTD measuring issue and presented a correction approach. However, there is evidence obtained from a site visit that the discharge line temperature sensor is not probably installed or insulated.

The normalized fault indicator for the evaporator fouling fault is plotted in Fig. 5. Most of the steady-state data points are at the right of the FDD threshold and the mean value is about 0.96, which indicates that the evaporator is dirty. If this fault occurs individually, it would result in about 19% cooling capacity degradation.

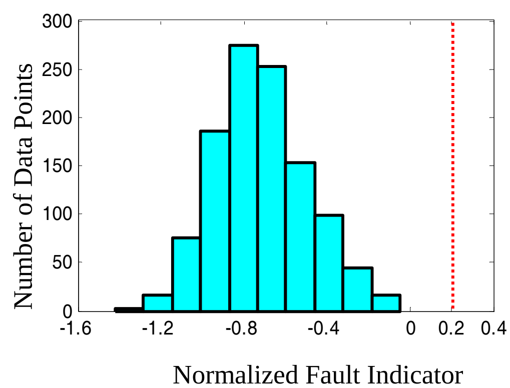

Fig. 4 Compressor leakage indicator distribution

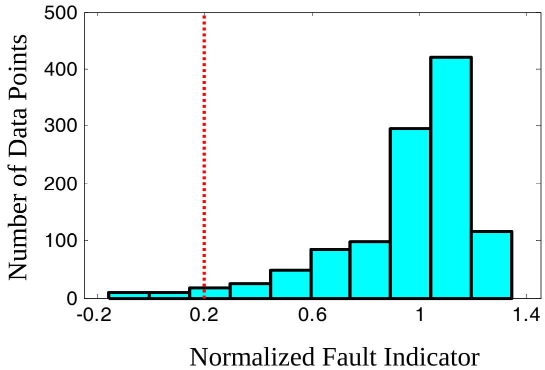

Fig. 5 Evaporator fouling indicator distribution

In summary, the system is impacted by four simultaneous faults, including low refrigerant charge, liquid line restriction, condenser fouling and evaporator fouling.

Fig. 6 plots the cooling capacity degradation associated with the combination of these faults for the case study site. The system cooling capacity is degraded 23~45% (average of about 32%), which is consistent with the degradation that would be determined for solely for the low refrigerant charge fault. This is becasue the low charge fault is a system-level fault which is not completely decoupled from other component-level faults and thus its indicator reflects the impact of other faults. The cooling capacity degradation is consistent with the return air temperature and system runtime. It can be seen from Fig. 7 that the average return air temperature is around 78 F and the highest is 88 F, which means that this equipment does not maintain comfortable space conditions much of the time. From Fig. 8, it can be seen that the system ran continuously for long periods of time (average of 2.5 hours, maximum of 9 hours). So, based on a comfort criterion, service should have been done to correct the diagnosed faults.

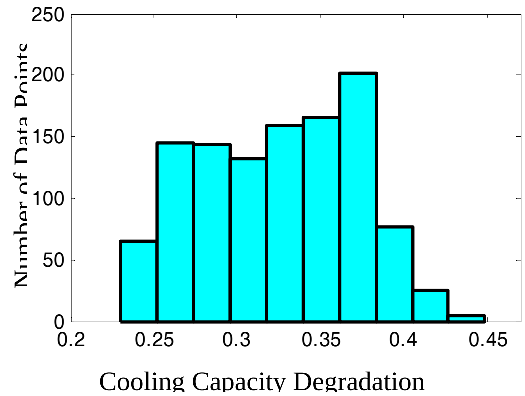

Fig. 6 Cooling capacity degradation distribution

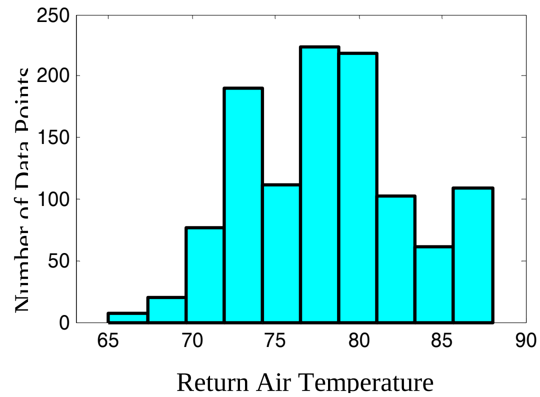

Fig. 7 Return air temperature distribution

Fig. 9 plots an economic criterion for service, EER degradation. It can be seen that the system EER degrades between about 10~40%, depending on the operating conditions. Compared with the cooling capacity degradation, the EER degradation is a little smaller. Fig. 10 plots the system power consumption reduction. The average power consumption reduction is about 15%, which is smaller than the average cooling capacity degradation of 32%. The average degradation in EER is 21%.

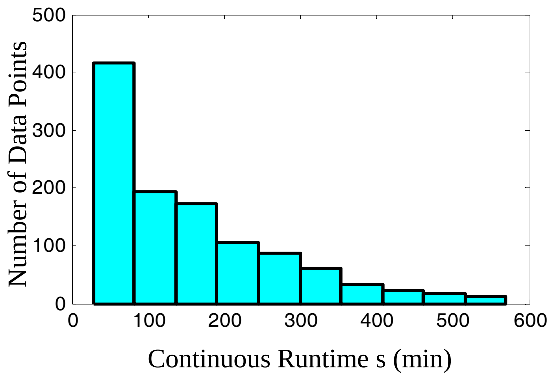

Fig. 8 Continuous runtime distribution

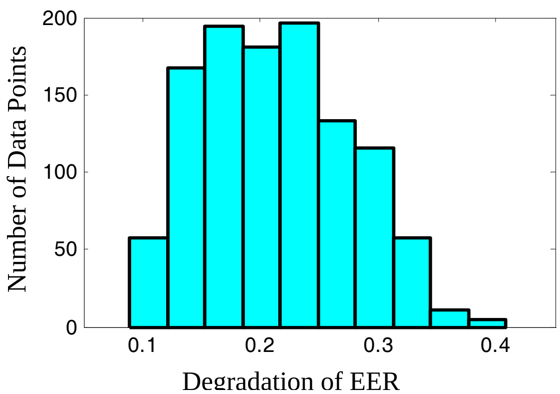

Fig. 9 EER degradation distribution

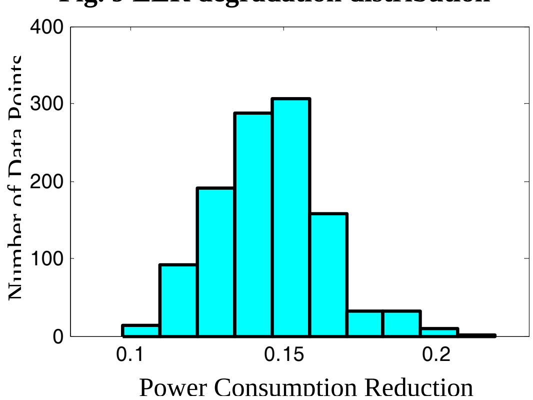

Fig. 10 Power consumption reduction distribution

4 RESULTS FOR OTHER SITES

Since the sites in California were originally configured for application of another FDD technique [5, 6, 7], some necessary information about the compressor, expansion device and system configuration are not available for full application of the FDD method. Therefore, the FDD technique is only partially applied to the other sites. Similar to the Oakland fastfood restaurant site, data collected from April to October in 2002 are used to do analysis except for the Anaheim retail store site, which is based on data collected in 2003.

The diagnosis results for these sites are summarized in Tab. 1, 2, 3 and 4. The initial investigation shows that faults happen very frequently at field sites. Fifteen of the twenty-one systems (71%) are significantly impacted by faults: eleven (52%) systems have filter/drier restrictions, ten (48%) systems have refrigerant charge faults, eight (38%) systems have more than two simultaneous faults and nine (43%) should have been serviced immediately based on degradations in capacity and EER.

Tab. 1 FDD results for modular school sites

	Woodland		Oakland	
	Unit 1	Unit 2	Unit 1	Unit 2
Refrigerant Charge	Normal	Normal	Normal	Over
Liquid-line Restriction	Yes	Yes	Yes	No
Evaporator Fouling	No	No	No	Yes
Service	Not yet	Yes	Not yet	Yes

Tab. 2 FDD results for fast-food restaurants

	Brad-shaw	Castro Valley		Watt Avenue	
		Stage 1	Stage 2	Stage 1	Stage 2
Ref. charge	Low	Normal	Normal	Low	Normal
Llrestr	Yes	No	No	No	No
Service	Yes	NA	NA	Not	NA

Tab. 3 FDD results for retail stores at Rialto

	UNIT 1	UNIT2	UNIT3	UNIT4	UNIT5
Ref. charge	Low	Low	Normal	Normal	Over
Llrestr	No	Yes	No	No	No
Service	Yes	Yes	NA	NA	No

Tab. 4 FDD results for retail stores at Anaheim

	UNIT1	UNIT2	UNIT3	UNIT4	UNIT5
Ref. charge	Low	Low	Normal	Low	Normal
Llrestr	Yes	Yes	Yes	Yes	Yes
Service	Yes	Yes	Not yet	Yes	Not yet

5 INSPECTION OF FAULTS THROUGH SITE VISITS

Several field site visits have been made to provide some confirmation of the type and level of faults that are indicated through data analysis. This project does not have the resources necessary to verify faults through application of service and post-repair data processing. Only qualitative assessments of fault occurrences are made through visual inspections. Therefore, only those faults which could be confirmed visually are considered.

For refrigerant leakage, visual evidence appears as lubricant residual at piping connections or fittings. For example, Fig. 11 gives some snapshots taken at field sites that indicate leakage occurred at the pressure sensor fittings. Fig. 12 shows a case where leakage occurs at the brazed or welded areas of condenser tube bends. Fig. 13 shows another leakage case which occurs at the compressor service ports. Tab. 5 summarizes the earlier diagnoses based upon sensor readings and the on-site evidence for refrigerant leakage. Most of the cases are confirmed by visual signs of lubricant leakage. However, lubricant leakage is only a sufficient condition for refrigerant leakage and not a necessary condition. Refrigerant leakage could occur without visual evidence. What's more, the refrigerant charge could be low due to inadequate charging at the time of service. Also, it is impossible to find visual signs for refrigerant overcharge as well.

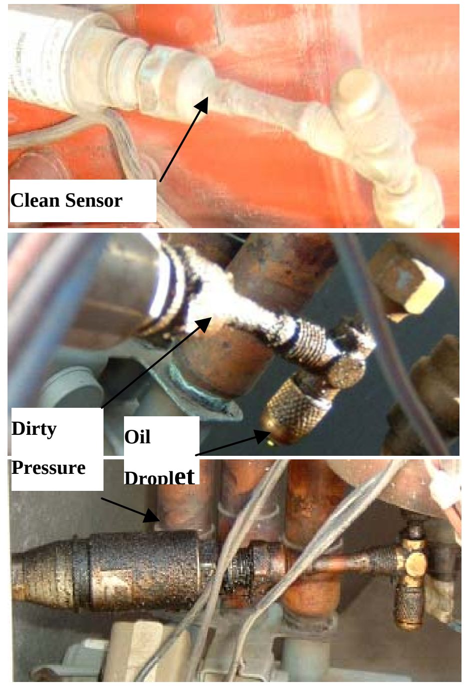

Fig. 11 Pressure sensor fitting leakage

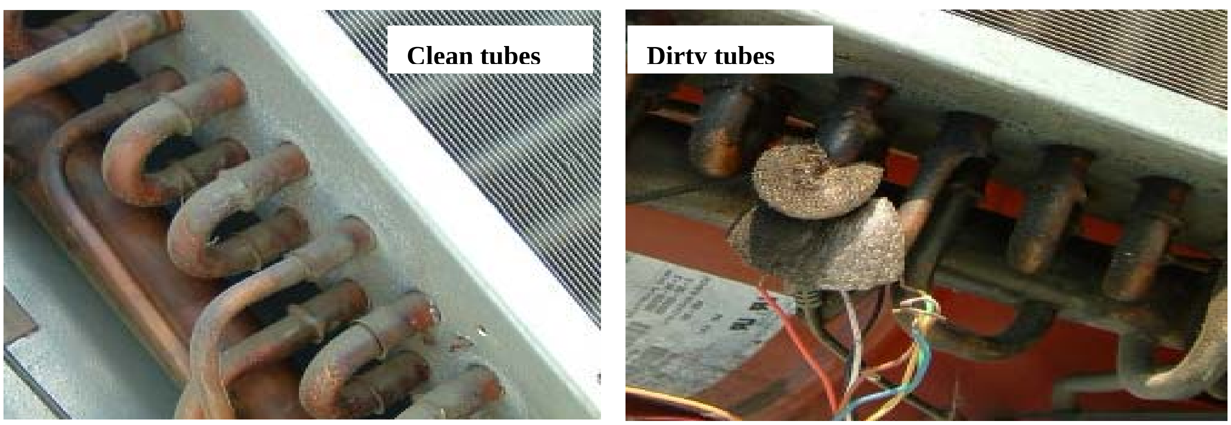

Fig. 12 Evidence of leakage occurring at the tube bends

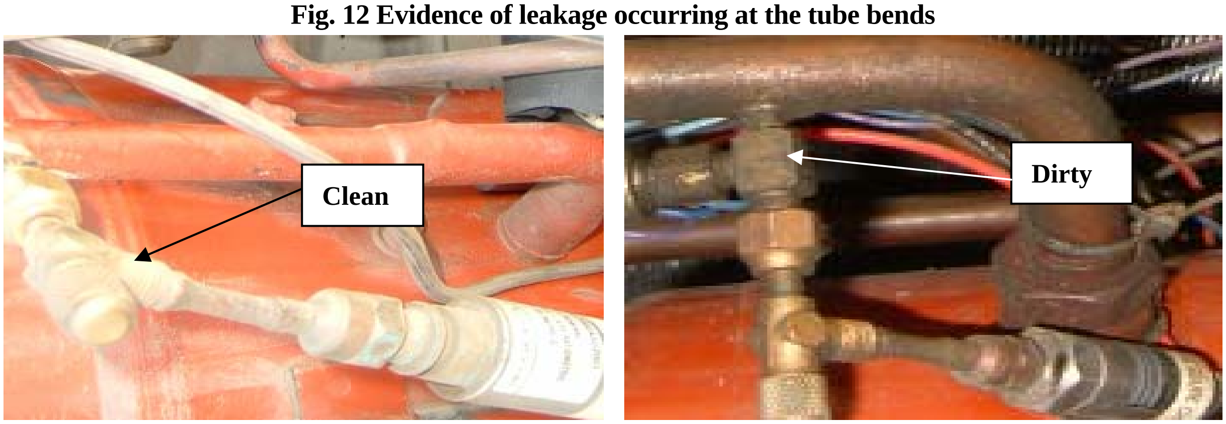

Fig. 13 Lubricant leakage

Tab. 5 System charge diagnostics

Site Name		Lubricant Leakage Sign			Previous Diagnosis	Notes
		Suction Pressure Sensor	Discharge Pressure Sensor	Others	Charge	
Rialto	VM3	Information is missed			Low	
	VM1	Leakage	No	Condenser tube bends	Low	
	VM5	No	Leakage		Normal	Recent leakage
	VM2	Leakage	No		Normal	Recent leakage (oil droplet)
	VM4	No	Leakage		High	Recent leakage
Anaheim	VM2	Leakage	No		Low	
	VM1	No	No	Suction line	Low	
	VM5	No	No		Normal	
	VM4	No	No		Low	No lubricant leakage
	VM3	No	No		Normal	
Castro Valley	Stage1	No	No		Normal	
	Stage2	No	No		Normal	
Milpitas		No	Leakage		Low	
Bradshaw		No	Leakage		Low	Discharge pressure sensor is off
Watt Ave	Stage1	No	Leakage		Low	
	Stage2	No	No		Normal	

Fig. 14 shows several snapshots for evaporator air filter fouling which are taken from the Oakland fastfood Restaurant. It can be imagined that the air flow is significantly lowered for these cases, which confirms the previous diagnosis of a severe evaporator fouling. Evaporator filter fouling is quite common at the field sites, especially for the fastfood application. Another phenomenon is that filters of different RTUs at the same site had very different fouling levels. Some of them are very dirty as shown in Fig. 14 and others were lightly fouled, which means that regular preventive maintenance service is not ideal.

Unlike evaporators, condensers do not have air filters and fouling faults are not as obvious as those for evaporator filters. Snapshots shown in Fig. 15 are taken from different RTUs at the same site (Rialto Walgreens). Similar to evaporator air filters, some of them are clean and some of them are dirty. Liquid-line restriction faults are not visible unless the filter/drier is taken off and opened.

In summary, faults are common for the field sites. Heat exchanger fouling faults are more severe for fastfood restaurants than for retail stores. For the same application and location, faults occur randomly and develop with different speed.

Fig. 14 Evaporator air filter fouling snapshots

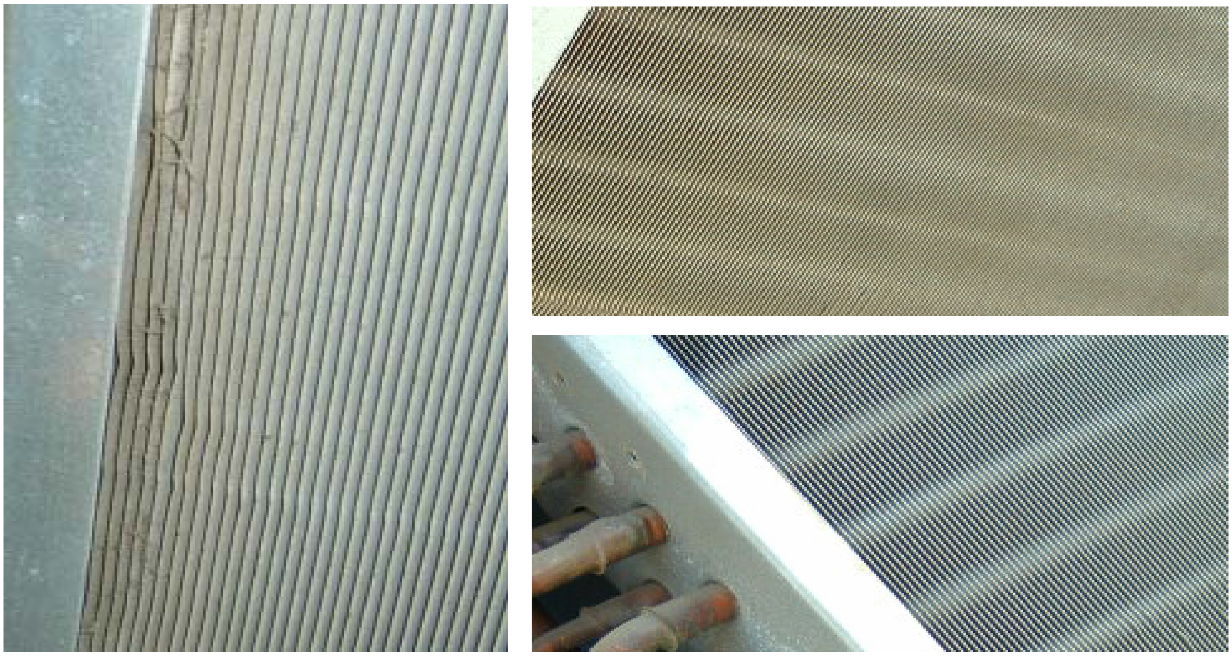

Fig. 15 Condenser snapshots

6 CONCLUSIONS

This paper presents the application of the DB FDD technique proposed by Li and Braun [1, 3]. The technique is applied to a number of California field sites which are selected so that they cover different climate types, different occupancy types and different equipment manufacturers. Detailed results are given for a single site whose system is impacted by four simultaneous faults, including low refrigerant charge, liquid line restriction, condenser fouling and evaporator fouling. Summary results are given for the other sites. Faults are common for the field sites: about 70% of the investigated systems are impacted by faults and about 40% of them have more than one fault. Service is justified for about 40% of the units. Heat exchanger fouling faults are more severe for fast-food restaurants than for retail stores. For the same application and location, faults occur randomly and develop with different speeds. Field visits verify most of the diagnosed faults.

ACKNOWLEDGEMENTS

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NOMENCLATURE

COP	=	Coefficient of performance
DB	=	Decoupling based
EER	=	Equipment efficiency ratio
FDD	=	Fault detection and diagnosis
FXO	=	Fixed orifice
llrestr	=	Liquid-line restriction
RTU	=	Rooftop unit
TXV	=	Thermostatic expansion device

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