Is This My Fault? A Laboratory Investigation of FDD on a Residential HVAC Split System

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ABSTRACT

Fault detection and diagnostics (FDD) technologies are essential to preserve and enhance the next generation of energy efficiency. Traditionally, HVAC maintenance practices are a daunting enterprise, open to varying interpretations of many dynamic parameters. These practices are conventionally reactive and don't necessarily emphasize optimization of equipment efficiency. FDD may provide the intelligence needed to implement enhanced HVAC maintenance practices. In order to realize the potential of FDD, it is imperative that we better understand how FDD technologies perform and the impacts of the faults they encounter.

This paper presents the findings of a research project conducted in the laboratories of Southern California Edison's (SCE) Technology Test Centers. The project leveraged expertise from a technical advisory group comprised of diverse subject matter experts and intends to inform utility energy efficiency programs, California statewide codes and standards, and national efforts like ASHRAE SPC207P. The project focused on:

1. Developing a laboratory test method for evaluating FDD
2. Evaluating the performance of an in-field FDD technology
3. Quantifying the adverse energy and demand impacts of commonly overlooked HVAC maintenance faults

The project evaluated an in-field FDD technology on a 3-ton, standard-efficiency residential split system. Tests covered various typically encountered faults in single and multiple instances across different indoor and outdoor test chamber conditions. The FDD technology provides a significant amount of additional intelligence and performed fairly across the gamut of test scenarios, but it did not diagnose simultaneous multiple faults. In worst case scenarios, faults produced anywhere from 60% to 90% efficiency degradation.

Introduction

California homes consume approximately 220 billion kilowatt-hours (kWh) of electricity annually (EIA 2009). Of this, heating, ventilation, and air conditioning (HVAC) equipment accounts for 30% (EIA 2009). Residential HVAC equipment also accounts for approximately 24% of the peak demand in California (Close 2010). For all central air conditioners serving California homes, nearly half are over 10 years old (EIA 2009).

Current residential HVAC maintenance practices face many challenges and opportunities for enhancement. Traditionally, these practices are open to varying interpretations and are reactive in nature. Homeowners typically do not have maintenance contracts established for regular servicing of their HVAC equipment. Homeowners usually call in for maintenance after their equipment fails. HVAC service contractors are then placed in reactionary situations, requiring them to assess and resolve issues chaotically and rapidly. Often, current repair and maintenance practices are not necessarily aimed at bringing HVAC equipment back up to optimum efficiency levels. In addition, some variables influencing HVAC performance (equipment type, faults, indoor/outdoor conditions, etc.) are largely uncontrollable in the field and present their own unique challenges for accurately assessing and resolving maintenance issues. More information is needed to enhance the understanding of the impacts of common faults on HVAC equipment as well as the capabilities of available fault detection and diagnostics (FDD) technologies.

FDD technologies have enormous potential to enhance the future of energy efficiency. FDD can provide the information necessary to accurately and reliably understand HVAC equipment performance, and improve HVAC maintenance through enhanced preventative strategies. FDD technologies interpret operational parameters to detect the symptoms of a faulty operating state, and help diagnose the root cause(s). FDD technologies may come in various forms: software-based, in-field technologies or onboard technologies (factory-installed or retrofit).

The FDD technology tested in this project is intended for use as an HVAC service technician's tool. FDD performance was evaluated through laboratory testing at SCEs Technology Test Centers (TTC). The FDD was tested with various fault scenarios comprised of either single or varying combinations of multiple faults. The scope of faults included low/high refrigerant charge, liquid line restrictions, non-condensables, evaporator airflow reduction, and condenser airflow reduction.

Project Description

Southern California Edison (SCE) initiated projects to evaluate Fault Detection and Diagnostics (FDD) technologies as viable solutions for reducing energy and demand consumption in California homes (Gouw 2012a, 2012b, and 2012c). These projects sought to inform SCE's Energy Efficiency Programs, as well as other developing FDD-related efforts such as, but not limited to, Codes and Standards Enhancement (CASE) studies for the California Code of Regulations, or efforts conducted by the American Society of Heating, Refrigerating and Air Conditioning Engineers (ASHRAE), manufacturers, and other key industry stakeholders. These projects worked together cohesively to develop a working laboratory test method for FDD technologies, apply the working test method in a laboratory assessment, and report on FDD performance and on the observed effects of faults.

Industry input was important during development and scoping of the residential FDD project series. The FDD committee of the Western HVAC Performance Alliance (WHPA) was consulted continually, and a Technical Advisory Group (TAG) was also established to provide support with specialized HVAC and FDD industry expertise. Specifically, feedback was sought regarding the test method and the scope of test scenarios to explore across a wide range of participants which included California utilities, academia, FDD developers, and HVAC manufacturers.

The HVAC Test Unit

The HVAC test unit is a 3-ton (nominal), standard efficiency (13 SEER, 11 EER) residential split system air conditioner. This air conditioner consists of one indoor unit, containing both a cooling coil and a furnace (not used), paired to an air-cooled, outdoor condensing unit. It is a fixed capacity system (fixed-speed fans and compressor) that uses R-410a refrigerant and a thermostatic expansion valve (TxV).

Figure 1. HVAC test unit - indoor unit (left), outdoor condensing unit (right).

The In-Field FDD Test Technology

The FDD technology tested was purchased from an FDD manufacturer as a package of items, intended for use as a service technician's tool. A significant amount of HVAC maintenance-related information is also available through reference literature and training provided by the FDD manufacturer. The package includes a Personal Digital Assistant (PDA) mobile device, (2) Dual-sensor, air-side probes (supply air and return air) that each measure both dry-bulb (DB) and wet-bulb (WB) temperatures, (1) Air-side sensor that measures DB temperature (condenser inlet air), (2) Clamp-on thermocouple (T/C) sensors (suction and liquid line refrigerant temperatures), (3) Refrigerant pressure hoses, (1) Digital refrigerant manifold

Figure 2. The FDD technology.

The PDA displays several screens of measurements and calculations. The device steps through its internal algorithms and displays its diagnosis in real-time fashion. The device has approximately 50 discrete diagnostic messages. The PDA displays 19 measured/calculated parameters across several screens, and outputs a diagnostic based on these parameters. Measurements, calculations, and diagnostics messages were observed to be simultaneously populated about once every three seconds. This device does not log data, but is able to upload one set of readings to an online server for reporting.

Test Method

All testing is conducted similarly to the steady-state wet coil tests outlined in AHRI – 210/240-2008 (the effects of dry-coil vs wet-coil testing are not anticipated to be significant, but represent a possible point to explore for future testing). All test scenarios encompass a 1-hour span that comprises a 30-minute pre-test interval and a 30-minute data collection interval. For the purposes of this paper, discussion of FDD performance focuses on whether the predominant diagnostic correctly matches what was imposed.

Baseline Tests

Table 1 summarizes baseline test scenarios for this study. The Indoor (ID) and Outdoor (OD) test chamber air conditions were chosen with guidance from California Energy Code design conditions for SCE's Climate zones and feedback from the TAG.

Table 1. Baseline tests

Test #	Description	Indoor Chamber Air Condition	Outdoor Chamber Air Condition
1	Baseline	80 °F / 67 °F (DB / WB) (AHRI)	115 °F DB (Hot & Dry)
2			95 °F DB (AHRI)
3			80 °F DB (Low Ambient)
4		75 °F / 63 °F (DB / WB) (Medium)	115 °F DB (Hot & Dry)
5			95 °F DB (AHRI)
6			75 °F DB (Low Ambient)
7		70 °F / 59 °F (DB / WB) (Low)	115 °F DB (Hot & Dry)
8			95 °F DB (AHRI)
9			75 °F DB (Low Ambient)

Single Faults

Table 2 summarizes single-fault test scenarios for this study. For all single-fault testing scenarios, the general strategy was to:

- Capture the effects of three incremental fault levels at a standardized condition of 80°F/67°F (DB/WB) indoor chamber, 95°F outdoor chamber
- Capture the effects of the most pronounced fault level, at two extra combinations of indoor and outdoor test chamber air conditions

Increments of faults are generally chosen based on bounds set by criteria such as:

- Is the fault increment representative of what happens in the field?
- Does the fault increment induce a failure mode or otherwise prohibit the HVAC system from operating in a steady state fashion? Examples include:
    - A condenser airflow reduction may be severe enough to cause HVAC system shutdown, by tripping the high-pressure switch.

- A liquid line restriction could be severe enough to drop low-side pressures to a point that would cause HVAC system shutdown by tripping the low-pressure switch.
- A liquid line restriction could be severe enough to drop the evaporator temperature low enough to cause coil frosting.

Low refrigerant charge. The low refrigerant charge fault describes a state where an HVAC system contains charge levels significantly below that which was intended by the manufacturer. Low charge levels may occur as a result of improper charging or servicing practices or general system leakage. The system will have less working fluid available to remove heat from the conditioned space(s) and may operate with significant performance degradation. For lab purposes, fault increments are defined on a percent-under-nominal-charge basis.

High refrigerant charge. The high refrigerant charge fault describes a state where an HVAC system contains refrigerant charge levels significantly above the original manufacturer specifications. High charge levels may occur from improper charging/servicing. The system will have excessive working fluid available to remove heat from the conditioned space. As a result, the system may operate with increased high side pressures, significant performance degradation and may run the risk of introducing liquid refrigerant into the compressor. Fault increments are defined on a percent-above-nominal-charge basis.

Liquid line restrictions. The liquid line restrictions fault describes a state in which refrigerant flow is unintentionally restricted in a certain part of the liquid line. These cause unwanted pressure drops in the system and may result because of: bent refrigerant lines, dirty liquid line filter-driers, or solder blockages at pipe joints. Restricted/clogged expansion devices may also exhibit similar impacts to the HVAC system. High levels of line restriction may result in system failure on low suction pressure or evaporator frosting. Fault increments are simulated with a valve, installed on the liquid line. Fault increments are defined in terms of the pressure drop across the restriction valve, in pounds per square inch (psi).

Non-condensables. The refrigerant non-condensables fault describes a state in which contaminants such as air, water vapor, or nitrogen become mixed with the refrigerant in an HVAC system. The physical properties of these contaminants and their subjection to the system's working pressures mean they always exist as gases. These contaminants impose their own properties on the overall working fluid, which typically results in performance degradation. Non-condensables may be introduced through faulty equipment servicing. Non-condensables are simulated with dry nitrogen gas. Fault increments are defined on a mass-of-nitrogen added basis.

Evaporator airflow reduction. The evaporator airflow reduction fault describes a state in which the airflow across the HVAC system's evaporator is restricted to below-nominal levels. Airflow restrictions may be a result of dirty/clogged filters, evaporator inlet/outlet obstructions, or dirty/fouled evaporators. Evaporator airflow reductions result in lower evaporator temperatures/pressures and significant performance degradation may result. High levels of evaporator airflow reduction may result in system failure on low suction pressure or evaporator frosting. Fault increments are tracked by evaporator airflow in Standard Cubic Feet per Minute (SCFM). Faults are defined on a percent-under-nominal-evaporator-airflow basis.

Condenser airflow reduction. The condenser airflow reduction fault describes a state in which the airflow across the HVAC system's condenser is restricted to below-nominal levels. Airflow restrictions may be a result of condenser inlet/outlet obstructions, or fouling. Condenser airflow reductions result in higher refrigerant condensing temperatures/pressures and significant performance degradation may result. High levels of condenser airflow reduction may result in system failure on high head pressure. Fault increments are tracked by set values of compressor discharge pressure, because airflow measurements were not made on the condenser airstream.

Table 2. Single-fault test scenarios

Test #	Description		Indoor Chamber Air Condition	Outdoor Chamber Air Condition
10	Low Charge	(Low intensity) 13% under nominal charge	80 °F / 67 °F (DB / WB)	95 °F DB
11		(Medium intensity) 27% under nominal charge		
12		(High intensity) 40% under nominal charge		
13		(High intensity) 40% under nominal charge	75 °F / 63 °F (DB / WB)	115 °F DB
14		(High intensity) 40% under nominal charge	70 °F / 59 °F (DB / WB)	75 °F DB
15	High Charge	(Low intensity) 10% above nominal charge	80 °F / 67 °F (DB / WB)	95 °F DB
16		(Medium intensity) 20% above nominal charge		
17		(High intensity) 30% above nominal charge		
18		(High intensity) 30% above nominal charge	75 °F / 63 °F (DB / WB)	115 °F DB
19		(High intensity) 30% above nominal charge	70 °F / 59 °F (DB / WB)	75 °F DB
20	Liquid Line Restrictions	(Low intensity) 32 psi liquid line restriction	80 °F / 67 °F (DB / WB)	95 °F DB
21		(Medium intensity) 66 psi liquid line restriction		
22[1]		(High intensity) 98 psi liquid line restriction		
23[1]		(High intensity) 88 psi liquid line restriction	75 °F / 63 °F (DB / WB)	115 °F DB
24[1]		(High intensity) 96 psi liquid line restriction	70 °F / 59 °F (DB / WB)	75 °F DB
25	Non-Condensables	(Low intensity) 0.3 oz of nitrogen added	80 °F / 67 °F (DB / WB)	95 °F DB
26		(High intensity) 0.8 oz of nitrogen added		
27		(High intensity) 0.8 oz of nitrogen added	75 °F / 63 °F (DB / WB)	115 °F DB
28		(High intensity)	70 °F / 59 °F	75 °F DB

[1]The liquid line restriction imposed in Test 22 is the same restriction imposed in Tests 23 and 24. However, indoor and outdoor chamber air condition differences cause changes in operating refrigerant system pressures, thereby changing the measured pressure drop for the same restriction.

Test #	Description		Indoor Chamber Air Condition	Outdoor Chamber Air Condition
		0.8 oz of nitrogen added	(DB / WB)	
29	Evaporator Airflow Reduction	(Low intensity) 33% under nominal evaporator airflow	80 °F / 67 °F (DB / WB)	95 °F DB
30		(Medium intensity) 49% under nominal evaporator airflow		
31		(High intensity) 57% under nominal evaporator airflow		
32		(High intensity) 62% under nominal evaporator airflow	75 °F / 63 °F (DB / WB)	115 °F DB
33		(High intensity) 32% under nominal evaporator airflow	70 °F / 59 °F (DB / WB)	75 °F DB
34	Condenser Airflow Reduction	(Low intensity) 467 psig compressor discharge pressure	80 °F / 67 °F (DB / WB)	95 °F DB
35		(Medium intensity) 575 psig compressor discharge pressure		
36		(High intensity) 613 psig compressor discharge pressure		
37		(High intensity) 622 psig compressor discharge pressure	75 °F / 63 °F (DB / WB)	115 °F DB
38		(High intensity) 612 psig compressor discharge pressure	70 °F / 59 °F (DB / WB)	75 °F DB

Multiple-Faults

When considering the permutations of ID/OD conditions, possible fault combinations, and intensities, the result is a potentially astronomical amount of test scenarios. For the purposes of this study, the strategy was to focus on capturing the effects of several “cherry-picked” scenarios comprising of mostly two-fault scenarios and one set of three-fault scenarios, all anchored at the standardized condition of 80°F/67°F (DB/WB) indoor, and 95°F outdoor. Increments of faults are generally chosen with consideration of the intensities tested in the previous single-fault test runs.

Table 3. Multiple-fault test scenarios

Test #		Description	Indoor Chamber Air Condition	Outdoor Chamber Air Condition
39	Fault 1: High Refrigerant Charge Fault 2: Evaporator Airflow Reduction	(Low intensity) Fault 1: 30% above nominal charge Fault 2: 56% under nominal evaporator airflow	80 °F / 67 °F (DB / WB)	95 °F DB
40	Fault 1: Low Charge Fault 2: Non-Condensables	(Low intensity) Fault 1: 32% under nominal charge Fault 2: 0.3 oz of nitrogen added	80 °F / 67 °F (DB / WB)	95 °F DB
41		(High intensity) Fault 1: 76% under nominal charge Fault 2: 0.8 oz of nitrogen added		

Test #		Description	Indoor Chamber Air Condition	Outdoor Chamber Air Condition
**42	Fault 1: Evaporator Airflow Reduction Fault 2: Condenser Airflow Reduction	(Low intensity) Fault 1: 33% under nominal evaporator airflow Fault 2: 438 (467) psig compressor discharge pressure	80 °F / 67 °F (DB / WB)	95 °F DB
**43		(Medium intensity) Fault 1: 49% under nominal evaporator airflow Fault 2: 489 (575) psig compressor discharge pressure		
**44		(High intensity) Fault 1: 57% under nominal evaporator airflow Fault 2: 575 (613) psig compressor discharge pressure		
45	Fault 1: Low Charge Fault 2: Evaporator Airflow Reduction	(Low intensity) Fault 1: 13% under nominal charge Fault 2: 32% under nominal evaporator airflow	80 °F / 67 °F (DB / WB)	95 °F DB
46		(Medium intensity) Fault 1: 27% under nominal charge Fault 2: 49% under nominal evaporator airflow		
47		(High intensity) Fault 1: 40% under nominal charge Fault 2: 53% under nominal evaporator airflow		
**48[2]	Fault 1: Low Charge Fault 2: Condenser Airflow Reduction	(Low intensity) Fault 1: 13% under nominal charge Fault 2: 624 psig compressor discharge pressure	80 °F / 67 °F (DB / WB)	95 °F DB
**49		(Medium intensity) Fault 1: 27% under nominal charge Fault 2: 618 psig compressor discharge pressure		
**50		(High intensity) Fault 1: 40% under nominal charge Fault 2: 615 psig compressor discharge pressure		
**51	Fault 1: Low Charge Fault 2: Evaporator Airflow Reduction Fault 3: Condenser Airflow Reduction	(Low intensity) Fault 1: 13% under nominal charge Fault 2: 32% under nominal evaporator airflow Fault 3: 607 (624) psig compressor discharge pressure	80 °F / 67 °F (DB / WB)	95 °F DB
**52		(Medium intensity) Fault 1: 27% under nominal charge Fault 2: 43% under nominal evaporator airflow Fault 3: 601 (618) psig compressor discharge pressure		
**53		(High intensity) Fault 1: 40% under nominal charge Fault 2: 56% under nominal evaporator airflow Fault 3: 601 (615) psig compressor discharge pressure		

**Note:

Results

Table 4 and Table 6 summarize whether the prevailing diagnoses from the in-field FDD was considered to be correct, with regards to the single or multiple fault scenario it was subjected

[2]Compressor discharge pressure is presented in the form, P' (P), where P' = resultant compressor discharge pressure, after evaporator airflow reduction is imposed and P = the originally imposed pressure, prior to evaporator airflow reduction.

to. Table 5 and Table 7 summarize the normalized values of Energy Efficiency Ratio (EER), Cooling Capacity, and Total Power. Values are normalized to their appropriate baselines (tested at the same ID/OD condition).

Table 4. Diagnostic summary: single-faults

ID/OD Test Chamber Conditions →		AHRI ID/OD Rating Conditions			Hot & Dry OD, Medium ID Conditions	Low Ambient OD, Low ID Conditions
Low Charge	Intensity →	Low	Medium	High	High	High
	Diagnosed (Y/N)? →	Y	Y	Y	Y	Y
High Charge	Intensity →	Low	Medium	High	High	High
	Diagnosed (Y/N)? →	Y	Y	Y	Y	Y
Liquid Line Restriction	Intensity →	Low	Medium	High	High	High
	Diagnosed (Y/N)? →	N	N	Y	N	N
Non-Condensables	Intensity →	Low		High	High	High
	Diagnosed (Y/N)? →	N		N	N	N
Evaporator Airflow Reduction	Intensity →	Low	Medium	High	High	High
	Diagnosed (Y/N)? →	N	Y	Y	Y	Y
Condenser Airflow Reduction	Intensity →	Low	Medium	High	High	High
	Diagnosed (Y/N)? →	Y	Y	Y	Y	N

Table 5. Fault impacts summary: single-faults[3]

ID/OD Test Chamber Conditions →		AHRI ID/OD Rating Conditions			Hot & Dry OD, Medium ID Conditions	Low Ambient OD, Low ID Conditions
Low Charge	Intensity →	Low	Medium	High	High	High
	Normalized EER →	97%	46%	39%	25%	38%
	Normalized Cooling →	98%	48%	35%	23%	35%
	Normalized Total Power →	100%	95%	89%	92%	91%
High Charge	Intensity →	Low	Medium	High	High	High
	Normalized EER →	96%	99%	95%	94%	104%
	Normalized Cooling →	98%	104%	107%	108%	116%
	Normalized Total Power →	102%	106%	113%	115%	112%
Liquid Line Restriction	Intensity →	Low	Medium	High	High	High
	Normalized EER →	101%	102%	67%	94%	82%
	Normalized Cooling →	102%	103%	66%	95%	73%
	Normalized Total Power →	101%	101%	98%	102%	89%
Non-Condensables	Intensity →	Low		High	High	High
	Normalized EER →	99%		88%	91%	90%

[3]Cooling capacity and EER normalization reported here are based on air-side analyses.
AHRI Rating Condition EER, Cooling Capacity, Total Power = 10 Btu/W-h, 33,319 Btu/h, 3,325 W
Hot & Dry Condition EER/Cooling Capacity/Total Power = 7.1 Btu/W-h, 26,613 Btu/h, 3,769 W
Low Ambient Condition EER/Cooling Capacity/Total Power = 11.9 Btu/W-h, 33,104 Btu/h, 2,774 W

ID/OD Test Chamber Conditions →		AHRI ID/OD Rating Conditions			Hot & Dry OD, Medium ID Conditions	Low Ambient OD, Low ID Conditions
	Normalized Cooling →	103%		98%	98%	98%
	Normalized Total Power →	105%		111%	107%	109%
Evaporator Airflow Reduction	Intensity →	Low	Medium	High	High	High
	Normalized EER →	92%	104%	101%	93%	95%
	Normalized Cooling →	87%	95%	90%	79%	86%
	Normalized Total Power →	95%	92%	89%	85%	91%
Condenser Airflow Reduction	Intensity →	Low	Medium	High	High	High
	Normalized EER →	80%	65%	58%	80%	47%
	Normalized Cooling →	89%	83%	78%	93%	71%
	Normalized Total Power →	112%	128%	133%	116%	150%

Table 6. Diagnostic summary: multiple-faults

ID/OD Test Chamber Conditions →	AHRI ID/OD Rating Conditions		
Intensity →	Low		
Fault 1: High Charge Diagnosed (Y/N)? →	N		
Fault 2: Evap. Airflow Red. Diagnosed (Y/N)? →	Y		
Intensity →	Low		High
Fault 1: Non-Condensables Diagnosed (Y/N)? →	N		N
Fault 2: Low Charge Diagnosed (Y/N)? →	N		N
Intensity →	Low	Medium	High
Fault 1: Evap. Airflow Red. Diagnosed (Y/N)? →	N	N	Y
Fault 2: Cond. Airflow Red. Diagnosed (Y/N)? →	N	Y	Y
Intensity →	Low	Medium	High
Fault 1: Low Charge Diagnosed (Y/N)? →	Y	Y	Y
Fault 2: Evap. Airflow Red. Diagnosed (Y/N)? →	N	Y	Y
Intensity →	Low	Medium	High
Fault 1: Low Charge Diagnosed (Y/N)? →	N	N	N
Fault 2: Cond. Airflow Red. Diagnosed (Y/N)? →	Y	Y	Y
Intensity →	Low	Medium	High
Fault 1: Low Charge Diagnosed (Y/N)? →	N	N	N
Fault 2: Evap. Airflow Red. Diagnosed (Y/N)? →	N	N	N
Fault 2: Cond. Airflow Red. Diagnosed (Y/N)? →	Y	Y	Y

Table 7. Fault impacts summary: multiple-faults[3]

ID/OD Test Chamber Conditions →		AHRI ID/OD Rating Conditions		
Fault 1: High Charge Fault 2: Evap. Airflow Reduction	Intensity →	Low		
	Normalized EER →	107%		
	Normalized Cooling →	109%		
	Normalized Total Power →	102%		
Fault 1: Non-Condensables Fault 2: Low Charge	Intensity →	Low		High
	Normalized EER →	34%		5%
	Normalized Cooling →	33%		4%
	Normalized Total Power →	97%		79%
Fault 1: Evap. Airflow Reduction	Intensity →	Low	Medium	High

ID/OD Test Chamber Conditions →		AHRI ID/OD Rating Conditions		
Fault 2: Cond. Airflow Reduction	Normalized EER →	77%	65%	62%
	Normalized Cooling →	78%	69%	70%
	Normalized Total Power →	102%	106%	113%
Fault 1: Low Charge Fault 2: Evap. Airflow Reduction	Intensity →	Low	Medium	High
	Normalized EER →	96%	78%	52%
	Normalized Cooling →	91%	69%	43%
	Normalized Total Power →	94%	89%	83%
Fault 1: Low Charge Fault 2: Cond. Airflow Reduction	Intensity →	Low	Medium	High
	Normalized EER →	52%	31%	8%
	Normalized Cooling →	71%	43%	11%
	Normalized Total Power →	137%	137%	136%
Fault 1: Low Charge Fault 2: Evap. Airflow Reduction Fault 2: Cond. Airflow Reduction	Intensity →	Low	Medium	High
	Normalized EER →	52%	43%	22%
	Normalized Cooling →	66%	54%	27%
	Normalized Total Power →	128%	127%	126%

Discussion

The FDD technology reported correct diagnostics in 19/29 of the single fault scenarios. With the exception of non-condensables, most single faults were eventually diagnosed within the tested range of fault thresholds. In single-fault testing, the following trends were observed:

- Low and high charge were diagnosed at all tested levels
- Line restrictions were diagnosed at the most severe threshold, but only at the AHRI ID/OD test chamber conditions
- Non-condensables were not diagnosed at the tested thresholds
- Evaporator airflow reductions were diagnosed for all but one of the tested thresholds
- Condenser airflow reductions were diagnosed for all but one of the tested thresholds

The FDD technology did not diagnose multiple faults simultaneously. However, it correctly diagnosed at least one of the imposed faults in 12/15 multiple fault scenarios. The FDD was observed to be more sensitive to diagnosing certain faults over others for a given fault combination. It is likely that eventually, all faults would be remedied through correct systematic identification of at least one fault at a time.

All faults under steady state conditions demonstrated the potential for significant performance degradation. The single-faults that produced the highest measured steady-state impacts were low charge and condenser airflow reduction. The following multiple-fault test scenarios produced the highest measured steady-state impacts:

- Low charge and non-condensables
- Low charge and condenser airflow reduction

These multiple fault scenarios yielded extraordinary results: the HVAC system was able to operate in steady state with highly compromised performance. Especially in the most severe case of non-condensables and low charge, the HVAC unit operated at a mere 4% of its original cooling capacity, at a total power input of 79% (high demand for functionally no cooling output!). These are scenarios that would not likely go unnoticed in the field, but if allowed to operate would likely cause excessive wear on the compressor from elevated discharge pressures and temperatures. The severe test scenario of low charge and non-condensables was originally established to mimic a scenario where an HVAC system, vented to atmosphere, was not subjected to any vacuum before being charged with refrigerant to a target sub-cooling value.

Conclusions and Recommendations

The families of faults tested in this study all demonstrated significant potential for steady-state performance degradation on a 3-ton residential air conditioner in both single-fault and multiple-fault test scenarios. The low charge and non-condensables multiple fault scenario demonstrated the biggest impact (reduced to 5%/4%/79% of baseline EER/Cooling/Power). These faults have historically been, and should continue to be, a high priority for technicians to diagnose and remedy. The in-field FDD technology correctly reported correct diagnostics in 19/29 of the single fault scenarios. It was not able to diagnose multiple faults simultaneously, but correctly diagnosed at least one of the imposed faults in 12/15 multiple fault scenarios.

More information is still needed to better understand the impacts of faults across more permutations of equipment types, fault combinations, intensities, ID/OD conditions, etc. More information is also needed to better understand the capabilities of all FDD technologies. In order to do this, more development is needed to establish a consistent mechanism for evaluation. Lab testing alone is a very labor-intensive process that will be difficult to implement for all existing FDD technologies. However, it could potentially serve as a continually expanding database that could be leveraged to simulate scenarios for FDD technologies to process at their algorithm level.

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