DEVELOPMENT OF AN AUTOMATED FAULT DETECTION AND DIAGNOSTIC TOOL FOR UNITARY HVAC SYSTEMS AT INDUSTRIAL ENERGY AUDITS

A Thesis

by

PRIYAM PARIKH

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Chair of Committee,	Bryan Rasmussen
Committee Members,	Michael Pate
	Natarajan Gautam
Head of Department,	Andreas Polycarpou

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ABSTRACT

Industrial energy audits generally focus on optimization of manufacturing process systems but fail to focus on the non-process industrial HVAC systems. This is in spite of the well-documented widespread prevalence of efficiency degrading faults occurring in the HVAC systems used in these facilities. Since these unitary air conditioners are not the primary energy consumers in the facility, energy auditors of IAC can find it difficult and time-consuming to identify air conditioning faults and justify their repair with a monetary value without the use of a quick tool. Existing methods and tools require system specific models or manufacturer's map models that are not easily available to energy auditors.

The proposed automated fault detection and diagnostic device for unitary air conditioners overcomes these challenges. It uses 7 surface temperature and 2 pressure sensors, with easily obtainable information to detect refrigerant undercharge, refrigerant overcharge, liquid line restriction, condenser fouling and evaporator fouling faults, and also predict the related energy and cost saving for each fault. It generates 'features' from the sensor inputs that are sensitive to the fault, but less sensitive to operating conditions. The fault detection rules are based on whether a set of features are High, Low or Normal in comparison to the thresholds. Multiple fault detection is achieved by first checking for charge related faults and then checking for fouling faults in presence or absence of the charge related faults.

The developed device was tested for individual and multiple faults with systems using thermal expansion valve and fixed orifice valve. Results showed that the sensitivity of the device was good for refrigerant line faults but not as good for the fouling faults. Results of the multiple fault tests showed that the device could detect at least one of the two faults, generally the refrigerant line fault, over 60% of the time. Overall, the device gave conservative estimates of energy and cost savings, which is usually preferred by IAC energy auditors.

Finally, the device was also prepared for field tests, to verify that it was quick, low cost and easy to use. It took about 20 minutes to install the device that cost less than $2,500.

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CHAPTER I

INTRODUCTION

Motivation

The industrial sector worldwide consumes about one-half of the world's total delivered energy. In the United States particularly, the industrial sector consumes majority of the end use energy (31%), more than the transportation sector at 28%, residential sector at 22% and commercial sector at 19% [1]. However, this trend has been changing over the last few decades as the gap between the energy consumption by the transportation sector and the industrial sector narrows (Figure 1). According to the EIA's Manufacturing Energy Consumption Survey [2], the energy consumption of the manufacturing sector has reduced by 17% from 2002 to 2010, even though the manufacturing gross output decreased by only 3 percent in this time. This significant decline in the amount of energy used per unit of gross manufacturing output is being attributed to improvements in energy efficiency and changes in the manufacturing output mix.

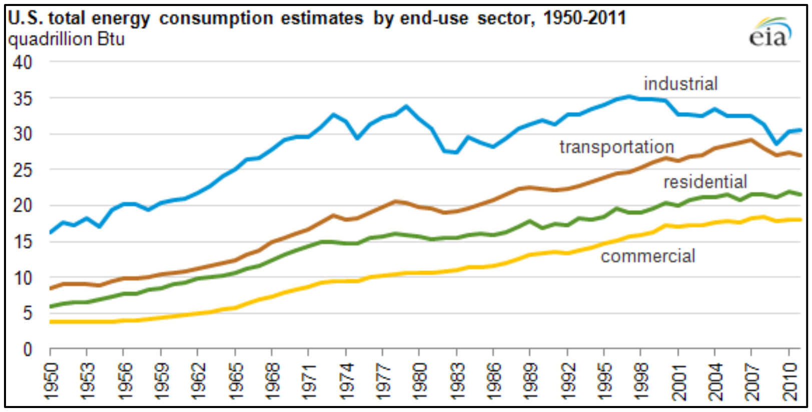

Figure 1: U.S. Total Energy Consumption estimates by end-use sector **[**1]

In spite of these improvements, the *world* industrial energy consumption is expected to increase by 50% in only 30 years; from 200 quadrillion BTUs in 2010 to 307 quadrillion BTUs in 2040, increasing at the rate of 1.4% a year [3]. Moreover, estimates show that a significant amount of this energy remains unused. Mechanical and thermal limitations of equipment and processes cause energy losses at the generation stage, transmission and distribution stage and finally at the end use stage. These onsite losses for a manufacturing plant are substantial; it is estimated that about 32% of the energy input to the plant is lost inside the plant boundary. Approximately 15% of energy in process heating, 10% in cooling systems, 40% in fans and pumps and 80% in compressed air systems is not converted efficiently [4] (Table 1).

Table 1: Percentage energy lost due to inefficient conversion in different industrial systems [4]

Energy System	Percent Energy Lost
Process Heaters	15%
Cooling Systems	10%
On site Transportation Systems	50%
Electrolytic Cells	15%
Pumps	40%
Fans	40%
Compressed Air	80%
Refrigeration	5%
Materials Handling and Processing	95%

Industrial Assessment Center

To identify and eliminate some of these losses the U.S. Department of Energy sponsors the Industrial Assessment Center (IAC) in 24 universities across the country. Student technicians at the IAC perform one-day energy audits in small to medium sized manufacturing facilities where they identify energy saving, waste reducing and productivity improvement opportunities in the plant, and predict the related environmental impact and the cost savings.

The energy saving recommendations made by the IAC generally involve changing the maintenance practices in the plant, retrofitting the inefficient system, or altering the way the equipment is operated. In this thesis, the recommendations that involve operating the equipment more efficiently are explored. One way to achieve this would be by optimizing the *control system* elements of the equipment. However, a fully optimized control system could still develop faults or disturbances, which could increase the energy consumption of the equipment. Thus, more specifically, this thesis discusses the use of sensors to identify and eliminate these faults in industrial equipment. In this case, the fault detection tool is developed for industrial air conditioning systems, where performance degrading faults like incorrect refrigerant charge, restrictions in refrigerant lines and fouled heat exchangers are common. The proposed tool will also help student technicians of the IAC predict the related energy and cost saving from eliminating the identified faults thus opening up a new set of energy saving recommendations.

Organization of Thesis

Chapter 1 is an introduction to the scope of industrial energy saving potential, and the work done by the Industrial Assessment Center. Chapter 2 talks about the impact of controls system strategies on industrial energy savings using the IAC database of recommendations. Chapter 3 explains the working of a basic air conditioning system, and discusses the wide spread prevalence of the faults in air conditioning systems. The cause and effect of the faults on the air conditioning system is discussed. Thus the symptoms related to the faults that are used in the development of the device are also identified. Chapter 4 reviews the existing literature in fault detection for HVAC systems. It focuses on the methods used by previous researchers for detecting faults in unitary air conditioners and the existing commercial FDD devices. In Chapter 5 the development of the algorithm of the proposed device is discussed. In Chapter 6 the algorithm is tested for individual faults using data generated at the Thermo-Fluids Controls Laboratory and the results of the tests are discussed. In Chapter 7, the algorithm is tested for individual faults against data generated at the Energy Systems Laboratory and the results of the tests are discussed. In Chapter 8 the algorithm is tested for multiple simultaneous faults with data generated at the Thermo-Fluids Controls Laboratory. In Chapter 9, the device is prepared for field tests and the results from an actual field test is discussed. Chapter 10 concludes the thesis by summarizing its accomplishments, its shortcomings, and listing the potential for further improvements.

CHAPTER II

IMPACT OF CONTROL SYSTEM STRATEGIES ON INDUSTRIAL ENERGY SAVINGS

Introduction

In this chapter, the use of control system strategies in industrial energy audits is discussed, and its impact is quantified using the IAC database of recommendations. The database has information on energy saving recommendations made to manufacturing industries from the year 1981 to 2012. This covers over 15,000 industrial assessments and 110,000 recommendations. Out of these 110,000 recommendations, the recommendations that involved optimizing the control system were analyzed to quantify its impact on industrial energy savings. The recommendations were divided into 5 groups based on the control strategy they used. Before discussing these 5 control strategies, it is important to know the related terminology by understanding the working of a typical closed loop control system as shown in Figure 2.

The input to the control system is the desired value or the *setpoint*, which is reached when the *control algorithm* that evaluates the error, or the difference between the actual and desired output (carried by a sensor or the *feedback element*), decides an appropriate control action to reduce it. This control action is then performed by the *actuator* on the *system* till the system reaches its desired state. There may be *disturbances* that adversely affect the output of the system which causes the control system to continuously rework its actions so it can bring the system back to its desired state.

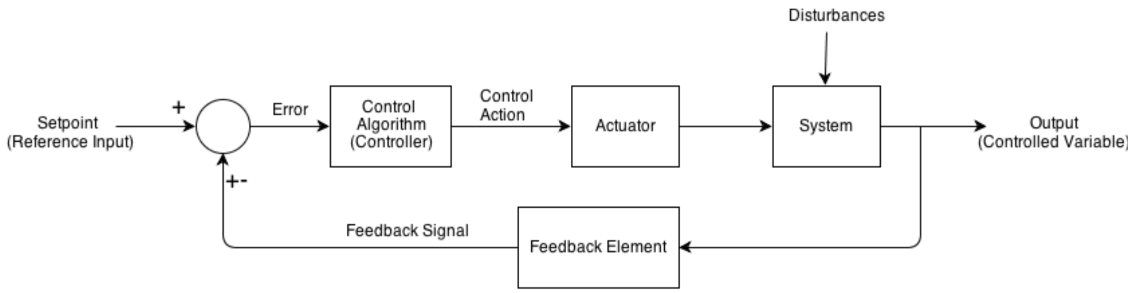

Figure 2: Typical closed loop control system

Control System Strategies

The 5 control system strategies applied on the above system to reduce its energy consumption are-Setpoint Adjustment, Algorithm Improvement, Actuator Retrofit, System Coordination and Fault Detection. The strategies are explained in the following paragraphs. They are also exemplified by recommendations from the IAC database.

Setpoint Adjustment

This strategy involves adjusting the system setpoint based on seasonal changes and production line changes to have fewer disturbances affecting the system. This reduces the system error and its energy consumption to eliminate this error. Some of the popular setpoint adjustment recommendations on industrial systems like modifying the pressure setpoints of the refrigeration system and resetting thermostatic setpoint of its air conditioning system seasonally, have high savings and very low implementation cost (Table 2).

Table 2: Common Setpoint Adjustment Recommendations

Description	Times Received	Average Annual Savings	Payback (Years)	Implementation (%)	Average Energy Saved (MMBTU/year)
Modify Pressure Setpoints of the Refrigeration System	252	$19,630	1.5	35.17%	2,926
Reset thermostatic temperature setpoints seasonally	617	$10,157	0.3	62.79%	1,346
Reduce the pressure setpoint of compressed air system	3,963	$3,792	0.5	49.29%	644
Reduce the steam operating pressure setpoint	148	$7,449	0.2	48.23%	1,638
Increase the temperature setpoint to the highest possible for chilling or cold storage	37	$10,332	0.4	42.42%	1,311

Algorithm Improvement

The control algorithm directs the working of the actuator to deliver the desired output. Therefore, by modifying the algorithm such that the least energy consumptive action for the actuator is chosen, the equipment can be made more efficient. Therefore in a facility that uses multiple pieces of equipment like compressors or boilers or chillers, the algorithm can be modified so that the load is distributed to the most efficient set of equipment to satisfy the demand. Or in case of the Building Management Systems (BMS) that control the working of the HVAC system, control algorithms can be adjusted to follow time schedules and setpoint schedules to save energy. These recommendations have low payback and high energy savings (Table 3).

Table 3: Common Algorithm Improvement Recommendations

Description	**Times Received**	**Average Annual Savings**	**Payback (Years)**	**Implementation %**	**Average Energy Saved (MMBTU/yr)**
Use Control Algorithms to distribute load among the Most Efficient Set of Equipment	272	$11,558	0.7	65.78%	1,913
Use a Centralized Building Management System to Optimize the HVAC System	420	$11,361	1.5	45.70%	2,193
Use Control Algorithms to Minimize Operation of Equipment Maintained in Standby Condition	100	$11,454	0.8	51.58%	2,181

Actuator Retrofit

The actuator consumes energy to execute the control action decided by the control algorithm. Replacing actuators by a more efficient actuator or by one that has an increased ability to follow the algorithm are common IAC recommendations. The implementation cost of an Actuator Retrofit is typically higher than the other strategies due to the high capital cost of new actuators and the labor cost involved with installing the actuator. However savings realized are also very high as seen as seen in Table 4.

Table 4: Common Actuator Retrofit Recommendations

Description	Times Received	Average Annual Savings	Payback (Years)	Implementation %	Average Energy Saved (MMBTU/year)
Use Variable Frequency Drives on pumps, motors and fans that don't always need to run on full load.	1,754	$18,183	2.1	28.91%	3,058
Install turbulators in boiler tubes to improve the heat transfer coefficient	148	$8,495	1.2	32.14%	3,011
Install economizer/outside air damper so the flow of outside air into the conditioned space can be adjusted based on demand and the weather	383	$9,436	1.9	29.91%	1,920
Use separate switches on perimeter lighting to be used in daylight	200	$3,155	0.9	49.74%	558

System Coordination

Using control systems, information can be exchanged by more than one type of industrial system to coordinate their working. As the controller receives information from multiple systems, it can oversee the operations of the overall process instead of a single equipment. This control strategy, of synchronizing the working of interdependent systems is System Coordination. A few good examples of this strategy are coordinating the working of lighting and HVAC systems in a room, based on occupancy sensor signals, and coordinating the working the turbine and boiler in a steam system. There are not many examples of this strategy in the IAC database.

The above 4 strategies could ideally optimize the energy consumption of the equipment. However in the real world there would be defects in the system over time that need to be accounted for. If not corrected, these disturbances or faults will not only increase the energy consumption of the system but also cause permanent damage to the equipment. Therefore to help detect system faults and to avoid any production downtime, one more control strategy is added to the list-

Fault Detection

This strategy involves using sensors to detect and diagnose any fault that degrades the system performance. Typically, faults arise due to a defective sensor or actuator. A faulty sensor that gives an incorrect reading of the variable it measures, adversely affects any control algorithm that uses the same variable. A faulty actuator takes positions or performs actions that are different from the command given by the control algorithm. Thus, even if the control algorithm is optimized, its actions aren't well executed by the actuator, causing the energy consumption of the system to increase. There are only two recommendations related to fault detection that were found in IAC's database, whose impact on industrial energy savings is seen in Table 5.

Table 5: Common Fault Detection Recommendations

Description	Times Received	Average Annual Savings	Payback (Years)	Implementation %	Average Energy Saved (MMBTU/year)
Detect incorrect air fuel ratio by analyzing the flue gas of a boiler	2,296	$8,957	0.6	68.43%	2,438
Repair faulty louvers and dampers of the HVAC system	6	$20,314	0.9	33.33%	1,942

Applying Fault Detection Strategies to Industrial HVAC Systems

Since the principal energy consumers in the industrial sector are process systems like steam and cogeneration systems, electric motors, compressed air systems and automation equipment, industrial energy auditors generally focus on optimizing their operations. The scrutiny demanded by them dwarfs the energy saving opportunities that can be realized by examining the non-process systems like HVAC and lighting. This was verified by a report–prepared by the Alliance to Save Energy on Promoting Energy

Efficient Buildings in the Industrial Sector. The report grouped the industrial manufacturing subsectors into “building intensive” and “process intensive” categories. The “building intensive” subsector included the Computers/Electronics, Heavy Machinery, Transportation Equipment, Fabricated Metals, Foundries, Plastic/Rubber Products, and Textile industries. And the remaining industries were grouped in the “process intensive” subsector. According to the analysis, the building energy use ranged anywhere from 4 to 41% of the total subsector energy use depending on how building intensive the subsector was. And HVAC was responsible for about 70% of this building energy use [5]. Since industrial buildings have higher HVAC loads and more operating hours compared to residential and commercial buildings, the energy saved by optimizing these systems could be significant. However according to IAC’s database of recommendations, HVAC related recommendations make only 7% of all energy saving recommendations. When these recommendations were organized based on the control system strategy used, it was found about 45% of the HVAC system related recommendations involved adjusting system setpoints, 20% involved improving the algorithm and about 34% of them involved retrofitting the actuator. There are almost no recommendations related to detecting faults in an HVAC system. This is in contrast with commercial buildings where fault detection algorithms are extremely popular as they are integrated in the facility’s computerized building management system. Small to medium sized manufacturing facilities generally don’t have such advanced building management systems to handle their air conditioning and lighting needs. This makes it tougher for energy auditors to perform on-site measurements to detect a potentially faulty HVAC system.

Therefore there exists the need for an automated fault detection and diagnosis tool for air conditioning units found in these plants that can be used by energy auditors to increase the scope of their assessment. The tool should be easy to install and should not be too time consumptive. It should be able to detect faults by simple, low cost, non-invasive measurements and predict the efficiency degradation due a fault. This would help auditors perform cost saving and payback calculations when proposing a recommendation. This thesis discusses the development of such a device to be used on industrial energy audits by student technicians. The faults that the device can detect in a unitary air conditioner are - an incorrect amount of refrigerant charge in the system (undercharge or overcharge), a restriction in the refrigerant line of the air conditioning system (liquid line restriction), and fouled heat exchanger coils (evaporator and condenser fouling).

CHAPTER III

FAULTS IN UNITARY AIR CONDITIONING SYSTEMS

The HVAC equipment in small to medium sized manufacturing facilities are generally unitary air conditioners (packaged and split units). Since these units are smaller and more numerous, they are not as well maintained as larger HVAC systems. They also lack advanced controls that would make scheduling their maintenance easier. Periodic maintenance practices generally involve changing the evaporator filters, but checking for leaks or restrictions in the refrigerant lines is a time consuming process for HVAC technicians and is generally not done. Therefore these faults go undetected till a loss in comfort is experienced. The wide spread prevalence of faulty air conditioners is well documented by a number of researchers. In one of these studies carried out on light packaged and split units in California, it was realized that about 70% of the investigated systems had faults and about 40% of them had more than one fault. The estimated 10-year cost savings for correcting these faults ranged from $800 to $1,700 per ton [6].

Before the types of faults and their effect on the performance of the system is discussed, it is necessary to understand the principle behind air conditioning or the Vapor Compression Cycle and the important terminology used in the thesis.

Background on Working of an Air Conditioner

Vapor Compression Cycle

The Vapor Compression Cycle shown in Figure 3 consists of 4 essential components: a compressor, a condenser coil, an expansion valve and an evaporator coil. The refrigerant absorbs the heat from the room by vaporizing on the low-pressure evaporator side and rejects the heat to the ambient by condensing on the high-pressure condenser side.

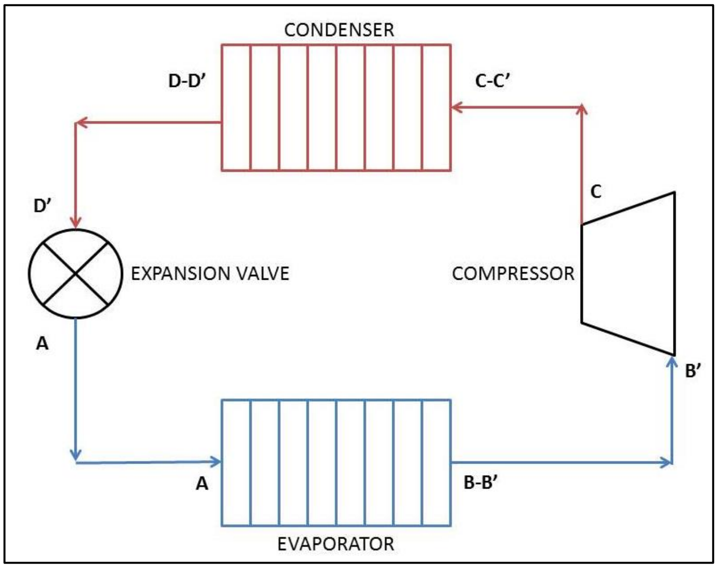

Figure 3: Components of the Vapor Compression Cycle

The energy exchange and phase change of the refrigerant through the system is better explained with the pressure-enthalpy diagram shown in Figure 4.

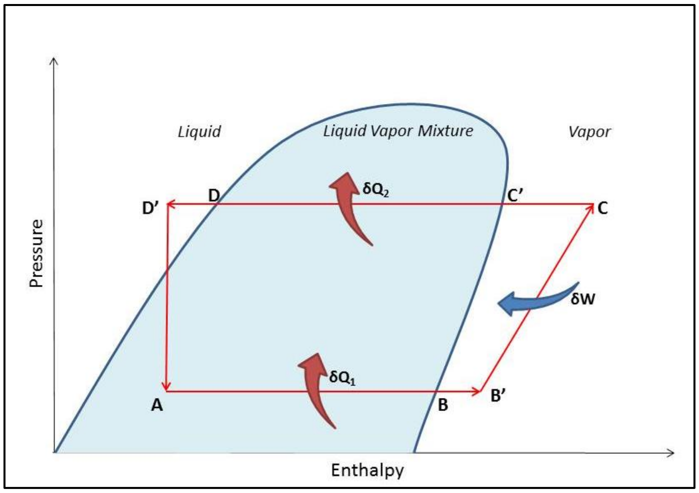

Figure 4: Pressure Enthalpy diagram for the Vapor Compression Cycle

- **Evaporator (A to B-B'):** A low temperature, vapor-liquid refrigerant mixture enters the evaporator coil. It turns first into saturated vapor (Point B) and then superheated vapor (point B') by absorbing heat from the return air of the space.
- **Compressor (B' to C):** The superheated refrigerant then enters the compressor at the suction side for isotropic compression. The compressor consumes work (δW) to discharge the refrigerant as a high pressure, high temperature superheated vapor.
- **Condenser (C to D'):** The superheated vapor from the compressor enters the condenser where the heat is rejected to the ambient (δQ_2). This happens in three stages: the vapor is first desuperheated (C to C'), then condensed (C' to D), and finally subcooled or cooled below its saturation temperature (D to D'). Thus the refrigerant leaves the condenser as a single phase, subcooled liquid.

- **Expansion Valve (D' to A):** As the high pressure subcooled liquid refrigerant enters the expansion valve, it undergoes isenthalpic expansion to form a low pressure, low temperature vapor-liquid mixture that is now ready to enter the evaporator coils again.

Important Terminology

- **Superheat:** Superheat is defined as the number of degrees the vapor is heated above its saturation temperature or its boiling point. In the figure, it is the difference between the temperature at B' and B. It is necessary to have a certain amount of superheat to ensure that the refrigerant enters the compressor as a single phase vapor and not liquid.
- **Subcooling:** Subcooling is defined as the number of degrees a liquid is cooled below is saturation temperature. In the figure, it is the difference between the temperature at D and D'. A certain amount of subcooling ensures that the refrigerant enters the expansion valve as a single phase liquid, which is necessary for the valve to properly meter the refrigerant into the evaporator.
- **Condenser Split:** The condenser split is the temperature difference between the condenser saturated temperature and the ambient air temperature. The condenser split decides the rate of heat rejection on the condenser side (δQ_2).
- **SEER:** The Seasonal Energy Efficiency Ratio or the SEER rating for an air conditioner is the cooling output in BTU during a typical cooling season divided by the total electric input in Watts-hours during the same period. A higher SEER rating means the air conditioning unit is more efficient.

- **COP:** The Coefficient of Performance or COP is a dimensionless representation of the efficiency of an air conditioner. It is the ratio of the heat supplied or removed from the room, to the work consumed by the air conditioner.
- **TXV:** The Thermal Expansion Valve (TEV or TXV), is a metering device used in the air conditioner for better control of the evaporator superheat. It controls the amount of refrigerant flow to the evaporator based on the evaporator superheat. A fixed orifice expansion device (FXO) on the other hand has a fixed opening and cannot control the refrigerant flow.
- **EEV:** Electronic Expansion Valves (EEVs) are a more sophisticated way of controlling the refrigerant flow to the evaporator coil. The flow is controlled using an electronic controller that sends signals to a stepper motor which controls the opening and closing of the valve. Pressure and temperature sensors are wired to the controller for better superheat and pressure control.

Faults in Unitary Air Conditioners

To identify what faults need to be included in the fault detection and diagnostic device, a few fault distribution databases were considered. Stouppe and Lau recorded the causes of over 15,000 air conditioning service calls over a period of 8 years (1980-1987) [7]. About 76% of the failures were attributed to electrical components, 19% to mechanical components and 5% to refrigeration circuit components. Most of the electrical component failures were due to failures in motor windings, the mechanical component failures were generally due to failed compressor valves, bearings, or connecting rods. However what was not recorded in the survey, were the initial faults that probably caused the eventual failure or loss in capacity of the system. The repair costs associated with these service calls were also not recorded.

Breuker and Braun [8] created a database of 6,000 different fault cases and analyzed the faults based on frequency of occurrence and repair cost of the fault. Based on frequency of occurrence it was concluded that mechanical faults constituted 60% of the total faults, and the remaining 40% of the faults were due to electrical and control problems. Mechanical problems were mainly the refrigerant cycle problems associated with the condenser, evaporator, compressor, and expansion device, or refrigerant charge problems associated with the whole cycle. Electrical and controls problems involved thermostat adjustments or replacements, wiring failure, damaged components, blown fuses or bad connections. When the faults were analyzed based on the cost of repair, it was concluded that the most expensive faults were related to compressor failures (24%) due to its high cost component cost and labor cost to replace it. The combined refrigerant cycle faults (condenser, evaporator, air handling unit and expansion valve) constituted 25% of the repair costs. The electrical and control related faults constituted 17% of the total costs only because of their high frequency of occurrence.

Based on their findings it can be concluded that since the compressor is the most expensive component to replace, frequent faults that may damage the compressor must be included in the proposed device. A compressor generally gets damaged due to lack of lubrication caused by presence of liquid in the compressor (liquid floodback). Liquid refrigerant in the compressor shell acts as a solvent and washes the oil film from adjoining surfaces like pistons, valves and rods in the compressor. This causes overheating and scoring which damages the compressor components. It also dilutes the lubricating oil thus compromising its ability to lubricate. The faults that could cause liquid flooding could be evaporator fouling, condenser fouling, refrigerant overcharge or a faulty expansion valve.

Therefore faults to be included in the fault detection device, were the ones that could cause excessive loss of air conditioner performance and eventual component failure, the faults that could lead to more expensive repair, and most importantly, what faults were tougher to detect and diagnose in a typical maintenance visit. Based on the frequency of occurrence and repair cost of faults, the following 5 faults were chosen to be detected by the device:

- Refrigerant Line Faults: Refrigerant Undercharge and Refrigerant Overcharge and Liquid Line Restriction
- Fouling Faults: Condenser and Evaporator Fouling

Refrigerant Line Faults

An air conditioning unit achieves its maximum cooling capacity and efficiency when the amount of refrigerant it holds exactly matches the amount specified by the manufacturer. If it is undercharged or overcharged, the performance and the life of the system is affected. Since most air conditioners undergo final assembly at the customer installation site, they are shipped from the factory with only enough charge for the compressor and a fixed diameter and length of refrigeration line. For final installation, charge has to be added or removed depending on the actual length of the tubing from the indoor to the outdoor unit. Quite often, due to defects in the metering device, evacuation techniques or other field installation problems, the system gets incorrectly charged and fails to match the manufacturer's specification [9]. As a result the system's performance will be affected due to the over- or undercharge.

Systems may also get undercharged over time due to leaks occurring at the pipe fitting connections and through the walls of the copper refrigerant tubes over the years. As refrigerant leaks out of the system into the open space, its high Global Warming Potential (GWP) harms the environment. Older refrigerants like R-22 also have some amount of Ozone Depleting Potential (ODP). Although these are phased out by the Montreal Protocol and are found only in older systems, newer systems still use refrigerants like R410A that have a global warming potential that is 2,088 times the effect of CO_2. Therefore checking the system for leaks as soon as an undercharge is detected is very important.

To quantify the performance loss of the system due to refrigerant undercharge or overcharge, a number of laboratory tests have been conducted over the years for systems using different expansion devices and different refrigerants. Farzad & O'Neal (1993) [10] conducted tests to find the loss in system performance due to incorrect R-22 refrigerant charge. Tests done on a fixed capillary system and a TXV system showed that an undercharge of 15% reduced cooling capacity by 8 to 22% and EER by 4 to 16% based on the outside air conditions. And an overcharge of 10% reduced the system's capacity by 1 to 9% and EER by 4 to 11%.

More recently, Kim and Braun [11] quantified the effect of different refrigerant charge levels for systems using R-22 and R410A, in heating and cooling mode. The R-

22 system used a TXV and showed a 7% reduction in cooling capacity, and 9% reduction in COP for a 30% undercharge. The R410a system showed a reduction of 70% in cooling capacity and 65% reduction in efficiency for 60% undercharge. On the other hand, overcharging by 30% increased the cooling capacity of both systems by 20% but reduced their efficiency by 10%.

In spite of the performance degradation caused by incorrect refrigerant charge, undercharged and overcharged systems have been widely prevalent. A report made for the American Council for an Energy-Efficient Economy (ACEEE) in February 1999 listed the contributions of researchers that surveyed a number of residential air conditioners and heat pumps, in existing and new homes. It was found that on average refrigerant charge was either too high or too low in approximately three-quarters of the central air conditioners and heat pumps tested. The report estimated an average energy saving potential of 13% from all the studies of incorrect charge [12].

When a computer expert system CheckMe® was used by HVAC technicians in California to gather measurements on their maintenance visits, performance data and diagnostic measurements from over 13,000 residential and commercial air conditioners was collected. The data revealed that about 57% of the systems were more than ±5% outside the manufacturer's specification of charge level. The refrigerant charge error percentage for 405 residential units and 316 commercial units is shown in Figure 5 to highlight the distribution of the *amount* of overcharge or undercharge in faulty systems. About 40% of commercial and residential systems were more than 17.5% undercharged, and at least 25% of commercial systems and 32% of residential systems were more than 7.5% overcharged [13].

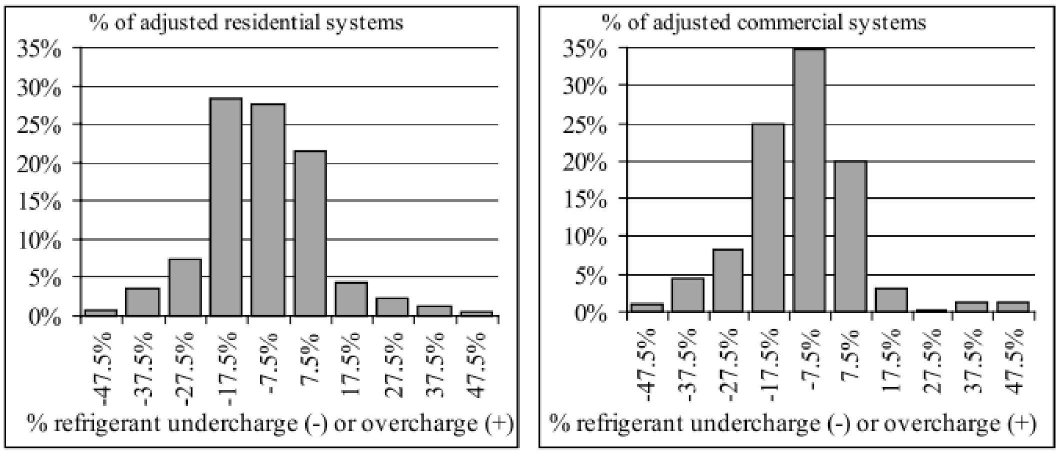

Figure 5: Refrigerant Charge Error Percentage in surveyed Residential and Commercial Systems [13]

The best way to identify an incorrectly charged system is to look for abnormal pressures and temperatures. The only other way to detect these faults would involve removing all the charge from the system and weighing it, which is an expensive and time-consuming process. The impact of the faults on system performance, and how they affect the temperatures and pressures in the system was explained in a series of articles by Mr. John Tomczyk for ACHR News[14, 15]. His explanations are summarized in the following sections to help identify the symptoms of the faults.

Refrigerant Undercharge

An undercharged system has lower cooling capacity, and it may cause overheating and eventual failure of some parts of the system. Its effect on individual components is explained below.

- Evaporator: In an undercharged system, all the components are starved of refrigerant. The starved compressor trying to draw refrigerant into its cylinders causes a low pressure on the evaporator side of the system. Evaporator pressure being low implies that its saturation temperature is low. This means for the same amount of heat absorbed at the evaporator and the reduced amount of refrigerant, the refrigerant evaporator exit temperature will be higher, or the superheat will be high.
- Compressor: Since the compressor sees more superheated, lower density vapors, its amperage draw is lower. As it compresses the vapor, the superheat increases even more, increasing the discharge temperature at the compressor outlet.
- Condenser: The starved condenser does not see as much heat to reject to the ambient. Therefore, it has a lower temperature and pressure and a low condenser split. Its 100% saturation point is very low since there is lesser refrigerant vapor to condense into a liquid, thus reducing the condenser subcooling.

Therefore the symptoms of an undercharged system are:

- Low evaporator pressure
- High superheat
- Low compressor amperage draw

- High compressor discharge temperature
- Low condenser split
- Low subcooling

Refrigerant Overcharge

Refrigerant overcharge may not reduce the cooling capacity, but certainly reduces the efficiency of the system and may potentially damage the compressor. The effect of refrigerant overcharge on the individual components of the system is explained below.

- Condenser: When the system gets overcharged, the excess refrigerant is backed up in the condenser as a subcooled liquid. Therefore a greater percentage of condenser tubing holds liquid, leaving lesser tubing for the vapor to undergo condensation. To reject the same amount of heat with the reduced area entails increasing the "condenser split" or the temperature difference between condenser saturated temperature and the ambient temperature. Thus, the condenser saturated temperature increases, and the corresponding condenser saturated pressure also increases. The excess subcooled refrigerant also increases the condenser subcooling.
- Evaporator: If the system uses a thermal expansion valve, the evaporator pressure will be normal to slightly high depending on the amount of overcharge, and the TXV will try to maintain normal superheat even at excessive overcharge. However, in case of a fixed orifice expansion device the superheat will be lower and the evaporator pressure will be higher.

- Compressor: Due to the higher condenser pressure, the compressor will have to do more work to compress the refrigerant to this pressure. Thus the amperage draw of the compressor will be more, as will its compression ratio and discharge temperature. At higher levels of the fault, the excess refrigerant may not vaporize completely in the evaporator thus entering the compressor as a liquid. Liquid refrigerant in the compressor can cause slugging or flooding of the compressor, and compressing the liquid will cause permanent damage to the valves of the compressor.

In summary, the following are the symptoms of an overcharged air conditioner: .

- High subcooling
- High condenser split
- High condenser pressure
- Normal to high evaporator pressures
- Low superheat in case of fixed orifice expansion device
- High compressor amperage draw
- High discharge temperatures

The other refrigerant line fault that may develop over time due to poor maintenance of the air conditioner is liquid line restriction. The liquid line is the refrigerant line between the condenser outlet and the expansion device inlet. The refrigerant flow in this line may get restricted due to a clogged filter/drier or a TEV strainer, or a kinked up liquid line. This causes low pressures downstream of the restriction, resulting in loss of cooling capacity due to the reduced refrigerant flow in the evaporator, or in some cases severe damage to the compressor. Rossi and Braun (1997) showed that a 20% increase in pressure difference across the liquid line due to a restriction could cause a 17% loss in capacity and 8% loss in COP [8].

A crude way of detecting liquid line restriction is by looking for a cold spot somewhere on the liquid line, downstream of the restriction, since the pressure drop due to the restriction causes some amount of liquid flashing. By running the hand over the liquid line, near the filter drier a cold spot could be found. However, the human hand is not capable of sensing temperature differences less than 10°F, thus the restriction could go undetected. If the system has a sight glass just after the restriction and before the expansion valve, bubbling in the sight glass could also be an indication of liquid line restriction, but this may not be always true. Bubbles in sight glasses are seen due to various other reasons like rapid increases in loads or undercharge. Therefore the best way to confirm the fault is to look for the symptoms of the fault whose presence is explained as follows [16].

Liquid Line Restriction

The symptoms of liquid line restriction and its effect on the components of the air conditioning system are explained as follows:

- Expansion Valve: The restriction in the liquid line introduces an additional pressure drop. This pressure drop causes some of the liquid refrigerant to vaporize before it reaches the expansion valve, which affects the functioning of the expansion valve as it now sees a two-phase mixture instead of a pure liquid.

- Evaporator: Since components downstream of the restriction are starved of refrigerant, more refrigerant is drawn from the evaporator by the compressor. Now the evaporator is starved of refrigerant and it will have a lower pressure. This implies the evaporator saturated temperature is also lower, which means for the same amount of heat load the evaporator superheat will be higher. With a restriction in the liquid line that affects the inlet to the expansion valve, the TEV cannot be expected to control superheat as well as it would.
- Compressor: The compressor may get severely overheated due to the lack of refrigerant that would otherwise keep it cool. This means that the discharge temperatures of the compressor will be high. Its amperage draw will be low since there is lesser refrigerant and lower density refrigerant enter the compressor. However, it may short cycle due to the low pressure on its suction side, and once some refrigerant enters it to increase its pressure, it would go on again. This will keep occurring till it gets overheated. Short cycling will cause damage to the compressor motor and capacitors.
- Condenser: The restriction causes lesser refrigerant to flow through the system. Lesser heat is introduced in the condenser, since lesser refrigerant enters the condenser from the evaporator and compressor. Since lesser heat has to be rejected, the condenser split need not be high. Thus the condenser saturated temperature (and therefore condenser pressure) is lower. The refrigerant backs up into the condenser due to the restriction and gets more subcooled.

Therefore a summary of the symptoms is:

- Low evaporator pressure
- High superheat
- High compressor discharge temperature
- Compressor short cycling
- High condenser subcooling

Fouling Faults

For an air conditioner to adequately heat or cool a space, its heat exchangers need to be able to absorb and reject heat at a sufficient rate. This rate is a function of the temperature difference between the refrigerant in the tubes and the air crossing the tubes, the surface area of the tubes exposed to the air and the heat coefficient of the tubes. Since the temperature difference depends on the operating conditions, to ensure that the system can cool or heat the space up to its capacity, it is important to keep the coils clean thus ensuring sufficient area for heat exchange.

As the condenser coil is placed outdoors, its coils get covered with leaves, dust, wool, pollen and dust, thus reducing the effective air flow over the coils. When the condenser fouling is severe, the system can't reject heat at a fast enough rate causing all its parts get overheated resulting in component damage reduced system efficiency. In case of the evaporator, the evaporator filter may clog up with dirt, thus reducing the air flow to the evaporator coil. If the evaporator fouling is severe enough, the refrigerant fails to vaporize and enters the compressor as liquid, permanently damaging its parts.

To quantify the loss in system efficiency due to evaporator fouling, Breuker and Braun [8] conducted tests on a three ton packaged air conditioner that used a fixed orifice expansion device. They simulated the condenser fouling fault by covering the condenser with strips of paper. The evaporator filter fouling fault was simulated by changing the speed of the air flow across the evaporator by using a variable speed fan. The resulting decrease in cooling capacity varied from 3 to 11% for condenser fouling of 14 to 56%. The corresponding decrease in COP was 4 to 18%. The decrease in cooling capacity for evaporator fouling from 12 to 36% varied from 6 to 19% and the COP decreased by 6 to 17%.

Some industrial facilities have 'clean rooms' that use a high efficiency filter, others have excess dust and dirt in the return air due to manufacturing operations carried on in the air conditioned space which can easily clog up even a low efficiency filter. Li and Braun [17] tested impact of evaporator fouling on the performance of the air conditioner and heat pump for different levels of filtration. For one year's dust loading (600 grams of dust), the 35 ton, 5 ton and 3 ton units had EER degradations ranging from 2% to 10%. Lower degradation for lesser efficient filter and bigger sized units.

In the report prepared for ACEEE that summarized the work of researchers that surveyed a number of residential air conditioners and heat pumps, it was found that nearly 70% of indoor air coils had inadequate air flow (where normal air flow was considered to be 400 cfm per ton of cooling capacity). The average airflow of the faulty systems was nearly 20% below the manufacturer's recommended airflow. The report estimated an average energy saving potential of 8% for such units [12]. In a different study that surveyed more than 13,000 systems in California, it was found that at least 21% of the systems had low evaporator air flow problems [13].

Although fouling faults are visible, their detection is automated by the proposed device by making use of the abnormal pressures and temperatures caused by these faults. These symptoms are summarized in the following sections.

Evaporator Fouling

The effects of a fouled evaporator coil or clogged evaporator filter on each component of the system are explained as follows.

- Evaporator: Since a fouled evaporator filter does not allow as much warm return air to enter, the refrigerant in the evaporator may not get superheated enough, or in some severe cases of fouling, it may not even get vaporized. Thus the temperature and pressure in evaporator is low. Sometimes, frost forms on the exterior of the evaporator coil since the low temperature refrigerant inside has not picked up enough heat. This frost further impedes the heat exchange at the evaporator coil.

  So if the evaporator *coil* is fouled, there is lesser surface for heat exchange for the warm return air, resulting in insufficient cooling of the air. Therefore the temperature difference of air across coil decreases. But in case the evaporator *filter* is fouled, there is lesser air coming in contact with the coil, resulting in overcooling of the air. Therefore for evaporator filter fouling the temperature difference of the air across coil increases.

- Compressor: If the refrigerant in the evaporator is not completely vaporized, it may enter the compressor as a liquid. This will cause flooding of the crankcase in the compressor and dilution of the compressor oil. Since the refrigerant entering the compressor is less superheated and has a greater density, it increases the amperage draw of the compressor.

- Condenser: Since the fouled evaporator does not absorb much heat from the space, the condenser has lesser heat to reject to the ambient surrounding. Thus it doesn't need to have a very high condenser split. This implies the condenser saturated pressure and temperature does not need to be too high either.

Thus the symptoms to look for when detecting a fouled evaporator are-

- Low evaporator superheat
- Temperature difference of air across evaporator high in case of fouled evaporator filter and low in case of fouled evaporator coil.
- Frost on the evaporator coils, or refrigerant lines entering the compressor
- Lower compressor discharge temperature
- Low condenser split
- Low condenser pressure

Condenser Fouling

The effects of condenser fouling on the individual components of the system are explained as follows:

- Condenser: Heat from evaporator, compressor motor, suction line and from the compression of the refrigerant is all rejected in the condenser. If the condenser coil is fouled, the condenser cannot reject this heat fast enough. This means to increase the rate of heat rejection, the condenser split (or the difference between the condenser saturated temperature and outside air temperature) is increased.

Due to the pressure-temperature relationship, a higher condenser saturated temperature would imply a higher condenser pressure.

Therefore, since the area exposed to the ambient air is reduced, to dissipate the same amount of heat, the temperature difference of the air across the coil increases.

- Evaporator: Since all the heat absorbed by the refrigerant in the evaporator is not rejected by the condenser at a fast enough rates due to a fouled coil, the evaporator may not be able to cool the space up to its potential. In cases of severe condenser fouling, the high condenser pressure may cause the evaporator side pressure to slightly increase as well.
- Compressor: Since the condenser pressure is higher, the compressor has to work harder or draw more current to compress the refrigerant to the higher pressure. The high heat of compression from the higher compression ratio will increase the discharge temperature of the compressor.

Therefore the symptoms of a fouled condenser are:

- High condenser split
- High condenser pressure
- High evaporator pressure
- High compression discharge temperature
- High temperature difference of air across condenser coil

Looking for abnormal pressures and temperatures in an air conditioning system is the best way to correctly detect and diagnose the faults affecting it, as it requires non-invasive, low cost measurements. However, to know if the measured temperature and pressure is too high or too low, we first need to know what temperatures and pressures to expect. With the wide variety of air conditioning systems in terms of size, type, working in different operating conditions, this requires the expertise and knowledge of an experienced technician. Moreover, incase an overcharge or undercharge is detected, there is no way for the technician to predict the *amount* of incorrect charge and the related efficiency loss. The proposed device tries to overcome these challenges. It uses the listed symptoms along with typical thresholds to make fault detection and diagnosis simpler for student energy auditors.

CHAPTER IV

LITERATURE REVIEW

Introduction to Fault Detection in HVAC Systems

In early 1970s fault detection and diagnosis (FDD) was explored for use in life-critical systems and processes in the fields of nuclear power, aerospace, process controls, automotives, manufacturing, and national defense. FDD in these fields were developed to improve safety and reliability of the equipment and to prevent loss of life. Research in FDD in the air conditioning and refrigeration field was only explored after the decreasing cost of microprocessors and hardware over the years made it economically viable. Numerous surveys of air conditioners and refrigerators by investigators aided by technicians helped realize the wide spread prevalence and effects of faults in HVAC systems.

Researchers mostly referred to Isermann's (1978) generic method of fault detection and diagnosis to develop their FDD method for HVAC&R [18]. FDD is made of three key steps. The first step is Fault Detection which involves checking if a particular measureable or unmeasurable signal was within a certain tolerance of the normal value. This is followed by Fault Diagnosis which identifies the location and cause of the fault. FDD for HVAC in particular includes a third step which is Fault Evaluation which involves analyzing the short term and long term effects of the faults to check if the benefit of servicing justifies its expense. This is different from FDD in critical systems which has zero tolerance for faults and requires no decision making.

FDD in HVACR was first tried in the late 1980s for fault detection in household refrigerators by Mc Kellar in 1987 [19] and Stallard in 1989 [20]. The faults considered were compressor valve leakage, heat exchanger fan failures, frost on the evaporator, partially blocked capillary tube, and refrigerant charging failures. McKellar found that each of these faults had unique effects on three measures: suction pressure, discharge pressure, and discharge-to-suction pressure ratio and concluded that these measures were sufficient for developing a FDD system. Based upon the work of McKellar, Stallard (1989) developed an expert system for automated FDD applied to refrigerators. Directional change of measured quantities like condensing and evaporating temperatures and discharge and suction pressures, with respect to expected values were used to diagnose faults.

Since this first attempt, HVAC FDD has seen a growth in interest from researchers. This is seen by the increasing number of papers related to the topic since 1996 [21]. Although half of these papers focused on FDD for air handling units and variable air volume terminal boxes, FDD in vapor compression systems like chillers and packaged air conditioners still saw lesser but significant contributions.

FDD was applied to chillers by Grimmelius et al. in 1995[22] . A cause and effect analysis for different faults was developed to arrive at a failure symptom pattern for each fault. By using a reference regression model, and over 20 different measurements of temperature, pressure, power consumption and oil level, residuals were generated. A residual pattern particular to a fault mode was developed and faults were diagnosed by scoring how well the fit was into a residual pattern. Stylianou and

Nikanpour (1996) [23] used a similar pattern matching approach, but instead used a thermodynamic model in their FDD system. In fact, their FDD system was divided into three parts- one when the chiller is off, one during start up and one during its steady state operation. They required 17 different temperature, pressure and flow measurements to refrigerant leak, refrigerant line flow restriction, condenser waterside flow resistance, and evaporator waterside flow resistance.

Jia and Reddy (2003) [24] used a characteristic parameter approach, to detect and diagnose faults in chillers. The performance of every component of the chiller (motors, heat exchangers etc.) is quantified by one or two parameters. Since each parameter is indicative of the health of a particular component, fault detection and diagnosis is easier. This method however is suitable only for larger HVAC systems that generally have numerous sensors.

Fault Detection Methods in Unitary Air Conditioners

Although majority of FDD algorithms were made for chiller and air handling units, interest in FDD on residential, low tonnage air conditioners, that is, split and packaged direct exchange systems grew due to two reasons: because these systems are used widely and because are not very well maintained by their owners.

FDD in unitary air conditioners was first attempted by Yoshimua and Noboru in 1989 who used a combination of six temperature and two pressure measurements to perform FDD for packaged water cooled and air cooled air conditioners of a telecommunications building [25]. They developed an algorithm to detect condenser and evaporator coil fouling, and detect an abnormal evaporator and chilled water pump operation. They used superheat, subcooling, ratio of rated and actual condenser pressure and evaporator pressure and the temperature difference of air across the evaporator and air (or water) across condenser, as their six diagnosis parameters. These diagnosis parameters were compared to fixed thresholds as per a diagnostic flow diagram to detect the faults. Expected values of pressure and temperatures were obtained from the manufacturer and they were compared to the actual values. Actual test results, or any information about the threshold values and the sensitivity of the method is not provided.

Rossi and Braun (1997), developed the statistical rule based model using 9 temperature measurements and one humidity measurement to successfully detect and diagnose five faults: leaky compressor valve, liquid line restriction, evaporator filter fouling, condenser fouling and refrigerant undercharge [26]. A steady state model was used to relate operating conditions of the system (ambient temperature, indoor temperature and humidity) to the expected output states occurring at no-fault conditions. These expected output states were temperature measurements at different points in the vapor compression system, and they were compared to actual temperature measurements to generate residuals. Fault detection was achieved by evaluating the statistically evaluating these residuals. The overlap of the residual probability distribution for a normal and faulty operation was the classification error, which reduced as the level of fault increased. For fault diagnosis, directional changes of the residuals were related to a specific fault based on a set of rules. Diagnosis was done when the probability of the most likely fault is greater than the probability of the second most likely fault by a certain threshold. The method was tested and evaluated on a 3 ton rooftop unit that used a fixed orifice expansion device. It could detect and diagnose a 2% reduction in refrigerant charge, 5% compressor valve leak, 20% condenser fouling, and 40% evaporator fouling. In the laboratory tests, liquid line restriction could only be detected at a level greater than 80%. The method didn't require any equipment specific experimentation since the diagnostic rules were generic. However the method also requires the development of a model for the system which is time consuming and expensive as the model needs to be trained over a wide range of conditions. It also introduces modeling errors to the method.

The FDD sensitivity is greatly improved by using model-based pre-processing and statistically based thresholds, but these system specific models require extensive experimentation for each fault. Since the faults need to be detected in smaller HVAC systems that are inexpensive themselves, the software and hardware related to the FDD for the systems need to be less expensive too for it to be economically viable.

Therefore to eliminate the requirement of an expensive measurements and a model that requires extensive testing, Chen and Braun (2000) came up with two methods- the "Sensitivity Ratio Method" and the "Simple Rule Based Method" to detect faults in unitary air conditioners [27]. The faults detected were evaporator and condenser fouling, refrigerant overcharge and undercharge, liquid line restriction, non-condensable gas and compressor valve leakage. Unlike Rossi's tests in 1995, the tests were done on a 5 ton rooftop unit that used a thermal expansion valve instead of a fixed orifice valve. In his first method, the "Sensitivity Ratio Method" a unique pair of sensitive and insensitive residuals were used to calculate sensitivity ratios for each fault. If a fault occurred, the value of the ratio would go below a preset threshold and fault would be detected. A noise filter was used so if the residual was less than 2°F, it was reset to 0.1°F. In this way if the system was faultless the sensitivity ratio would be 1, and if the ratio went below 1 a fault was detected. These checks against thresholds were done in a methodical way using a diagnostic flow chart developed by the authors. 11% LLR, 20 to 30% condenser fouling, 7 to14% evaporator fouling, 5 to 10 % undercharge and 10% overcharge and 0.09% non-condensable gas were the minimum fault levels that were sensitive to this method.

The second method- "Simple Rule based method" performed just as well as the first without the use of a model to generate residuals. It required only six temperature measurements and no humidity measurements. It used performance indices computed from raw measurements that are independent of operating conditions but are sensitive to the fault. The performance indices were liquid line subcooling, condenser split, evaporator split, temperature difference across liquid line, and evaporator split. There is a unique pattern of change of these performance indices for the different faults, and the thresholds to detect a fault using these performance indices were experimentally determined at different conditions. This method works well for low cost FDD applications. However, like the other fault detection methods developed so far, this method couldn't detect multiple faults.

In 2007, Li and Braun developed a decoupling methodology to detect multiple simultaneous faults in a system. The authors use 'decoupling features' that are uniquely dependent on individual fault, as the key to handling multiple simultaneous faults. The decoupling features for the faults were identified as evaporator and condenser volumetric air flow rate for evaporator and condenser fouling, compressor discharge temperature for compressor valve leakage, a refrigerant charge indicator that used subcooling and superheat to detect incorrect refrigerant charge and pressure difference across the expansion valve was used to detect liquid line restriction. For fault detection, a fault indicator was calculated as the ratio of the current value of the decoupling feature to its value for a 20% cooling capacity loss. For all the different combinations, 41 different tests were done on a 5 ton rooftop unit using at TXV. Multiple fault diagnosis was done using a modified error indicator where the decoupling feature for an individual fault and case and a multiple simultaneous fault case were related. Based on the results of the 41 different tests, the authors concluded that only two false alarms occurred for the 41 different fault combinations and a sensitivity loss for LLR fault occurred.

The challenge with such a method was that measuring some of the decoupling features like liquid line pressure, air flow rate and refrigerant mass flow rate would require expensive sensors. Therefore Li and Braun also developed 'virtual sensors' that would use thermodynamic relations and map models of compressors and expansion valves to calculate the decoupling features from low cost temperature measurements [28]. Compressor power consumption and mass flow rate of refrigerant was predicted using the compressor map model which is a 10 coefficient polynomial available from manufacturers. The prediction accuracy was within 5% of actual value. Volumetric air flow rate across condenser and evaporator and expected compressor discharge temperature were calculated using thermodynamic relationships.

A different approach to fault detection worth citing was tried using electrical signal measurements instead of temperature and pressure measurements [29]. This approach of Non-Intrusive Load Monitoring used the starting transient signals and reduced them to ‘signatures’. Changes in the signatures helped detecting faults in the system. The advantage of this approach was that it reduced the number of measurements needed; but it also made device expensive and system specific.

Therefore, the final device could not use the Statistical Rule Based method, Sensitivity Ratio method or the Non-Intrusive Load Monitoring method in its algorithm, as these methods require an online model. Since the device is meant to be portable and needs to be able to work with different types and sizes of equipment, developing a model is expensive and time consuming. The decoupling method also cannot be used in the proposed device, as it requires information of compressor map models that is not easily available to student technicians. The challenge is to achieve fault detection and diagnosis with minimal, easy to obtain information. Thus the proposed device uses an algorithm that is based on the Simple Rule Based method. However, it goes a step ahead as it tries to achieve multiple fault detection.

Existing Commercial FDD Devices in HVAC

Fault detection in HVAC has seen growing popularity over the past few years. In mid 1990s an ASHRAE Technical Committee on Smart Buildings became active in FDD research. The 2013 California Title 24 energy code (California Energy Commission [CEC] 2012) now requires FDD on all newly installed unitary equipment. As a result, now there are several equipment manufacturers who include FDD capabilities in some of their unitary equipment product lines. However, FDD in HVAC is still in its infancy when compared to other fields like automobiles, where FDD has been incorporated for more than a decade. Much of the research and development in FDD for HVAC&R is still performed in universities and national laboratories and there are only a few commercialized tools available on field which use these techniques [30]. Some indicate operational faults in the system, the others continuously monitor the performance of the system to indicate the presence of a possible fault. Some of these devices are:

1. **Virtjoule:** Virtjoule uses non-invasive electricity and/or vibration sensors that are attached to the outside of the air conditioning unit [31]. The device monitors compressor and outdoor fan operation and analyzes this data to catch air conditioner failures before they occur. The sensor data can be accessed real-time via a web application where alerts for under-cycling or over-cycling, non-operation can be created. This would also help the user know if the air conditioner is left running after operating hours.
2. **Smart Monitoring and Diagnostic System (SMDS):** The SMDS was developed to detect a change in performance in the refrigerant side of the packaged air conditioning systems. Therefore it can be used to quantify the impact on the performance and the cost savings resulting from servicing. It can help the building owner decide when to schedule servicing based on increased energy cost due to performance degradations and servicing costs [32]. It detects operational

faults in the system like – supply fans always being on, compressor always being on, RTU always off and supply fan cycling.

3. **FDSI- Synergy:** Synergy is a software application that uses data from the building management software, and uses mathematical models and fault detection algorithms to detect the faults existing in the air conditioning unit. It collects set points, run times, interior and exterior temperatures daily, and uses the facilities' utility data (peak demand and electricity cost), to estimate possible cost saving opportunities. It organizes these cost saving opportunities in different categories- based on difficulty, urgency, payback period and equipment type.
4. **Sensus MI:** Sensus MI is an automated fault detection system to give an early indication if a machine is working properly or installed properly to the service company [33]. The device continuously learns about the equipment, as it can diagnose a few faults like incorrect refrigerant charge or a dirty evaporator or condenser coil. As the service company technician can view the condition of the system on a dashboard in his office, it helps the company schedule their maintenance visits better, before there is significant discomfort felt by the users of the HVAC system, or before the system completely breaks down.
5. **ClimaCheck:** ClimaCheck technology can detect faults in air conditioning systems in two ways- a fixed installation as well as a field inspection unit [34]. The field inspection units uses a current measurement, 7 temperature measurements and two pressure measurements to define actual performance and compare it to the ideal system performance. It is used to estimate the cost and

benefits of operational improvements and optimization. It can be integrated with the building management system for chillers and heat pumps, as a portable performance analyzer.

Almost all of the above devices (SMDS, Synergy, Virtjoule, Sensus MI) require permanent installation on the air conditioning unit. They are made either for the building owner or from the point of view of a service technician. They need to collect data from the system over a long period and are not portable or made for energy auditing purposes. Some of them can only predict operational faults (cycling, incorrect fan operation etc.) but not system faults like refrigerant over- and undercharge (Virtjoule, SMDS). The device that comes close to meeting these challenges (ClimaCheck) is too expensive and relies on a large database for its working. It is unclear whether the portable ClimaCheck device can diagnose all faults, or only sets off an alarm when a reduction in the performance of the system is detected.

The following chapters explains the development of the proposed device that can meet these challenges of portability, low cost, and cost saving prediction.

CHAPTER V

DEVELOPMENT OF THE PROPOSED ALGORITHM

Developing a robust fault detection and diagnostic algorithm for air conditioners had many challenges.

- The rules and thresholds chosen had to work for a wide range of operating conditions such as diverse climates and weather conditions.
- The sensitivity of the system was a tradeoff for avoiding false alarms or overestimation of energy and cost savings.
- The algorithm also had to be kept as generic as possible so it could work for a wide variety of air conditioner types and sizes found in the industries.

The proposed algorithm tries to meet these challenges while meeting the requirements of the device- easy to use, quick, portable and low cost, with the ability to evaluate a detected fault. The majority of the work for the development of the device was done using data generated at the Thermo-Fluids Controls Laboratory (TFCL) by introducing known faults to a system to test the algorithm. This chapter will discuss the development of the proposed fault detection and diagnosis algorithm and its components.

Background to the Proposed FDD Method

While developing the Statistical Rule Based method, Rossi and Braun [26] divided their FDD algorithm into a preprocessor and a classifier. The preprocessor would calculate ‘features’ from actual measurements which were used by the classifier for fault detection and diagnosis. Fault detection classifier has a binary output – fault or no fault, and the fault diagnostic classifier has to choose from a list of faults.

The preprocessor could generate features of three types: simple transformations, characteristic quantities or model residuals. Simple transformations involve generating time derivatives or trends to detect faults. Characteristic quantities involve generating features that are directly calculated from measurements, and model based preprocessors use mathematical models to predict the performance, which is compared to the actual performance of the system to generate residuals as features that would be used by the classifier. Since the proposed fault detection device is intended to be quick, and would collect data for less than an hour a time derivative approach isn't used. Developing a mathematical model would make the device very specific to only a certain type and size of air conditioner, which is also not desired. Therefore, the proposed fault detection algorithm uses a preprocessor that generates characteristic quantities from actual measurements. The characteristic quantities or features are used by the classifier for fault detection and diagnosis.

The method chosen for the working of the preprocessor and classifier is loosely based on the Simple Rule Based method put forward by Chen and Braun [27]. In that, it uses 7 performance indices or features that are insensitive to operating conditions but sensitive to faults. The proposed algorithm then uses simple if-then-else rules to detect and diagnose faults. The method requires a total of 9 temperature and pressure measurements from the system, and some basic information of the system that is available on its name plate or its user/maintenance manual. By using the fault symptoms as explained in Chapter 3 and based on whether a combination of features are High, Low or Normal, fault detection and diagnosis is performed for individual and multiple faults.

Proposed FDD Method

The development of the algorithm is explained using the 4 components shown in Figure 6- Input, Preprocessor, Classifier and Fault Evaluation. Details about each of these components is provided in the following paragraphs.

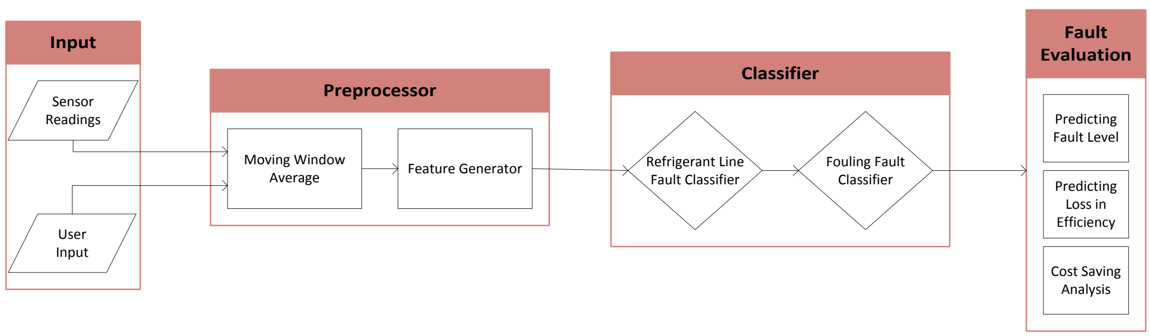

Figure 6: Flowchart of the Proposed FDD Method

Inputs

Sensor Readings

The device needs 9 inputs from sensors; 7 temperature measurements and 2 pressure measurements. The pressure measurements are made by attaching a pressure sensor to the refrigerant charging ports that are found near the outdoor unit of the system. The temperature measurements are surface measurements, 3 on the refrigerant side and 4 on the airside at the indoor and outdoor units. All the measurements are non-invasive and are summarized in Table 6.

Table 6: Required Inputs from Temperature and Pressure Sensors

Measurement	**Nomenclature**
Evaporator Pressure	P_E
Condenser Pressure	P_C
Evaporator Refrigerant Exit Temperature	T_{ERO}
Compressor Refrigerant Exit Temperature	T_{CRI}
Condenser Refrigerant Exit Temperature	T_{CRO}
Evaporator Air In Temperature (or Return Air Temperature)	T_{EAI}
Evaporator Air Out Temperature (or Supply Air Temperature)	T_{EAO}
Condenser Air In Temperature (or Ambient Air Temperature)	T_{CAI}
Condenser Air Out Temperature	T_{CAO}

User Input

Apart from temperature and pressure measurements, the device requires inputs from the user that provide a better description of the system. These 9 user inputs are seen on the name plate of the air conditioning system or can be found in the maintenance brochure of the system. Default values are assumed for some of the inputs in case information is not provided. The user inputs are summarized in Table 7.

Table 7: Required User Inputs found on Nameplate and Maintenance Brochure

User Input	Nomenclature	Where is it found?
Capacity of the System	Q	Nameplate
Rated Subcooling	SC_{Rated}	Maintenance Brochure
Rated Superheat	SH_{Rated}	Maintenance Brochure
Type of expansion device in the system	FXO/TXV	TXV if a bulb is seen near the evaporator coil. Else a fixed orifice device.
SEER Rating of the System	SEER	Nameplate
Type of Refrigerant Used	R410A/R22	Nameplate
Presence of accumulator in the system	Yes/No	Can be viewed
Avoided Cost of Electrical Energy	C_{ELEC}	Calculated by IAC personnel
Hours of Operation per Year	t_O	From facility personnel

Preprocessor

The preprocessor of the system manipulates the inputs to make them easier for the classifier to handle. This involves filtering the sensor inputs and then generating features that are used in the decision making process of the classifier. Thus, the two parts of the preprocessor are the Moving Window Average Filter and the Feature Generator.

Moving Window Average Filter

Input: Sensor Inputs from the Data Acquisition Device

Output: Filtered Temperature and Pressure Signals

Air conditioning systems generally reach steady state in about 10 to 15 minutes of their operation. The intention of the device is to be able to collect data within an hour; therefore, it can start logging data after 10 minutes of operation. This data is filtered by a Moving Window Average filter that smoothes the data with a window size of 750 samples.

Feature Generator

Input: Filtered Temperature and Pressure Measurements, Refrigerant Type

Output: 7 Features to be used by the Classifier

Filtered signals from the Moving Window Average Filter are manipulated by the Feature Generator to create features that can be used by the classifier. These features are temperature differences that are insensitive to the operating conditions but sensitive to the different faults. The pressure measurements and the user input for the refrigerant type is used to calculate the evaporator and condenser saturated temperature (T_{Evap} and T_{Cond} respectively) by using the refrigerant saturation curves. The saturated temperatures are then used with the remaining temperature measurements to calculate the 7 features that are shown in Table 8.

Table 8: Features created by the Feature Generator

Feature	Nomenclature	Calculation
Subcooling	SC	$T_{Cond} = f(P_C)$ $SC = T_{Cond} - T_{CRO}$
Superheat	SH	$T_{Evap} = f(P_E)$ $SH = T_{ERO} - T_{Evap}$
Condenser Split	CS	$CS = T_{Cond} - T_{CAI}$
Evaporator Split	ES	$ES = T_{EAI} - T_{Evap}$
Temperature difference of air across condenser	dT_{CA}	$dT_{CA} = T_{CAO} - T_{CAI}$
Temperature difference of air across evaporator	dT_{EA}	$dT_{EA} = T_{EAI} - T_{EAO}$
Compressor Refrigerant Exit Temperature	T_{CRI}	-

Classifier

The classifier detects and diagnoses the 5 different faults by comparing the values of the 7 features with a certain threshold range that helps classify the feature value as High, Normal or Low. Minimum and maximum values or thresholds that help define these levels are carefully chosen based on the type of air conditioning system and its expansion device. Since some features are more sensitive to a fault than others are, different combinations of features are used to detect each fault. These combinations detailed in Table 9 are based on the fault symptoms explained in Chapter 3.

Table 9: Feature Combinations used for Fault Detection

Fault	**Feature Combination**
Condenser Fouling	High CS, High dT_{CA}
Evaporator Fouling	High ES, High dT_{EA}
Refrigerant Undercharge	Low SC, High SH
Refrigerant Overcharge	High SC, Low to Normal SH, Normal T_{CRI}
Liquid Line Restriction	High SC, Normal to High SH, High T_{CRI}

These combinations would work well for a device that only detects single faults. However, the challenge lies with being able to detect multiple faults where the directional change of a feature due to one fault, may either be amplified or negated due to the effect of another fault. This is understood by referring to Table 10 that summarizes the typical directional change of each feature for the different faults.

Table 10: Effect of Faults on all Features

	SC	**SH**	**CS**	**ES**	**dT_{CA}**	**dT_{EA}**	**T_{CRI}**
Refrigerant Undercharge	↓	↑	↓	↑	↓	↓	↑=
Refrigerant Overcharge	↑	=	↑	=	=	=	=
Liquid Line Restriction	↑	↑	↓	↑	↓	↓	↑
Compressor Valve Leakage	↑	↑	↓				↑
Condenser Fouling	=	=	↑	=	↑	=	↑
Evaporator Fouling	=	=	=	↑	=	↓	↑

As seen in Table 10, the fouling faults are affected by fewer features than the charge related faults. So the features that can be used to detect fouling faults can be affected by charge related faults, but the converse may not be true. So for a system that suffers from Refrigerant Undercharge and Condenser Fouling, the increase in dT_{CA} and CS due to Condenser Fouling maybe negated by its decrease due to Refrigerant Undercharge. On the other hand, in a system that suffers from only Refrigerant Undercharge, the increase in ES and decrease in dT_{EA} may lead to an incorrect detection of Evaporator Fouling.

Therefore, in conclusion, the existence of a charge related fault might lead to incorrect detection of a fouling fault if each fault was checked for independently. To avoid this, the classifier of the proposed device was divided into two steps; first step works exclusively to detect refrigerant line faults and then the second step checks for fouling faults in presence or absence of the refrigerant line faults.

Refrigerant Line Fault Classifier

Input: SC, SH, T_{CRI}, Rated subcooling, Rated superheat, Type of expansion device

Output: Presence of Refrigerant Undercharge, Overcharge or Liquid Line Restriction faults.

The refrigerant line fault classifier, classifies the three input features (SC, SH, T_{CRI}) as High, Normal or Low based on the thresholds (seen in Table 11). Faults are detected based on the type of expansion device used in the system. In general, refrigerant undercharge is detected when the subcooling is low and superheat is high, refrigerant overcharge is detected when the subcooling is high and the superheat is low or normal, and liquid line restriction is detected when subcooling, superheat and compressor discharge temperature are all high.

Table 11: Threshold Values for Refrigerant Line Fault Classifier

Expansion Device	Feature	Thresholds
Fixed Orifice Device	Superheat	±4°C of Rated Superheat
	Subcooling	±1.5°C of Rated Subcooling
	Compressor Discharge Temperature	70 to 98°C
Thermal Expansion Valve	Superheat	±1°C of Rated Superheat
	Subcooling	±1.5°C of Rated Subcooling
	Compressor Discharge Temperature	70 to 98°C

Table 12 are the rules for a Fixed Orifice Device and Table 13 are the rules for a system using a Thermal Expansion Device.

Table 12: Rules for Refrigerant Line Fault Classifer (FXO valve)

SC condition	SH Condition	T_{CRI} Condition	Fault Detected
SC high	SH high	-	LLR
	SH normal	T_{CRI} high	LLR
		T_{CRI} normal	Overcharge
	SH low	-	Overcharge
SC normal	SH high	T_{CRI} high	LLR
		T_{CRI} normal	Undercharge
SC low	SH high	-	Undercharge

Table 13: Rules for Refrigerant Line Fault Classifer (TXV valve)

SC condition	SH Condition	T_{CRI} Condition	Fault Detected
SC high	SH high	-	LLR
	SH normal	T_{CRI} high	LLR
		T_{CRI} normal	Overcharge
SC normal	SH high	T_{CRI} high	LLR
SC low	SH high	-	Undercharge
	SH normal	T_{CRI} normal	Undercharge

Fouling Fault Detection Classifier

Input: dT_{CA}, CS, dT_{EA}, ES, SEER rating of the system, Presence of Undercharge, Overcharge, or Liquid Line Restriction.

Output: Presence of Condenser and Evaporator Fouling.

After knowledge of any possible charging or refrigerant line faults, the next step is to detect any possible fouling faults. The threshold value for the CS and dT_{CA} depends on the efficiency of the air conditioning system or its SEER rating. Higher efficiency units have more condenser coils, thus the temperature difference between the saturated condenser temperature and the ambient air temperature or the Condenser Split can be lower. Since the saturated temperature and pressure can be lower for higher SEER rated units, lesser heat needs to be rejected. Therefore the temperature difference of the condenser inlet and outlet air is also lower. The thresholds used by the Fouling Fault Detection Classifier are summarized in Table 14.

Table 14: Thresholds used by the Fouling Fault Detection Classifier

Feature	Thresholds
Condenser Split	For SEER >13, 8±2°C for SEER= 11 or 12, 10±2°C and for SEER < 10, 14±2°C
Evaporator Split	18 to 25°C
Temperature difference of air across Condenser	For SEER >13, 4 to 6°C for SEER= 11 or 12, 8 to 11°C and for SEER < 10, 12 to 15°C
Temperature difference of air across Evaporator	10 to 16°C

The rules for detecting the fouling faults vary based on the presence or absence of charge and refrigerant line faults. In general, condenser fouling is detected when both the condenser air temperature difference and the condenser split are high. Evaporator fouling is detected when the evaporator air temperature difference is low and the evaporator split is high. To prevent any incorrect diagnosis, this classifier also makes use of user prompts to verify the presence of evaporator and condenser fouling.

The rules used to detect fouling faults are summarized in Table 15. Since like Evaporator Fouling, Refrigerant Undercharge and Liquid Line Restriction faults also result in low dT_{EA} and high ES, a user prompt to check for Evaporator Fouling appears in the presence of these charge related faults. In the same way, since both Refrigerant Overcharge and Condenser Fouling cause a high CS and dT_{CA}, in the presence of the Overcharge fault, the user is prompted to check for any visible Condenser Fouling. Since fouling faults are visible unlike charge related faults, this check by the user reduces any possibility of incorrect fault detection and an exaggeration of efficiency loss and cost saving values.

Table 15: Rules Used to Detect Fouling Faults

Detected Refrigerant Line Fault	**Condition**	**Fouling Fault Detected**
Refrigerant Undercharge	User prompt for EF	Evaporator Fouling
	Check for high dT_{CA}	Condenser Fouling
Liquid Line Restriction	User prompt for EF	Evaporator Fouling
	Check for high dT_{CA}	Condenser Fouling
Refrigerant Overcharge	User prompt for CF	Condenser Fouling
	Check for high ES	Evaporator Fouling
None	Check for High ES and Low dT_{EA}	Evaporator Fouling
	Check for High CS and Low dT_{CA}	Condenser Fouling

Presence of Liquid Line Restriction and Refrigerant Undercharge cause a reduction in CS. So if the system also suffers from Condenser Fouling, the CS may lie in the normal range. Therefore, only dT_{CA} is used to check for Condenser Fouling in the presence of these faults. In the same way, Refrigerant Overcharge increases dT_{EA}, therefore to detect Evaporator Fouling in presence of this fault only ES is used.

Fault Evaluation

Once a fault is detected, the fault must evaluated to know if the benefit of repairing the fault will justify its expense. This involves three things- predicting the level of fault, predicting the efficiency loss due to the fault, and finally calculating the corresponding cost saving and the payback for repairing the fault.

Refrigerant Undercharge and Overcharge

Input: SC, Rated Subcooling, SH, Rated Superheat, Presence of Accumulator, Type of Expansion Device, Type of Refrigerant

Output: Predicted Percent Incorrect Charge and Predicted Loss of EER

The device can predict the percentage overcharge and undercharge by using a virtual refrigerant charge sensor. The sensor uses actual values of subcooling and superheat, with rated values of subcooling and superheat to estimate the amount of incorrect charge in the system. It also uses a few constants like $K_{sc\text{-}sh}$, $K_{ch,}$,$X_{hs,rated}$ and α_o whose values would ideally depend on the type of expansion valve, type of system and the size of the system. However tests comparing the use of experimentally determined parameters and default parameters showed that for the purposes of the device, the default parameters could be used [35]. $X_{hs,rated,}$ is the ratio of high side refrigerant charge to the total refrigerant charge, and α_o which is the ratio of the refrigerant charge necessary to have saturated liquid at the exit of the condenser to the rated refrigerant charge. $K_{sc\text{-}sh}$ is a constant calculated using rated subcooling and superheat with the subcooling and superheat measured at some other operating condition.

After conducting several tests by changing the operating conditions and the expansion valve, the default values for all constants were assumed as follows: α_o is 0.75 and $X_{hs,rated}$ is 0.73 for all systems, and. $K_{sc\text{-}sh}$ could be averaged to 1/2.5.

The results for the differences in default and actual parameter values showed that the error for TXV systems ranged from -8% to 7% and for FXO systems ranged from -15% to 6%. The error increased with increasing amount of undercharge and overcharge. For the purposes of the low cost device, these errors were acceptable. After confirming these parameter values, the following equations can be used to predict the level incorrect charge.

$$\text{Percent Incorrect Charge} = \left\{\frac{1}{K_{ch}}[SC - SC_{rated}] - [(K_{sc-sh})(SH - SH_{rated})]\right\} \times 100$$

where, $$K_{ch} = \frac{SC_{rated}}{(1 - \propto_o)(X_{hs})}$$

and $\propto_o = 0.75, X_{hs} = 0.73$ and $K_{sc-sh} = 0.4$

The sensor ignores the amount of charge held per unit length in the refrigerant tubing running between indoor and outdoor units and is thus not as accurate. It also does not work well at higher levels of under- and overcharge. Nevertheless, it still provides a rough estimate of percent overcharge or undercharge that is sufficient for auditing purposes. The corresponding efficiency loss due to the predicted amount of incorrect charge is calculated by referring to tests conducted by researchers to quantify the related loss in EER.

Undercharge – EER loss

Input: Percent Undercharge, Type of Expansion Device, Type of Refrigerant, Presence of Accumulator

Output: Percent loss in EER

Tests done by Kim and Braun (2010) [11] that recorded the effect of undercharge on the efficiency of air conditioning systems using different expansion devices (TXV or FXO) and different refrigerants (R22 or R410A) were used to develop a linear relationship between percent level of undercharge and the related EER loss.

$$\text{Percent EER Loss} = (100 - \%\text{underchage})(\text{A}) + \text{B}$$

For a fixed orifice device, the constants A and B changed based on the absence and presence of an accumulator. For a thermal expansion device, the constants changed based on the type of refrigerant (Table 16).

Table 16: Constants used in Equation to predict EER Loss due to Undercharge

Fixed Orifice, Accumulator	A= -0.5558 and B=56.256
Fixed Orifice, No Accumulator	A= -0.6833 and B=66.53
TXV, R410A	A= 0.9198 and B=88.868
TXV, R22	A= -0.6962 and B=70.708

Overcharge – EER Loss

Input: Percent overcharge and type of expansion device

Output: Percent loss in EER

Similar to predicting the EER loss due to undercharge, a linear relationship relating overcharge level with the EER loss was used using constant determined from the tests conducted by Kim and Braun [18].

$$\text{Percent EER Loss} = (100 + \%\text{overcharge})(\text{A}) + \text{B}$$

In this case, constants changed based on only the type of expansion device (Table 17).

Table 17: Constants used in Equation to predict EER Loss due to Overcharge

TXV	A= 0.3144 and B=-33.103
FXO	A= 0.1 and B=-10.667

Evaporator Fouling

Input: dT_{EA}, ES, Type of Expansion Device

Output: Level of Evaporator Fouling and EER loss because of Fouling

Unlike Refrigerant Undercharge and Overcharge, the device cannot predict the amount of Evaporator Fouling. However, based on the amount of deviation from the maximum or minimum feature values, it can predict whether the amount of Evaporator Fouling is Low, Medium or High. The deviation of the features from the maximum or minimum thresholds value gives some idea about the fault level. Therefore, the Evaporator Fouling Level is low when the deviation is closer to 0 and higher as it moves away from 0 to this maximum value.

$$|(20°C - ES)| + |(dT_{EA} - 10°C)| = \text{Evaporator Fouling Level}$$

The device can predict the maximum and minimum amount of EER loss due to evaporator fouling based on the type of expansion device. Tests were done by Watt(1997)[36] to estimate the amount of efficiency loss due to evaporator fouling in a TXV and FXO system. The results from these tests were used in the device.

Table 18: Maximum and Minimum EER Loss due to Evaporator Fouling

TXV	Maximum EER Loss= 7% Minimum EER Loss=1%
FXO	Maximum EER Loss= 10% Minimum EER Loss=5%

Condenser Fouling

Input: dT_{CA}, CS, Type of Expansion Device

Output: Level of Condenser Fouling and EER loss because of Fouling

Like Evaporator Fouling, in case of Condenser Fouling, the device bases the amount of Condenser Fouling on the amount of deviation from the maximum CS and dT_{CA} values. Therefore, the Condenser Fouling Level is low when the deviation is closer to 0 and higher as it moves away from 0 to this maximum value.

$$|(6°C - dT_{CA})| + |(10°C - CS)| = \text{Condenser Fouling Level}$$

The device predicts the maximum and minimum amount of EER loss due to condenser fouling based on the type of expansion device. Results from the tests done by Watt(1997) [36] were used to estimate the maximum and minimum EER loss (Table 19).

Table 19: Maximum and Minimum EER Loss due to Condenser Fouling

TXV	Maximum Loss= 15% Minimum Loss=5%
FXO	Maximum Loss= 30% Minimum Loss=5%

Liquid Line Restriction

Input: Rated Subcooling and Superheat, Actual Subcooling and Superheat

Output: Level of Liquid Line Restriction and EER Loss due to Liquid Line Restriction

The level of liquid line restriction using non-invasive temperature and pressure measurements cannot be predicted with certainty. Instead, like the fouling faults, the deviation from the expected feature values is used to classify the level of the fault as low, medium or high. The expected values of SC and SH are nothing but the rated values of SC and SH. Therefore, the fault level is Low when this value is closer to 0 and High as it moves towards the maximum deviation value.

$$|(\text{Rated SH} - \text{SH})| + |(\text{Rated SC} - \text{SC})| + |(T_{\text{CRI}} - 71°\text{C})| = \text{Liquid Line Restriction Level}$$

The maximum and minimum EER loss due a restricted liquid line is based on tests conducted by Braun[8] for different amounts of pressure difference across the valve.

Minimum EER loss= 3%

Maximum EER loss=9%

Estimating the Cost Savings

Input: Capacity of the Unit, SEER rating, Operating Hours, Cost of Electrical Energy and Maximum and Minimum Percent EER loss due to the Faults

Output: Current Operating Cost, Proposed Operating Cost and Cost Savings.

The operating cost is calculated using the nameplate SEER rating, cooling capacity and operating hours of the system using the following formula-

$$\text{Operating Cost} = \frac{\left(\text{Capacity in } {}^{\text{BTU}}/_{\text{hr}}\right)(\text{Operating hours per year})(\text{Cost of Electrical Energy})}{\left(1000\ {}^{\text{W}}/_{\text{kW}}\right)(\text{SEER rating})}$$

All the parameters in the above formula remain the same, except the SEER rating which decreases because of the presence of faults. Therefore, a maximum and minimum SEER rating is calculated based on the product of the EER percent loss of the detected faults.

$$\text{Minimum Reduced EER \%}$$
$$= (\text{Condenser Fouling Loss}_{\text{Min}})(\text{Evaporator Fouling Loss}_{\text{Min}})(\text{LLR Loss}_{\text{Min}})$$
$$(\text{Loss due to Undercharge})(\text{Loss due to Overcharge})$$

$$\text{SEER}_{\text{Min}} = (\text{Minimum Reduced EER\%})(\text{SEER})$$

$$\text{Maximum Reduced EER \%}$$
$$= (\text{Condenser Fouling Loss}_{\text{Max}})(\text{Evaporator Fouling Loss}_{\text{Max}})(\text{LLR Loss}_{\text{Max}})$$
$$(\text{Loss due to Undercharge})(\text{Loss due to Overcharge})$$

$$\text{SEER}_{\text{Max}} = (\text{Maximum Reduced EER\%})(\text{SEER})$$

The $SEER_{Max}$ and $SEER_{Min}$ are then used in the main SEER-cost equation to calculate the actual maximum and minimum cost. The nameplate SEER rating is used to calculate the proposed operating cost, and the difference between the actual and proposed cost gives the cost savings.

CHAPTER VI

TESTS: INDIVIDUAL FAULTS AT TFCL

The proposed algorithm was initially tested in the Thermo-Fluids Controls Laboratory by introducing the five faults individually to a 3-ton residential, split air conditioning system. These tests helped in two ways: they confirmed the effect of each fault on the 7 features, and helped realize the sensitivity of the algorithm to the 5 faults. In this chapter, a description of the air conditioning system and the method of introducing the faults in the system is discussed. The results of the tests follow.

System Description

The system used to test the algorithm of the device is a 3 ton, residential split heat pump system donated by Trane. It is installed with an electronic expansion valve from Parker. The system uses R410A refrigerant, and a two stage scroll compressor. The placement of temperature sensors, pressure sensors, mass flow rate sensor, and humidity sensors is shown in Figure 7, the parts are described in Table 20 and the user information for the system is summarized in Table 21.

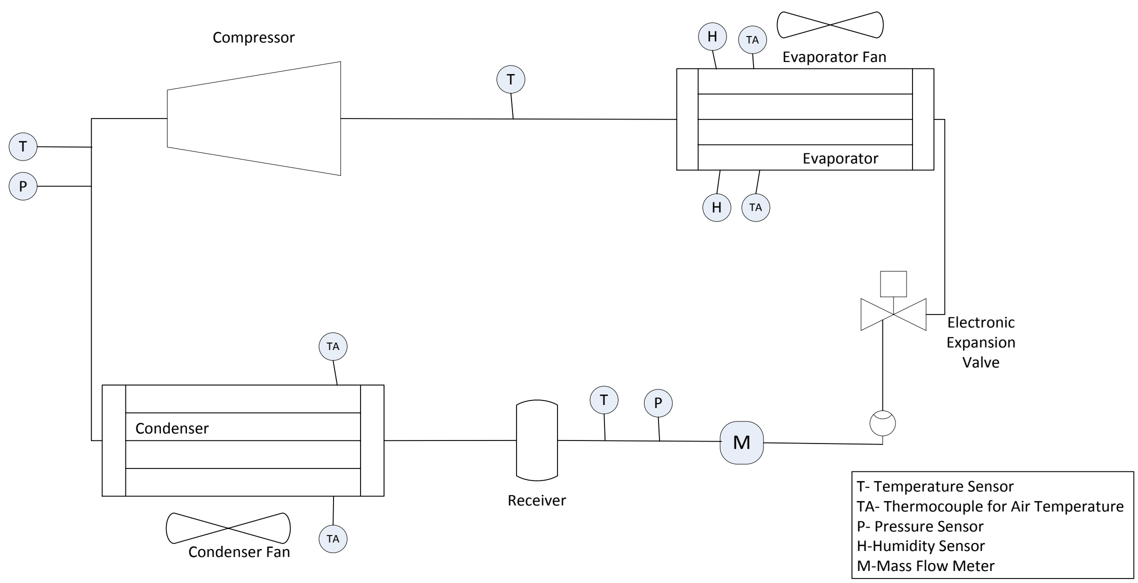

Figure 7: Location of Sensors in the TFCL System

Table 20: Parts of the TFCL System

Component	**Manufacturer**	**Model Number**
Residential Air conditioning Unit	Trane	4TWX6036
EEV	Parker	ESX24B-5S
Thermocouple	Omega	GTMQSS-062U-6
Pressure Sensor	Omega	PX309-500G5V
Humidity Sensor	Omega	HX94AV
Mass Flow Meter	McMillan	102 Range 8
DAQ Software	Wincon for MATLAB	

The temperature sensors were the T type with a range of -250°C to 350°C and error that is the greater of 1°C or 0.75%. The pressure sensors have a range of 0 to 500 psi and accuracy of ±0.25% of full scale at 25°C. The humidity sensors had a range of 3 to 95% and an accuracy of ±2.5% at 22°C from 20% to 80%. The mass flow rate sensor had a range of 200 to 5,000 ml/min and an accuracy of ±3% of full scale. Data from the humidity and mass flow rate sensors is not used in the algorithm, but was recorded. Therefore, the 7 temperature measurements and the 2 pressure measurements required by the proposed algorithm were available. The user inputs- SEER rating, capacity of the system and type of refrigerant was seen on the nameplate, and the rated subcooling was obtained from the maintenance brochure. The rated superheat was set to 10°C by the EEV that was controlled by a PID controller. A Simulink model was used to control the working of the air conditioning system. The evaporator and condenser fan speed, the compressor stage and the opening of the EEV could be controlled.

Table 21: User Inputs for the Laboratory Test System

	User Input	**Value**
1	Capacity of the System	36,000 BTU/h
2	Rated Subcooling	3.5°C
3	Rated Superheat	10°C
4	Type of expansion device in the system	TXV
5	SEER Rating of the System	16
6	Type of Refrigerant Used	R410A
7	Presence of accumulator in the system	Yes
8	Avoided Cost of Electrical Energy	$\frac{\$0.010}{\text{kWh}}$
9	Hours of Operation per Year	$\frac{8{,}760 \text{ hr}}{\text{yr}}$

Introducing Faults

Individual Faults were introduced to the system to-

- To verify the effect of the individual faults on the 7 different features, thus helping the development of the algorithm for multiple fault detection.
- Check the basic fault detection and evaluation algorithm developed. Thus, gaining an understanding of sensitivity of the algorithm, the chosen thresholds to the various faults, the predicted level of charging faults, and the related efficiency loss and cost savings.

The 5 faults that the device intends to detect were introduced in the system at different levels as shown in Table 22.

Table 22: Method used to Introduce Faults in the Laboratory Test System

Fault	Method of simulating the fault	Simulation Parameter	Level 1	Level 2	Level 3	Level 4	Level 5
Condenser Fouling	Covering the condenser with strips of paper.	% reduction in the area of condenser exposed to heat exchange	20%	40%	60%	80%	100%
Evaporator Fouling	Covering the evaporator coil with strips of paper	% reduction in the area of condenser exposed to heat exchange	20%	40%	60%	80%	100%
Refrigerant Undercharge	Removing some charge from the system	% reduction in the amount of refrigerant in the system	0%	9%	18%	28%	36%
Refrigerant Overcharge	Adding refrigerant to the system	% increase in the amount of refrigerant charge in the system	0%	5%	10%	15%	20%
Liquid Line Restriction	Restricting the opening of the electronic expansion valve by a fixed amount	% increase in the pressure difference across the restriction	0%	4%	11%	18%	24%

Results

Effect of Individual Faults on Features

The effect of the individual faults on the 7 features was analyzed to help the development of a more robust multiple fault detection algorithm.

Subcooling

The rated subcooling of the system is about 3.5°C. As seen in Figure 8, subcooling of the system is somewhat sensitive to all the 5 faults. However, the two faults that affect it the most are refrigerant overcharge and undercharge. It also increases with an increasing liquid line restriction as the fault causes some refrigerant to be backed up in the condenser. However, excessive testing on the system had caused a leak in the system, which was noticed towards the end when performing the tests for the liquid line restriction fault. This caused the subcooling at no fault conditions to reduce to a lower value. Therefore, when testing the algorithm for the liquid line restriction fault, the rated subcooling value was reset to the value that was seen right before introducing the fault. Therefore, an increase in subcooling is used to detect refrigerant overcharge and liquid line restriction, and a decrease in subcooling is used to detect refrigerant undercharge. As seen in the figure, subcooling isn’t affected as much by fouling faults.

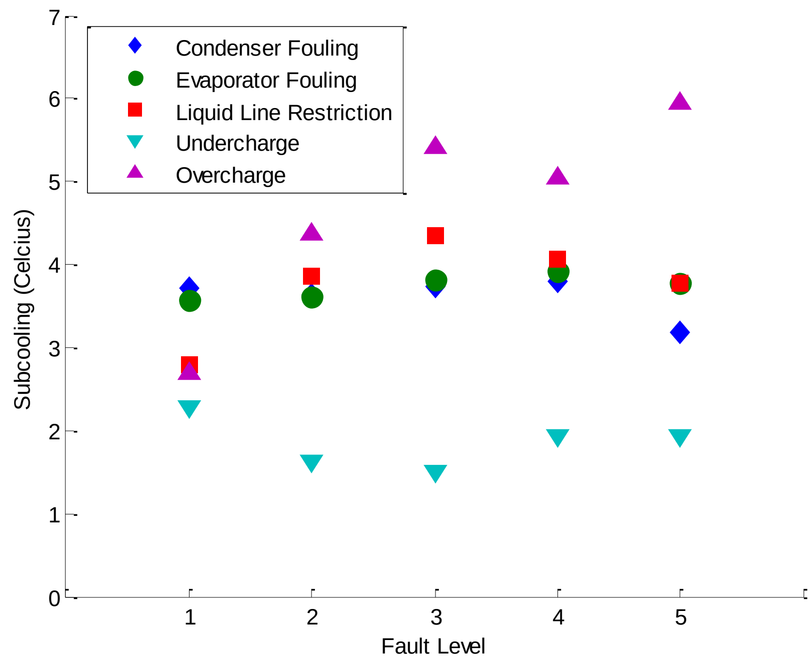

Figure 8: Effect of Faults on Subcooling

Superheat

The rated superheat of the system is 10°C. Since the system uses an EEV which keeps the superheat value constant as far as possible, Figure 9 shows an unchanging value of superheat for condenser fouling, evaporator fouling and refrigerant overcharge. However, when there is a lack of refrigerant, or a two-phase refrigerant entering the EEV, it cannot function as well to keep the superheat constant. Therefore, superheat increases for liquid line restriction and high levels for refrigerant undercharge.

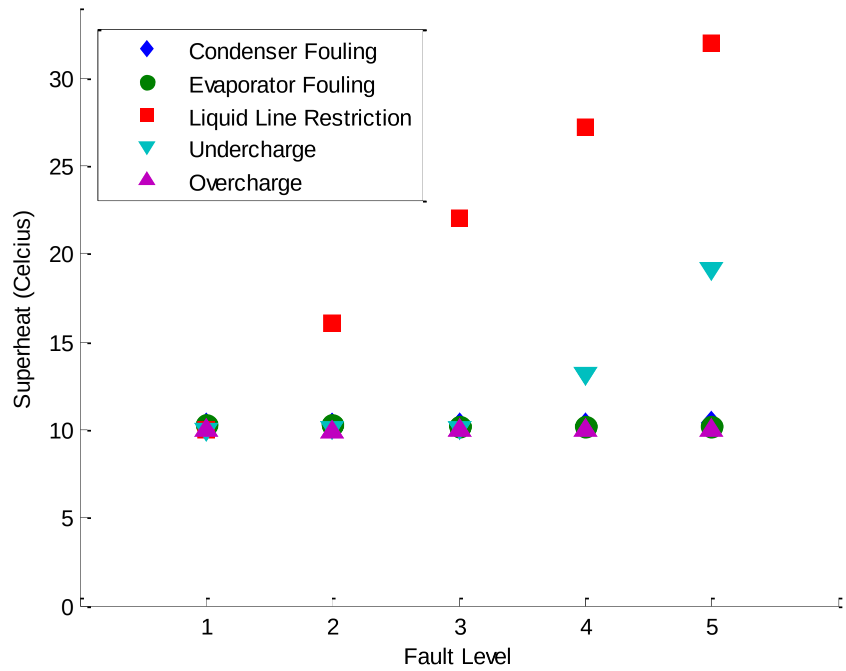

Figure 9: Effect of Faults on Superheat

Compressor Discharge Temperature

The compressor discharge temperature for this system varies between 55°C to 71°C. It is sensitive to the load and operating conditions of the system unlike the other features. However, it rises abnormally when there is a restricted liquid line. It also increases with a fouled condenser or refrigerant undercharge at high levels. With suitable thresholds, this feature can be used to detect liquid line restriction (Figure 10).

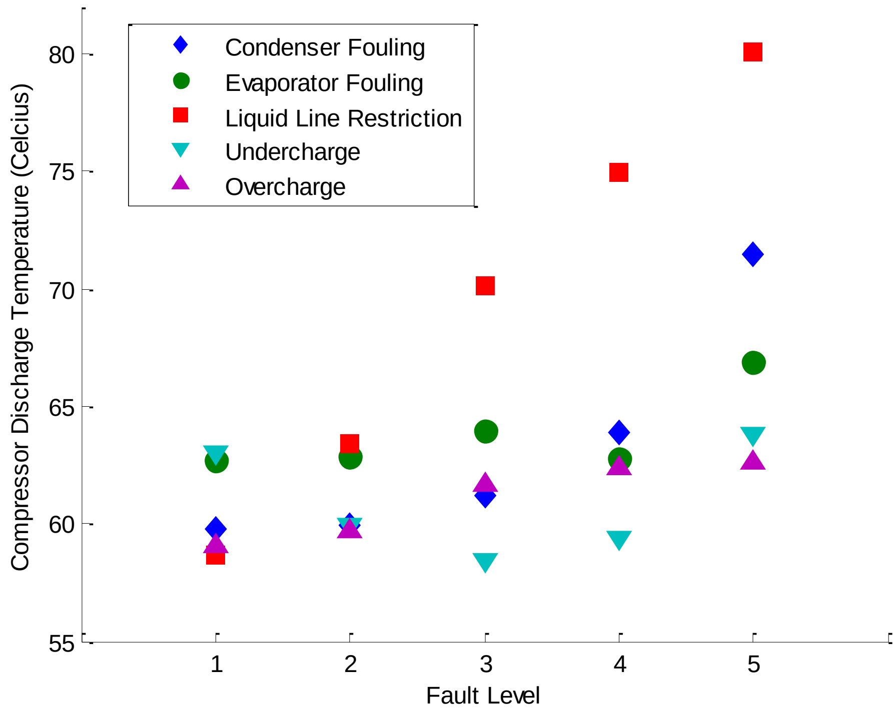

Figure 10: Effect of Faults on Compressor Discharge Temperature

Condenser Split

Increase in the condenser split of the system is a great way to detect higher levels of condenser fouling as seen in Figure 11. However, this feature is also affected by liquid line restriction and refrigerant undercharge in the opposite direction. Therefore, if a system suffers from a refrigerant undercharge and a fouled condenser, the condenser split could be in the normal range and condenser fouling may go undetected.

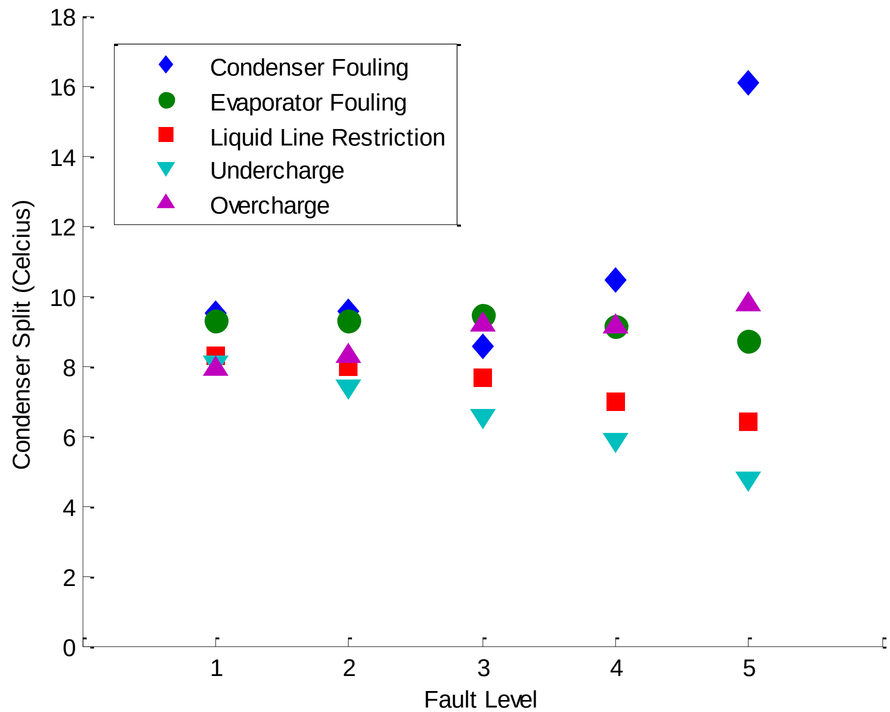

Figure 11: Effect of Faults on Condenser Split

Evaporator Split

In the same way as condenser split, an increase in evaporator split can be used to detect evaporator fouling. However, as seen in Figure 12, the evaporator split also increases with liquid line restriction and refrigerant undercharge. Therefore, a system suffering from liquid line restriction could incorrectly detect the evaporator fouling fault.

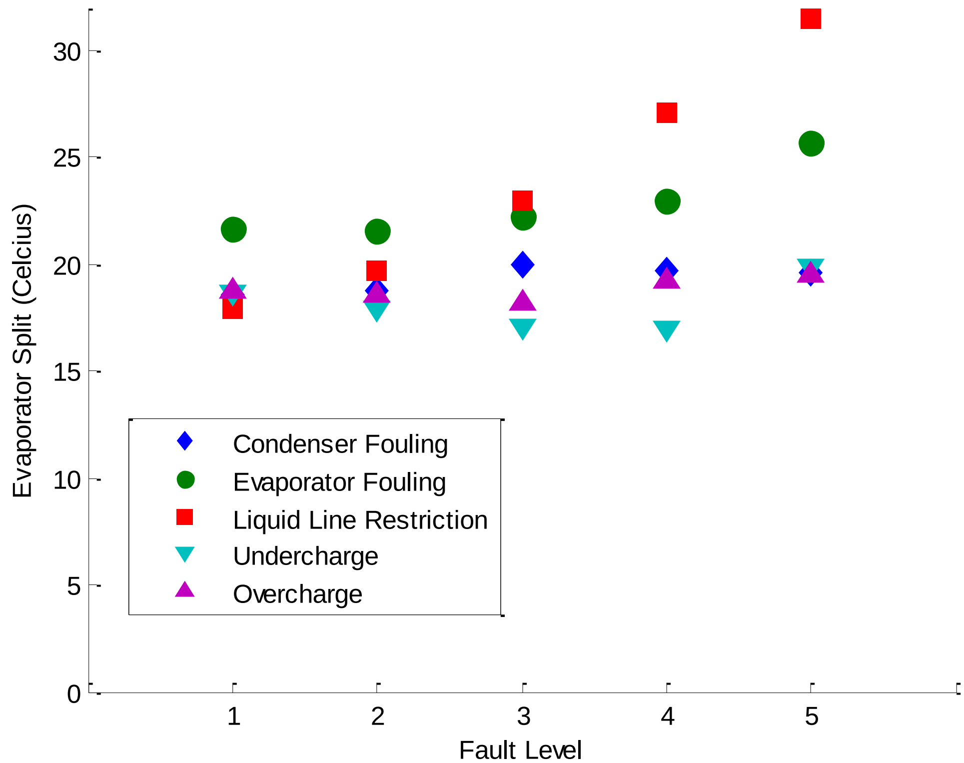

Figure 12: Effect of Faults on Evaporator Split

Condenser Air Temperature Difference

Since the condenser split alone is not a good enough indicator for condenser fouling, an increase in the temperature difference of the air across the condenser can be used as an additional feature to detect the fault. Figure 13 shows that this feature is sensitive to most faults, and is affected by operating conditions as well. Therefore, it can be used to detect only higher levels of condenser fouling.

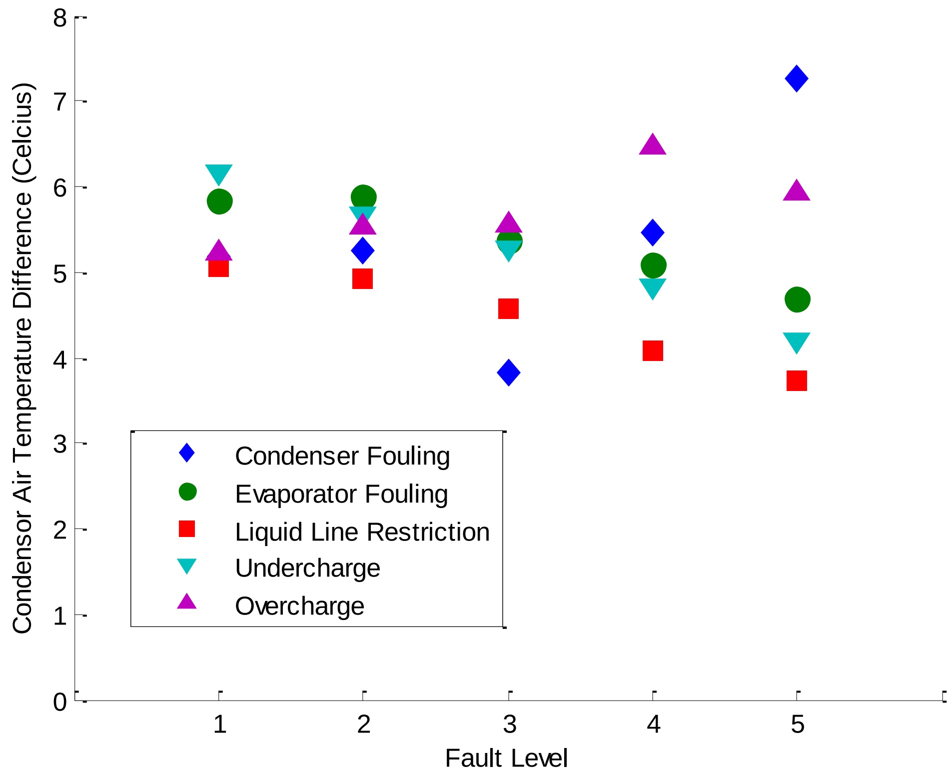

Figure 13: Effect of Faults on Condenser Air Temperature Difference

Evaporator Air Temperature Difference

The temperature difference of the air across the evaporator coil depends on how much cooling the system can achieve. This is why in Figure 14, a decrease in the value of this feature is seen for refrigerant undercharge, liquid line restriction and evaporator coil fouling – all of which affect the amount of refrigerant in the evaporator or the exposed surface for heat exchange- thus reducing the cooling capacity of the system and the temperature of air across the evaporator. Since evaporator split is not good enough to detect evaporator fouling, it is used with this feature to detect higher levels of fouling.

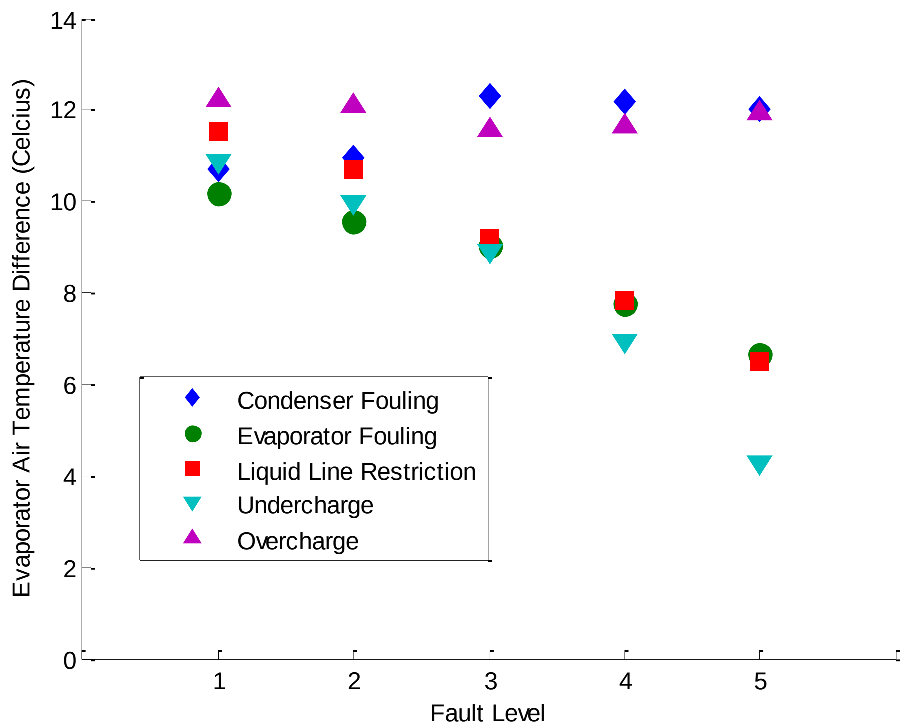

Figure 14: Effect of Faults on Evaporator Air Temperature Difference

Fault Detection and Evaluation for Individual Faults

The results of the tests for individual faults is shown in Table 23. It was realized that the algorithm is not very sensitive to the fouling faults, which are detected at a level only higher than 80%. In contrast, charge related faults and refrigerant line faults are detected at low levels. There were two instances of incorrect fault detection; Liquid Line Restriction at higher levels was incorrectly detected as Evaporator Fouling. This is because both faults have the same effect on dT_{EA} and ES, and the increase in the SC, SH and T_{CRI} that is normally caused by Liquid Line Restriction was within the thresholds.

This could have been improved if the thresholds were tighter, but it could have led to incorrect fault detection of other faults.

Table 23: Results of Tests for Individual Faults

Fault	Fault Levels Introduced	Level First Detected	Predicted Efficiency Loss	Predicted Annual Cost Savings Per Ton
Refrigerant Undercharge	9 to 36%	9%	6 to 14%	$37 to $105
Refrigerant Overcharge	5 to 20%	10%	1 to 2%	$3 to $12
Liquid Line Restriction	3 to 24%	11%	3 to 9%	$20 to $64
Condenser Fouling	20 to 100%	100%	5 to 15%	$34 to $116
Evaporator Fouling	20 to 100%	100%	1 to 7%	$6 to $49

Predict Incorrect Charge Level

Since fault levels could be predicted for only refrigerant undercharge and overcharge, Figure 15 and Figure 16 show how the actual incorrect charge level compares to the level predicted by the device. Since the virtual charge sensor makes many assumptions, it was known that the sensor would not be able to accurately detect the level of under- or overcharge. According to the results, it was learned that the inaccuracy did not lead to overestimation of the incorrect charge level. This would prevent energy auditors from over-estimating the efficiency loss, and help them predict realistic cost savings.

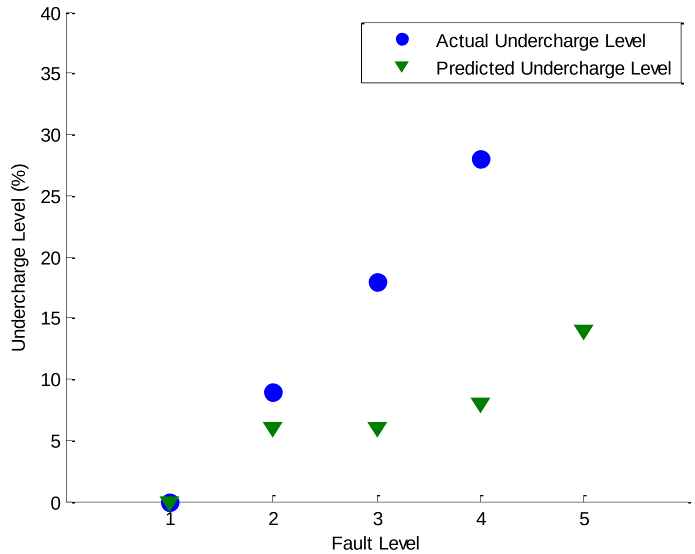

Figure 15: Actual and Predicted Refrigerant Charge for an Undercharged System

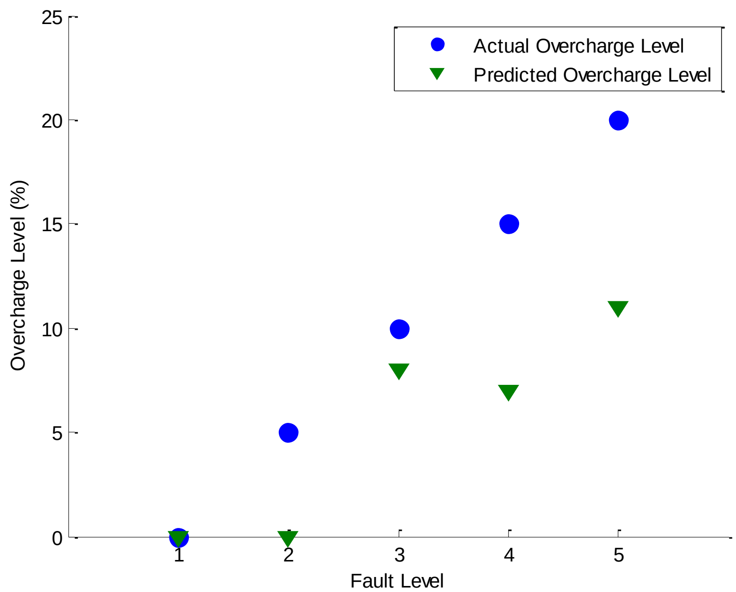

Figure 16: Actual and Predicted Refrigerant Charge for an Overcharged System

Thus, the effect of the different faults on the features helped verify the chosen thresholds and the rules for the proposed device. The sensitivity of the device to these faults was also recorded in these tests. As the next step, the device would be tested with a second set of data to check its sensitivity and working with a different system. The following chapter discusses the results from testing the algorithm with a set of data generated at the Energy Systems Laboratory.

CHAPTER VII

INDIVIDUAL FAULT TESTS AT ESL

The proposed algorithm was also tested against a second set of data, to verify its thresholds and validate the method. This dataset was generated at the Energy Systems Laboratory by Mr. James Watt for his tests used to identify temperature-based indicators that, together with one return-air humidity point, could detect performance deterioration resulting from equipment or system degradation [36].

System and Fault Description

For these tests, a split-system direct-expansion air conditioner was used, with the air-conditioner test bench equipped with the choice of either using a short-tube orifice (STO) or a thermal expansion valve (TXV). The degraded conditions studied included low evaporator airflow, high- and low-charge, and a blocked condenser coil. These degraded conditions have the same effect on the system as the evaporator filter fouling, refrigerant overcharge, refrigerant undercharge and condenser fouling faults respectively.

Table 24 shows how the degraded condition or the fault was simulated, the fault levels introduced and the number of tests for each expansion device.

Table 24: Fault Description for Tests at the ESL

Degraded Condition (or Fault)	**Method of Simulation**	**Expansion Device**	**Fault Level**	**Number of tests**
Low Evaporator Flow (Evaporator Filter Fouling)	Changing the speed of the Evaporator Fan	STO	40 to 100%	5
		TXV	30 to 100%	7
Low Refrigerant Charge (Refrigerant Undercharge)	Removing a measured amount of charge from the system	STO	40 to 91% of rated refrigerant charge	7
		TXV	38 to 92% of rated refrigerant charge	8
High Refrigerant Charge (Refrigerant Overcharge)	Adding a measured amount of charge to the system	STO	109 to 135% of rated refrigerant charge	4
		TXV	108 to 141% of refrigerant charge	5
Blocked Condenser Coil (Condenser Fouling)	Blocking condenser airflow	STO	20 to 100%	8
		TXV	30 to 100%	7

Testing the device with the set of data generated at the ESL was useful since it helped check the working of the device with two different expansion valves- Thermal Expansion Valve and Short Tube Orifice Valve (which acts like a Fixed Orifice device). Condenser Fouling, Refrigerant Undercharge and Refrigerant Overcharge faults were introduced in the same way as for the tests in TFCL. However, instead of simulating Evaporator Fouling by covering the evaporator coils with paper like it was done at TFCL, at ESL the fault was simulated by changing the speed of the evaporator fan. Thus, the fault simulated at the TFCL was Evaporator *Coil* fouling, and the fault simulated at ESL was Evaporator *Filter* Fouling.

- Evaporator Coil Fouling causes reduction in cooling capacity due to lesser surface area for heat exchange, thus the temperature of air across the evaporator (dT_{EA}) decreases.
- In case of evaporator filter fouling, the loss in cooling capacity is due to lesser air entering the system due to the restricted filter. Therefore, the small quantity of air that does enter the evaporator gets overcooled which causes the temperature difference of air across the evaporator (dT_{EA}) in case of Evaporator Filter Fouling to increase.

Thus, the device was modified to detect a sixth fault- Evaporator Filter Fouling .The only difference in the detection algorithm was that Evaporator Coil Fouling was detected when dT_{EA} was below the threshold and Evaporator Filter Fouling was detected when dT_{EA} was above the threshold value.

Results

As seen in Table 25, sensitivity of the device to faults for both expansion devices was almost the same. For the fouling faults, the device worked better on the ESL system than the TFCL system. However, in case of Condenser Fouling it also incorrectly detected Refrigerant Undercharge at higher levels of the fault. This was because in the condenser fouling tests, the subcooling of the system decreased with increasing levels of fouling. Another instance of incorrect fault detection was detecting evaporator coil fouling for overcharge at the highest level for the TXV system. This was because the high overcharge caused the dT_{EA} to decrease beyond its lower threshold.

Table 25: Individual Fault Test Results from Energy Systems Laboratory System

Fault	Type of Valve	Fault Levels Introduced	Level First Detected	Predicted Efficiency Loss	Predicted Annual Cost Savings
Refrigerant Undercharge	STO	9 to 60%	26%	11 to 37%	$211 to $544
	TXV	8 to 62%	24%	11 to 32%	$108 to $435
Refrigerant Overcharge	STO	9 to 35%	9%	4 to 15%	$37 to $161
	TXV	8 to 41%	8%	3 to 8%	$29 to $81
Condenser Fouling	STO	10 to 80%	60%	5 to 30%	$50 to $409
	TXV	10 to 70%	60%	5 to 13%	$28 to $94
Evaporator Filter Fouling	STO	9 to 45%	36%	5 to 10%	$50 to $106
	TXV	9 to 64%	18%	1 to 7%	$9 to $72

Overall, out of 51 individual fault tests at the ESL, 18 produced Type 2 Error (no fault detection), 4 produced Type 1 Error (incorrect fault detection) and 29 tests had no errors. Detailed results are shown in Table 26.

Table 26: Summary of Errors for ESL tests

Fault	Type of Valve	Type 1 Error (False Alarm)	Type 2 Error (Missed Fault)	No Error
Refrigerant Undercharge	STO	0	2	5
	TXV	0	2	6
Refrigerant Overcharge	STO	0	0	4
	TXV	1	0	4
Condenser Fouling	STO	1	5	2
	TXV	2	5	0
Evaporator Filter Fouling	STO	0	3	2
	TXV	0	1	6
TOTAL		4	18	29

Predicting Incorrect Charge Level

The working of the virtual charge sensor that predicts the incorrect charge level was checked with the different types of valves used in the ESL tests. Figure 17 and Figure 18 show the results of charge level prediction for undercharge and overcharge faults with the STO valve. It is seen that the sensor very rarely overestimates the level of the fault in case of undercharge. However, for the overcharge fault, the level of the fault is overestimated for the STO valve.

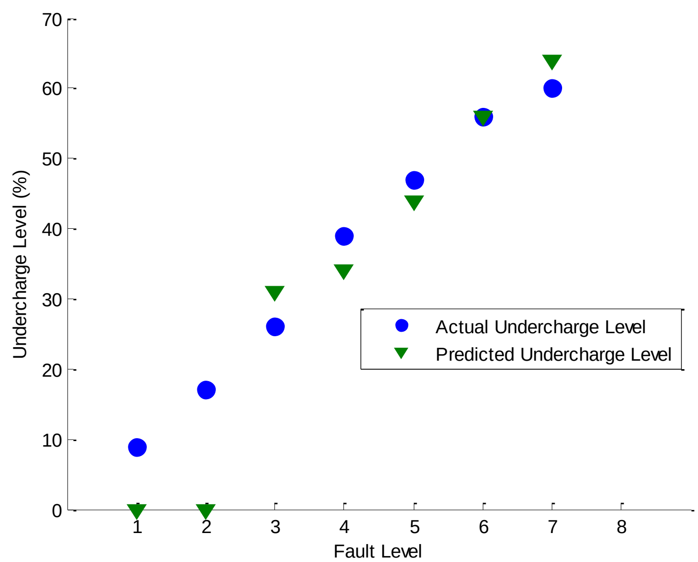

Figure 17: Undercharge Fault Level Prediction for STO valve

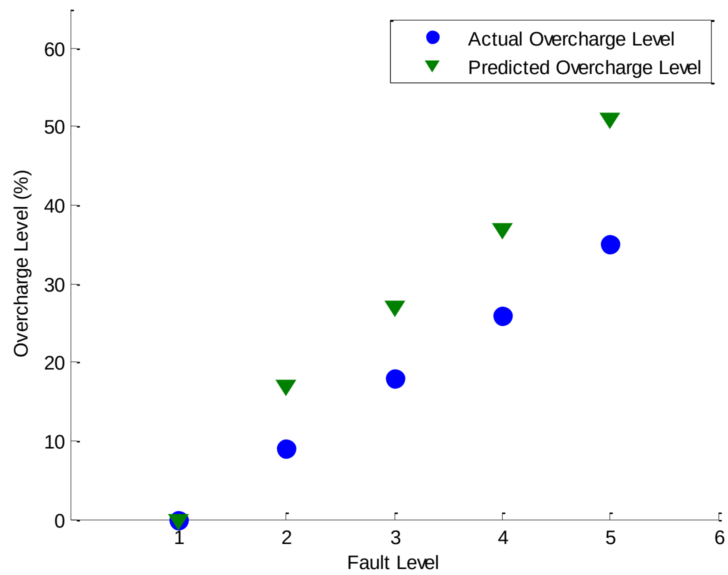

Figure 18: Overcharge Fault Level Prediction for STO valve

Figure 19 and Figure 20 show the results of charge level prediction for undercharge and overcharge faults with the TXV valve. It is seen that the sensor works better for the TXV valve. It very rarely over-estimates the incorrect charge level except for a few instances in the overcharge fault tests.

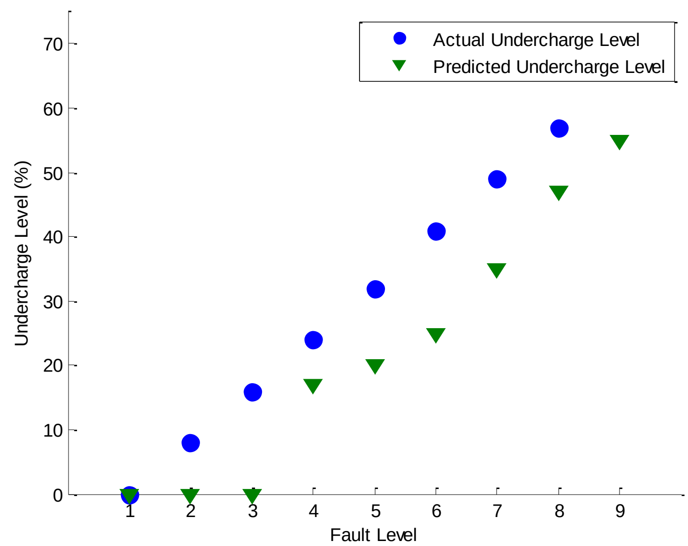

Figure 19: Undercharge Fault Level Prediction for TXV valve

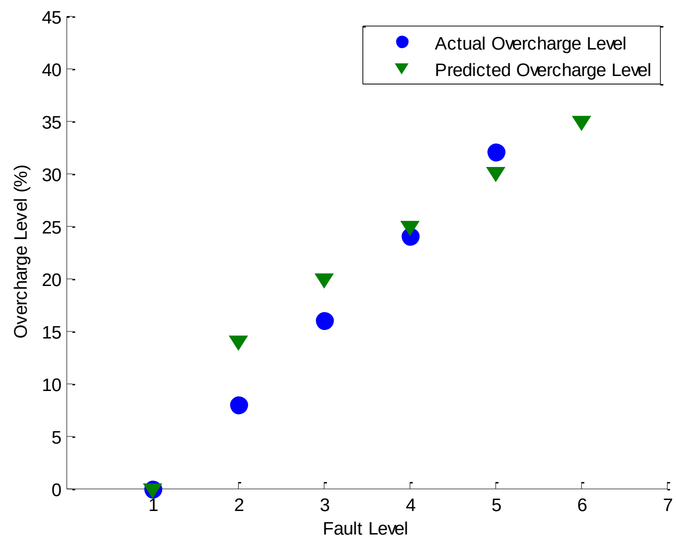

Figure 20: Overcharge Fault Level Prediction for TXV valve

According to the results, it can be said that the device worked better when detecting Evaporator Filter Fouling and predicting the level of incorrect charge for the thermal expansion valve tests, but in general, it performed well for both expansion devices.

CHAPTER VIII

MULTIPLE FAULT TESTS AT TFCL

After testing the device for individual faults, multiple faults were introduced to the TFCL air conditioner. In these set of tests, two faults were introduced at a time; a fouling fault with a refrigerant line fault. The level of the refrigerant line fault was varied, and both the fouling faults were introduced at two levels- 40% and 80%. Therefore, each combination had 4*2 = 8 tests.

Table 27: Fault Combinations Introduced for Multiple Fault Detection Tests

Refrigerant Line Fault	**Levels Introduced**	**Fouling Fault**	**Levels Introduced**
Refrigerant Overcharge	11 to 35%	Condenser Fouling	40% and 80%
Refrigerant Overcharge	11 to 35%	Evaporator Fouling	40% and 80%
Refrigerant Undercharge	5 to 20%	Condenser Fouling	40% and 80%
Refrigerant Undercharge	5 to 20%	Evaporator Fouling	40% and 80%
Liquid Line Restriction	10 to 32%	Condenser Fouling	40% and 80%
Liquid Line Restriction	10 to 32%	Evaporator Fouling	40% and 80%

In addition to the fault combinations listed in Table 27, both evaporator and condenser fouling fault were also introduced together at 5 different levels from 20 to 100% (5*5= 25 tests).

The results of multiple fault detection, and fault evaluation is discussed in this chapter.

Refrigerant Undercharge

With Condenser Fouling

For this combination of faults, refrigerant undercharge was not detected in 3 of the 8 tests (Figure 21). For the remaining tests, both faults were detected at low levels of undercharge and high levels of condenser fouling. This is because high refrigerant undercharge negates the increase of condenser split caused by condenser fouling. A check for high dT_{CA} is done in the presence of undercharge to check for condenser fouling.

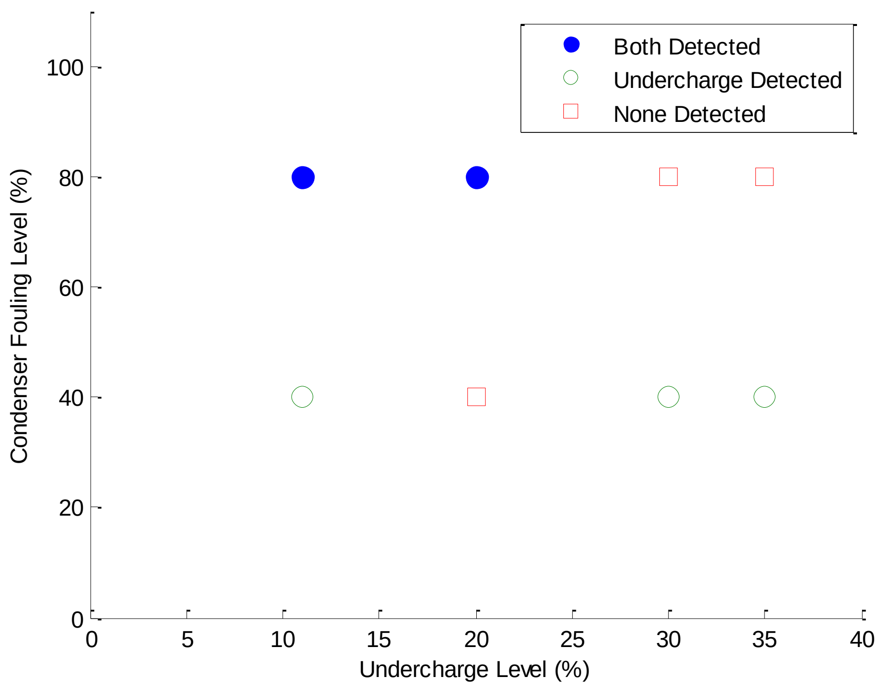

Figure 21: Results for tests on Undercharge and Condenser Fouling

With Evaporator Fouling

Out of the 8 tests, neither of the two faults in this combination are detected in 5 tests (Figure 22). However, in the remaining tests, after an undercharge is detected, the user is prompted to verify evaporator fouling as the symptoms of both faults are similar. Therefore assuming the user can see the fouled evaporator, both faults are detected in the remaining 3 of the 8 tests.

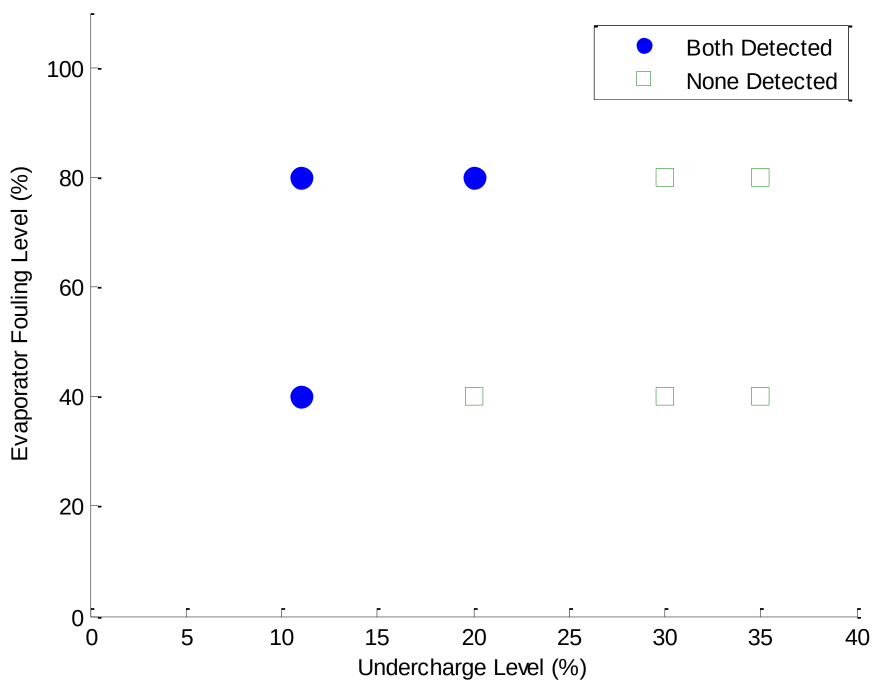

Figure 22: Results for tests on Undercharge and Evaporator Fouling

Refrigerant Overcharge

With Condenser Fouling

Just like the evaporator fouling with undercharge combination, in case of condenser fouling with overcharge, the user is prompted to check for condenser fouling in the presence of an overcharge. This is because both faults cause an increase in CS and $dT_{CA.}$ Assuming that the user can view the fouling on the condenser, 7 of 8 tests show successful fault detection (Figure 23).

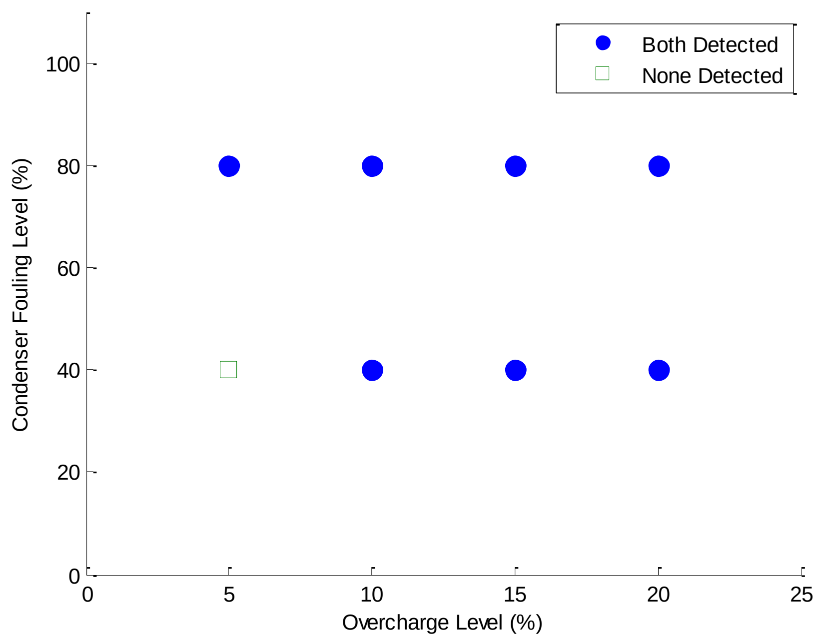

Figure 23: Results for tests on Overcharge and Condenser Fouling

With Evaporator Fouling

Refrigerant Overcharge is detected in 6 of 8 tests, but since symptoms of evaporator fouling are negated by refrigerant overcharge evaporator fouling was not successfully detected in any of the faults (Figure 24).

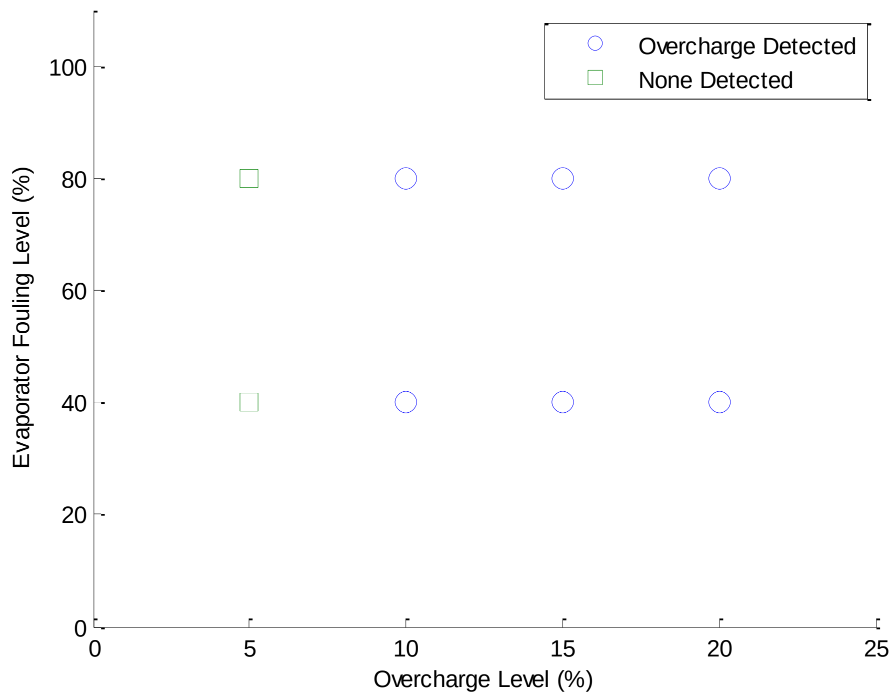

Figure 24: Results for tests on Overcharge and Evaporator Fouling

Liquid Line Restriction

With Condenser Fouling

In 5 of 8 tests for this combination LLR is detected, but condenser fouling is detected in only 1 test. This is because the effect of the features used to detect fouling is negated by high levels of LLR. There is one instance of incorrect fault detection in the test (Figure 25).

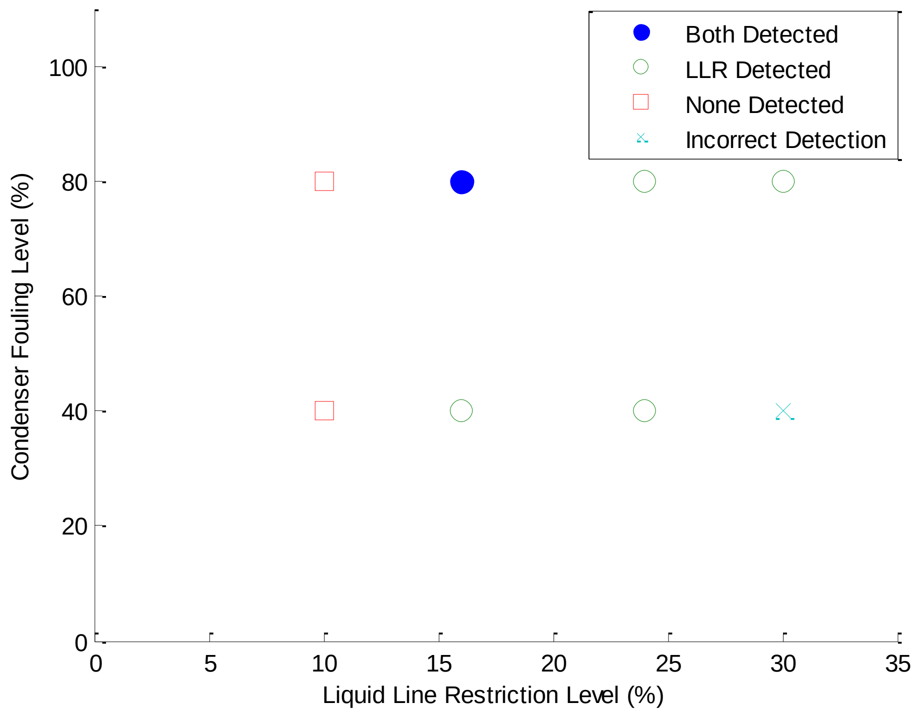

Figure 25: Results for tests on Liquid Line Restriction and Condenser Fouling

With Evaporator Fouling

For this combination, evaporator fouling was detected in 6 of 8 tests. LLR was detected in 4 of these tests (Figure 26). A user prompt was used to verify evaporator fouling in these 4 tests.

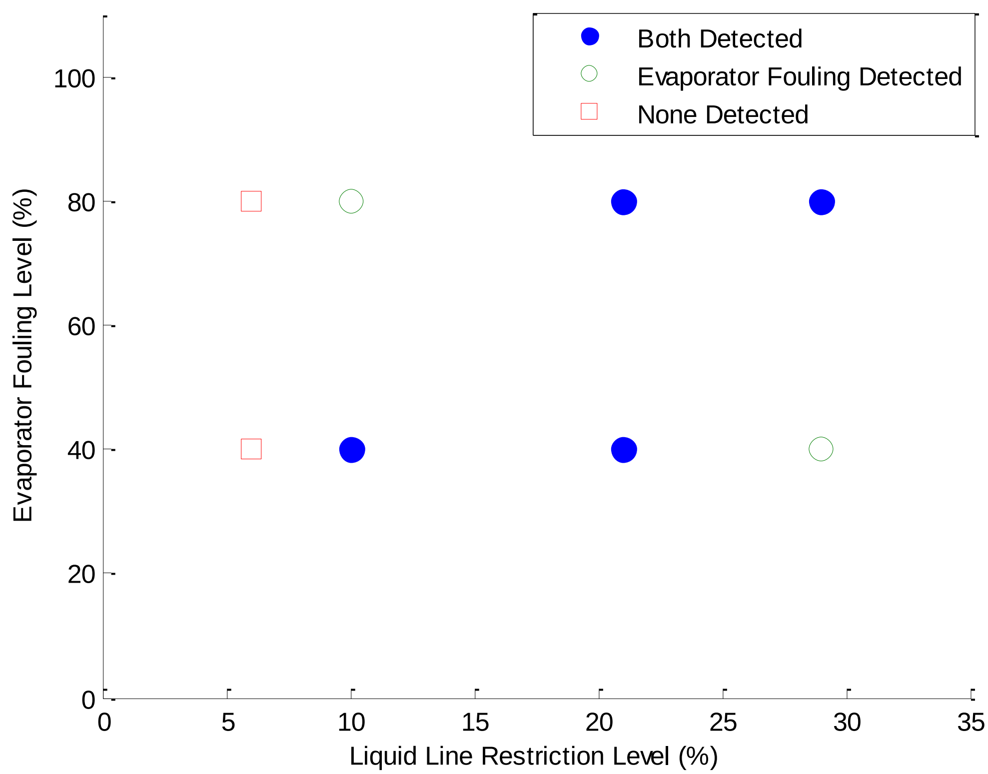

Figure 26: Results for tests on Liquid Line Restriction and Evaporator Fouling

Evaporator and Condenser Fouling

As is can be seen in Figure 27, both evaporator and condenser fouling were successfully detected only at the maximum fault levels. In general, the faults were detected at levels higher than 80%.

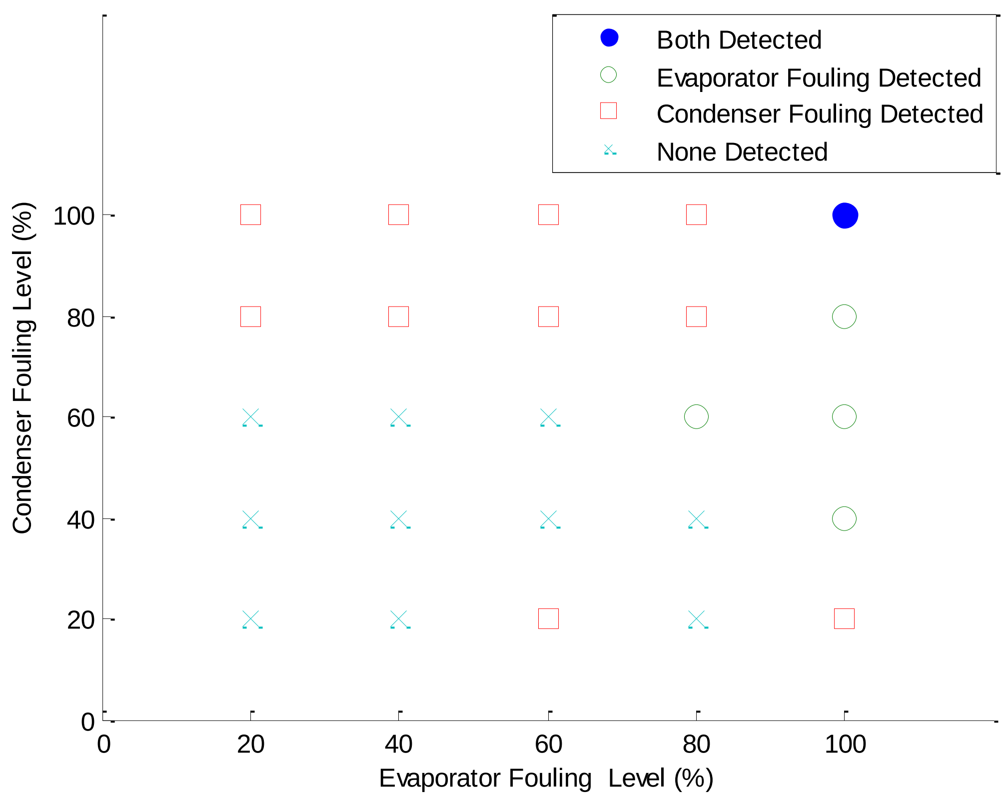

Figure 27: Results for tests on Evaporator and Condenser Fouling

Out of a total of 73 tests of multiple fault detection, 1 test detected a fault that was not present in the system (Type 1 Error), in 26 tests none of the two faults were detected (Type 2 Error: Both Faults), and 27 tests had incomplete fault detection where only one of two faults were detected (Type 2 Error: One Fault). Successful multiple fault detection occurred in 18 tests. Thus, at least one of the two faults were detected in over 60% of the tests with minimal instances of incorrect fault detection (Table 28).

Table 28: Summary of Errors for Multiple Fault Test Results from TFCL

Fault Combinations	**Type 1 Error (False Alarm)**	**Type 2 Error (Missed Fault): Both Faults**	**Type 2 Error (Missed Fault): One Fault**	**No Error**
Refrigerant Undercharge and Condenser Fouling	0	4	2	2
Refrigerant Undercharge and Evaporator Fouling	0	5	0	3
Refrigerant Overcharge and Condenser Fouling	0	1	0	7
Refrigerant Overcharge and Evaporator Fouling	0	2	6	0
LLR and Condenser Fouling	1	2	4	1
LLR and Evaporator Fouling	0	2	2	4
Evaporator and Condenser Fouling	0	10	13	1
TOTAL	1	26	27	18

Fault Evaluation for Multiple Faults

Table 29 shows a summary of the Fault Evaluation results of the Multiple Fault Tests. The level of the fault, the range of total efficiency loss and cost savings related to the fault combination is predicted. The device can predict the level of the refrigerant line fault (Fault 1) better than the fouling fault (Fault 2). Therefore, based on the level of the fouling fault visible to the user, the total efficiency loss and cost savings can be estimated from the maximum and minimum values predicted by the device.

Table 29: Summary of Fault Evaluation Results for Multiple Fault Tests

Fault 1	Level Predicted	Fault 2	Level Predicted	Efficiency Loss Predicted	Predicted Cost Savings
11% Undercharge	9%	40% Evap Fouling	High	7 to 13%	\$46 to \$92
11% Undercharge	9%	80% Evap Fouling	Medium	7 to 13%	\$48 to \$94
20% Undercharge	Not detected	40% Evap Fouling	Not detected	0%	No savings
20% Undercharge	10%	80% Evap Fouling	High	8 to 13%	\$50 to \$96
30% Undercharge	Not detected	40% Evap Fouling	Not detected	0%	No savings
30% Undercharge	Not detected	80% Evap Fouling	Not detected	0%	No savings
35% Undercharge	Not detected	40% Evap Fouling	Not detected	0%	No savings
35% Undercharge	Not detected	80% Evap Fouling	Not detected	0%	No savings
11% Undercharge	8%	40% Cond Fouling	Not detected	6%	\$37

Table 29: (Continued)

Fault 1	Level Predicted	Fault 2	Level Predicted	Efficiency Loss Predicted	Predicted Cost Savings
11% Undercharge	9%	80% Cond Fouling	Low	11 to 20%	$76 to $163
20% Undercharge	Not detected	40% Cond Fouling	Not detected	0%	No savings
20% Undercharge	8%	80% Cond Fouling	Low	10 to 20%	$69 to $155
30% Undercharge	11%	40% Cond Fouling	Not detected	7%	$48
30% Undercharge	Not detected	80% Cond Fouling	Not detected	0%	No savings
35% Undercharge	Not detected	40% Cond Fouling	Not detected	0%	No savings
35% Undercharge	Not detected	80% Cond Fouling	Not detected	0%	No savings
5% Overcharge	Not detected	40% Evap Fouling	Not detected	0%	No savings
5% Overcharge	Not detected	80% Evap Fouling	Not detected	0%	No savings
10% Overcharge	9%	40% Evap Fouling	Not detected	2%	$8
10% Overcharge	8%	80% Evap Fouling	Not detected	2%	$6
15% Overcharge	7%	40% Evap Fouling	Not detected	1%	$4
15% Overcharge	7%	80% Evap Fouling	Not detected	1%	$3
20% Overcharge	10%	40% Evap Fouling	Not detected	2%	$10
20% Overcharge	10%	80% Evap Fouling	Not detected	2%	$9
5% Overcharge	Not detected	40% Cond Fouling	Not detected	0%	No savings
5% Overcharge	8%	80% Cond Fouling	Low	6 to 16%	$40 to $122
10% Overcharge	9%	40% Cond Fouling	Low	7 to 17%	$44 to $126

Table 29: (Continued)

Fault 1	Level Predicted	Fault 2	Level Predicted	Efficiency Loss Predicted	Predicted Cost Savings
10% Overcharge	14%	80% Cond Fouling	Medium	8 to 18%	$54 to $137
15% Overcharge	8%	40% Cond Fouling	Low	6 to 16%	$41 to $124
15% Overcharge	13%	80% Cond Fouling	Medium	8 to 18%	$52 to $135
20% Overcharge	12%	40% Cond Fouling	Low	7 to 17%	$49 to $132
20% Overcharge	17%	80% Cond Fouling	Medium	9 to 19%	$62 to $147
10% LLR	Not detected	40% Evap Fouling	Not detected	0%	No savings
10% LLR	Not detected	80% Evap Fouling	Not detected	0%	No savings
16% LLR	High	40% Evap Fouling	Medium	4 to 16%	$27 to $119
16% LLR	Not detected	80% Evap Fouling	Medium	1 to 7%	$6 to $49
24% LLR	High	40% Evap Fouling	High	4 to 16%	$27 to $119
24% LLR	High	80% Evap Fouling	High	4 to 16%	$27 to $119
30% LLR	Not detected	40% Evap Fouling	High	1 to 7%	$6 to $49
30% LLR	High	80% Evap Fouling	High	4 to 16%	$27 to $119
10% LLR	Not detected	40% Cond Fouling	Not detected	0%	No savings
10% LLR	Not detected	80% Cond Fouling	Not detected	0%	No savings
16% LLR	High	40% Cond Fouling	Not detected	0%	No savings
16% LLR	High	80% Cond Fouling	Low	8 to 23%	$55 to $192
24% LLR	High	40% Cond Fouling	Not detected	3 to 9%	$20 to $65
24% LLR	High	80% Cond Fouling	Not detected	3 to 9%	$20 to $65

Table 29: (Continued)

Fault 1	Level Predicted	Fault 2	Level Predicted	Efficiency Loss Predicted	Predicted Cost Savings
30% LLR	Not detected	40% Cond Fouling	Not detected	Wrong EF	Incorrect
30% LLR	High	80% Cond Fouling	Not detected	3 to 9%	$20 to $65
20% Evap Foul	Not detected	20% Cond Foul	Not detected	0%	No savings
20% Evap Foul	Not detected	40% Cond Foul	Not detected	0%	No savings
20% Evap Foul	Not detected	60% Cond Foul	Not detected	0%	No savings
20% Evap Foul	Not detected	80% Cond Foul	Medium	5 to 15%	$34 to $115
20% Evap Foul	Not detected	100% Cond Foul	High	5 to 15%	$34 to $115
40% Evap Foul	Not detected	20% Cond Foul	Not detected	0%	No savings
40% Evap Foul	Not detected	40% Cond Foul	Not detected	0%	No savings
40% Evap Foul	Not detected	60% Cond Foul	Not detected	0%	No savings
40% Evap Foul	Not detected	80% Cond Foul	Medium	5 to 15%	$34 to $115
40% Evap Foul	Not detected	100% Cond Foul	High	5 to 15%	$34 to $115
60% Evap Foul	Not detected	20% Cond Foul	High	5 to 15%	$34 to $115
60% Evap Foul	Not detected	40% Cond Foul	Not detected	0%	No savings
60% Evap Foul	Not detected	60% Cond Foul	Not detected	0%	No savings
60% Evap Foul	Not detected	80% Cond Foul	Medium	5 to 15%	$34 to $115
60% Evap Foul	Not detected	100% Cond Foul	High	5 to 15%	$34 to $115
80% Evap Foul	Not detected	20% Cond Foul	Not detected	0%	No savings

Table 29: (Continued)

Fault 1	**Level Predicted**	**Fault 2**	**Level Predicted**	**Efficiency Loss Predicted**	**Predicted Cost Savings**
80% Evap Foul	Not detected	40% Cond Foul	Not detected	0%	No savings
80% Evap Foul	Medium	60% Cond Foul	Not detected	1 to 7%	$6 to $49
80% Evap Foul	Not detected	80% Cond Foul	Medium	5 to 15%	$34 to $115
80% Evap Foul	Not detected	100% Cond Foul	High	5 to 15%	$34 to $115
100% Evap Foul	Not detected	20% Cond Foul	High	5 to 15%	$34 to $115
100% Evap Foul	High	40% Cond Foul	Not detected	1 to 7%	$6 to $49
100% Evap Foul	High	60% Cond Foul	Not detected	1 to 7%	$6 to $49
100% Evap Foul	High	80% Cond Foul	Not detected	1 to 7%	$6 to $49
100% Evap Foul	High	100% Cond Foul	High	6 to 21%	$41 to $174

In the following chapter, the device is tested in the field to verify its ease of use, and understand its method of installation.

CHAPTER IX

FIELD TEST

To verify that the device will be quick and easy to install an actual field test was performed with the proposed device. This chapter goes over how the components of the proposed device were selected and the process of installation of the device.

Component Selection

The proposed device requires 4 things: temperature sensors, pressure sensors, data acquisition systems and a laptop with the loaded software. Details about each component is provided in the following paragraphs:

Temperature Sensors

To keep the measurements non-invasive and make installation of the sensors quick and easy, the temperature sensors chosen for the proposed device are T-type thermocouples. The wired T-type thermocouples work well for measurements in restricted spaces, like the outlet of the compressor that is covered by the condenser fan and panels. The user may also prefer to measure the evaporator saturated temperature with a temperature sensor rather than using the pressure measurement to predict the saturated temperature; in these cases, the T-type thermocouple would work best in the constricted space of the indoor coil. A clamp type thermocouple would not have allowed this flexibility.

Therefore, 7 T-type thermocouple wires were used for the proposed device. The sensors can be mounted using either a thermocouple tape or a temporary paste. The paste is preferred when the thermocouple tape does not stick very well due to condensation on the tubes.

Pressure Sensors

Pressure measurements are used to estimate the saturated temperatures on the evaporator and condenser sides. Surface temperature measurements can also be used to estimate these temperatures, but this would involve guessing the saturation point in the both coils to decide where to mount the sensor. Therefore, although the pressure measurements are more expensive and less easy in comparison, they are preferred over the temperature sensors for a more accurate measurement.

The pressure sensors are installed on the refrigerant charging ports that are found near the outdoor unit. The pressure sensors chosen for the device had a cable connection that could be connected to a DC power supply. They gave a 0 to 5 V output, and had a range of 0 to 300 psig for the evaporator side and 0 to 500 psig for the condenser side. Mounting the pressure sensor requires a combination fittings and hoses to connect the pressure sensor to the refrigerant tube. O-rings and Teflon tape are necessary to ensure that there are no leaks while attaching the sensor.

Data Acquisition Systems

There are 3 DAQs that are needed by the proposed device- one for temperature measurements on the outdoor unit, one for temperature measurements on the indoor unit and one for pressure measurements. The DAQ used for measurements on the indoor unit is a wireless thermocouple DAQ that can communicate to the laptop outside.

A multifunction DAQ that can read voltage measurements from the pressure sensor was used for pressure measurements, and a wired thermocouple DAQ was used for the remaining temperature measurements at the outdoor unit.

Laptop with Loaded Software

Since the DAQ's are connected to the laptop, the laptop has to be loaded with LabVIEW which can be used to record data. NI MAX should also be loaded on the laptop as it helps troubleshooting the working of the DAQ and checking the connections. The proposed algorithm of the device was also coded on LabVIEW.

Thus, the chosen set of hardware, is listed in Table 30 and shown in Figure 28.

Table 30: Selected Components used for the Proposed Device

Item No.	Part Description	Part Number	Total List Price
1	USB-6009 Multifunction NI-DAQ	779026-01	$279.00
2	cDAQ-9171, CompactDAQ Chassis (1 slot USB)	781425-01	$259.00
3	cDAQ-9191 CompactDAQ Chassis (1 Slot, Wireless)	781497-01	$459.00
4	Two NI 9211 4-Channel Thermocouple Input Module	779001-01	$678.00
5	Power Cord, AC, U.S., 120 VAC, 2.3 meters	763000-01	$9.00
6	Seven T-type Thermocouples (4 to 5 feet long)		$98.00
7	Wired Pressure Transducer Range 0 to 300 psig	PX309-300G5V	$275.00
8	Wired Pressure Transducer Range 0 to 500 psig	PX309-500G5V	$275.00
9	Thermocouple Tape		$12.68
10	Teflon Tape		$1.46
11	Flat head screwdriver for NI DAQ	781015-01	$27.90
12	O-rings for Pressure Transducers		$3.37
	TOTAL		$2,377.41

Figure 28: Components of the Automated Fault Detection and Diagnostic Device

System Description

The system that was tested was a residential, 2 ton split system that used a Thermal Expansion Valve with R22 refrigerant. The system had a SEER rating of 13, with constant speed fans and compressor.

Installing the Device

In the field test performed, installing and setting up the device took about 20 minutes once the different parts of the system were identified. This is provided the following things are verified before the audit-

- The laptop is equipped with LabVIEW and NI MAX.
- The wireless DAQ is configured to communicate with the laptop.

Knowing where the different components of the air conditioning system are typically found (condenser, expansion valve, compressor and evaporator) also reduces the time required to install the device.

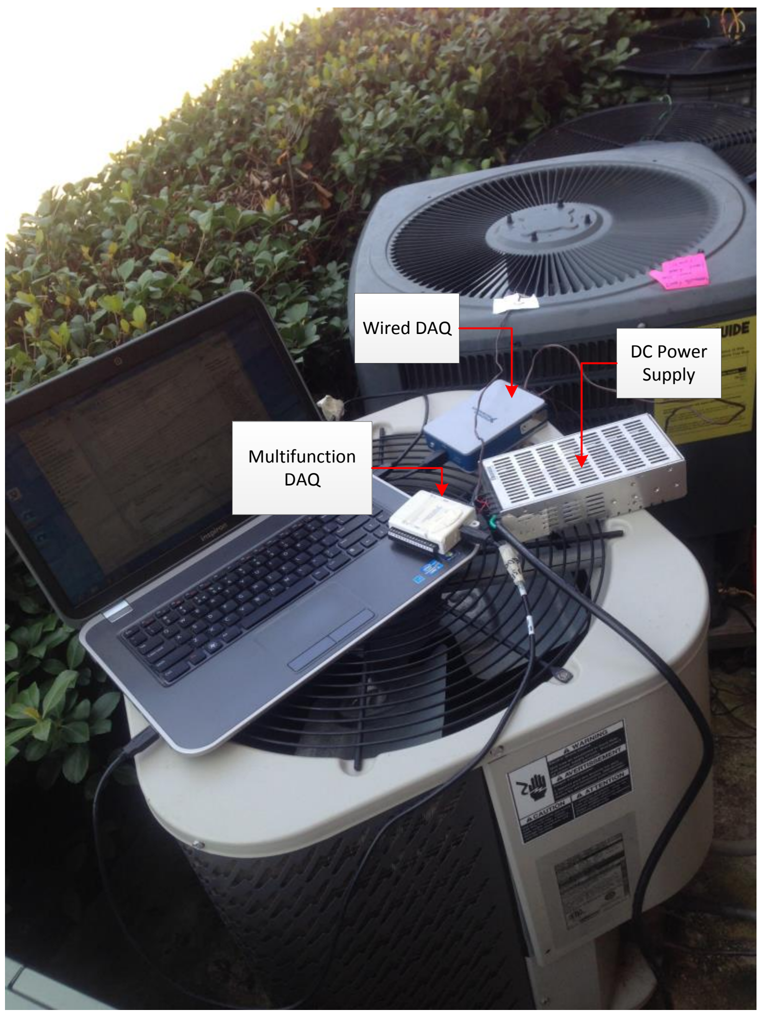

Figure 29: Data Acquisition Systems Required for the Outdoor Unit

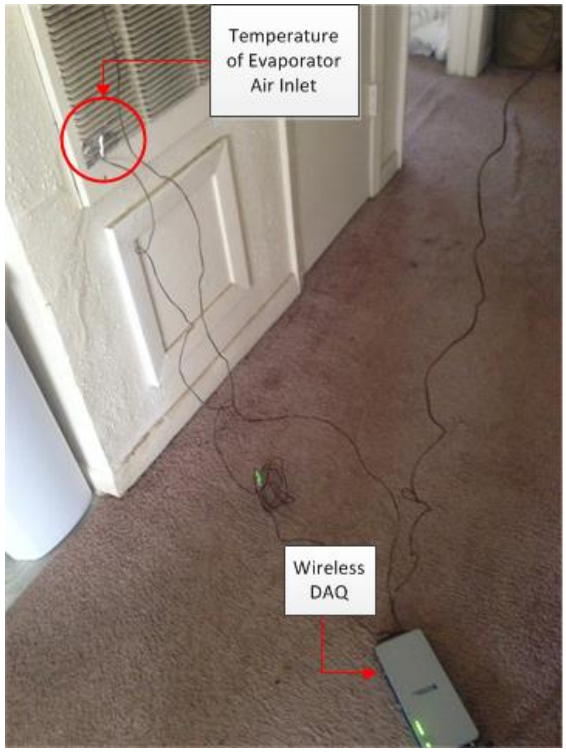

Figure 30: Temperature Sensor for Return Air Temperature and the Wireless DAQ at the Indoor Unit

During the audit, 5 of the 7 temperature sensors were connected to the wired DAQ at the outdoor unit (Figure 29) and the remaining 2 temperature sensors were connected to the wireless DAQ indoor (Figure 30). These temperature sensors are mounted as follows:

- One sensor is taped on the low pressure line going towards the condenser, as close as possible to the evaporator outlet to get a more accurate estimate of superheat (T_{ERO})(Figure 31).

- One sensor is taped to the outlet of the condenser (high-pressure line) to get an estimate of subcooling (T_{CRO}) (Figure 31).

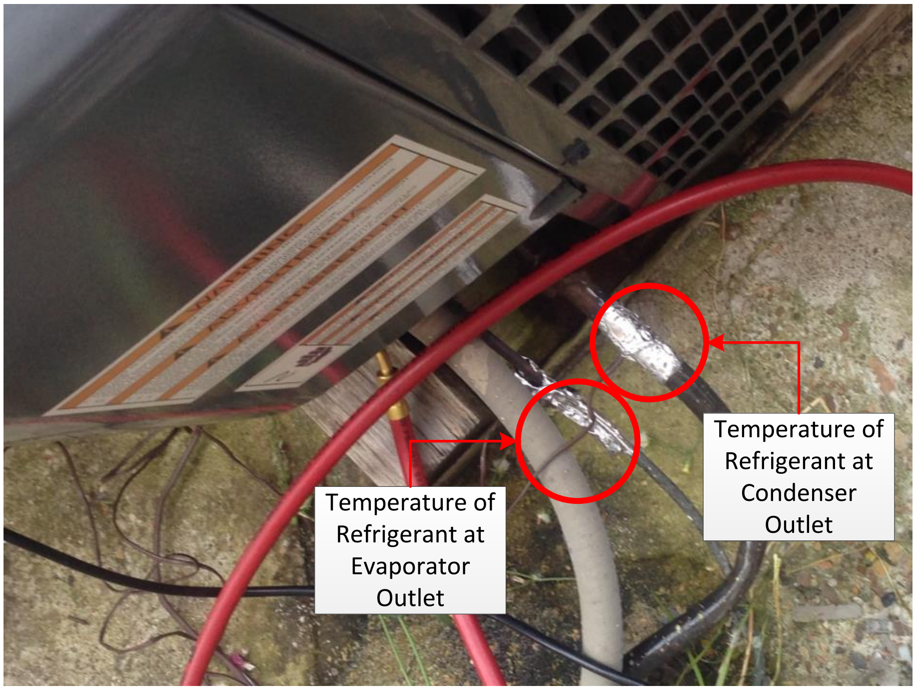

Figure 31: Temperature Sensors for Refrigerant Temperature at Evaporator Outlet and Condenser Outlet

- One sensor is placed right after the compressor. Installing this sensor may require displacing the condenser fan (T_{CRI})(Figure 32).
- Two sensors are taped at the inlet and outlet of condenser air at the side and at the top of the outdoor unit respectively (T_{CAI} and T_{CAO}) (Figure 32).

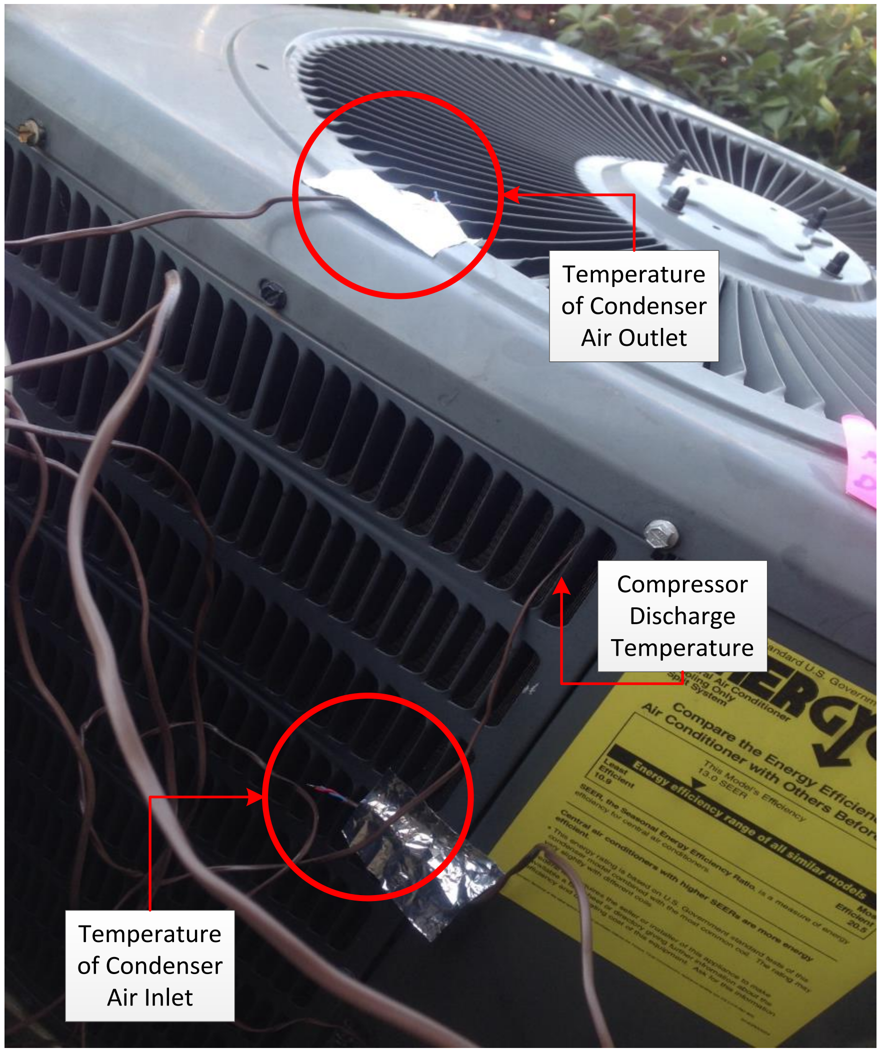

Figure 32: Temperature Sensors Measuring Condenser Air Inlet and Outlet, and Refrigerant Temperature at Compressor Discharge

- The remaining two sensors are taped to the return and supply air diffusers indoors (Figure 30, Figure 33).

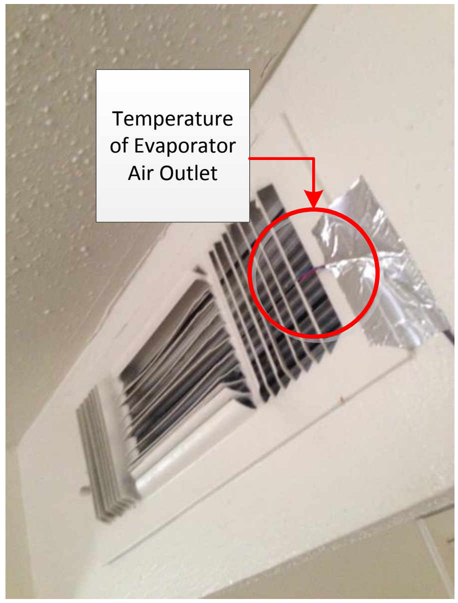

Figure 33: Temperature Sensor to Measure Supply Air Temperature

The pressure sensors are connected to a hose, which is then connected to the refrigerant charging port outdoors. The pressure sensors output a voltage value, which is recorded by the multi-function DAQ and then interpreted by LabVIEW. Installing the fittings to the refrigerant lines requires Teflon tapes and O-rings to ensure that there are no leaks while taking measurements. The O-rings are inserted into the thumb screw valve which fits over the end of the hose that is connect to the refrigerant charging port (Figure 34).

Figure 34: Mounting of the Pressure Sensor for Evaporator Pressure Measurement

Once the sensors are mounted, the air conditioning unit is turned on and the LabVIEW code is allowed to run for about 30 minutes. This operation doesn't need to be monitored, so while measurements are being recorded, energy auditors are free to look at other industrial equipment. At the end of 30 minutes, the data is saved, so that the saved file can be opened with the proposed Fault Detection and Diagnosis algorithm. Basic user information like SEER rating, type of refrigerant and capacity of the system can be found on the nameplate. Rated SC and SH is found in the installation brochure and the avoided cost of electricity and operational hours can be estimated.

The few issues that were encountered while installing the sensors in the field test were-

- Sweating on the evaporator outlet line which made it difficult to mount the sensor. A thermal paste can be used instead to mount the sensors.
- Pressure sensors require a DC power source, and if there is no power outlet close to the outdoor unit this can be an issue. Portable batteries can however be used.
- Installing the compressor discharge temperature sensor is time consuming since it requires removing the condenser fan and placing it back.

The findings of the field test is summarized in Table 31. Overall, the proposed device was quick and easy to install. In the field test performed, installing and setting up the device took about 20 minutes, and the data was recorded for about 30 minutes. Based on the recorded measurements, all the values were within thresholds, and it was confirmed that the system had no fault.

Table 31: Summary of Results from Field Tests

Ease of Installation:	
• Temperature Sensors	Easy and quick. T_{CRI} sensor may require more time.
• Pressure Sensors	Not as easy as the temperature measurements. Requires multiple fittings, and a power source. Leaks must be prevented while installing the sensor.
• DAQ	The wireless DAQ must be configured to communicate with the laptop.
Availability of User Information:	
• Maintenance Brochure	SC, SH
• Nameplate	Refrigerant type, Capacity, SEER rating
Time Required:	
• Time taken for Installation	About 20 minutes
• Time taken to collect data	About 30 minutes
• Time taken for uninstallation	About 10 minutes
Results:	
• Detected Fault	None.
• Predicted Loss in Efficiency	None
• Predict Cost Savings	None

CHAPTER X

CONCLUSION

Based on the results from laboratory tests and field tests it can be said that the developed device could detect faults and conservatively predict the related efficiency loss. It can do this with information that is easily available to the technicians performing an energy audit, and without the need for extensive measurements and tests to develop a model that is typically needed for fault detection.

All the components of the device cost less than $2,500, which made it affordable. However, the low cost and mobility of the device is a trade-off for its sensitivity to faults. The device works well for refrigerant line faults, but detects evaporator and condenser fouling only at higher levels. This is acceptable, since unlike refrigerant line faults, the fouling faults are easily visible to energy auditors. In case of multiple fault tests, it fails to detect both faults in about 40% of the tests, which generally happens for fault combinations that have opposite effect on the certain feature. However, it predicts the presence of at least one of the two faults in the remaining 60% of the tests, thus remaining conservative overall in its energy and cost savings estimate.

Although the rules used by the device were generic so that it could be used for different types of air conditioners, the sensitivity of the device could be further improved by using a broader set of thresholds. Thresholds of the features of a system are dependent on the type of system, its expansion device, its capacity and its SEER rating.

Therefore, in the future, a database of thresholds should be developed, and in addition, further testing could be done on packaged rooftop units, and systems having more than two simultaneous faults.

REFERENCES

[1] U. S. Energy Information Administration, " Annual Energy Review ", 2011.

[2] U. S. Energy Information Administration, "Manufacturing Energy Consumption Survey ", 2010.

[3] U. S. Energy Information Administration, "International Energy Outlook 2013", July 2013.

[4] J. L. Pellegrino, N. Margolis, M. Justiniano, M. Miller, and A. Thedki, "Energy Use, Loss and Opportunities Analysis: U.S. Manufacturing & Mining", prepared by Energetics, Incorporated and E3M, Incorporated For the U.S. Department of Energy Energy Efficiency and Renewable Energy Industrial Technologies Program, December 2004.

[5] A. Zhou, V. Tutterow, J. Harris, and P. Bostrom, "Promoting Energy-Efficient Buildings in the Industrial Sector ", prepared by Alliance to Save Energy, 2009.

[6] H. Li and J. E. Braun, "Application of Automated Fault Detection and Diagnostics For Rooftop Air Conditioners in California", presented at the ACEEE Summer Study on Energy Efficiency in Buildings, Monterey, CA, 2004.

[7] D. E. Stouppe and L. Y.S., "Air Conditioning and Refrigeration Equipment Failures", *National Engineer 93(9),* pp. 14-17, 1989.

[8] M. S. Breuker and J. E. Braun, "Common Faults and Their Impacts for Rooftop Air Conditioners", *HVAC&R Research,* vol. 4, pp. 303-318, July1998.

[9] California Utilities Statewide Codes and Standards Team, "Residential Refrigerant Charge Testing and Related Issues", for the California Public Utilties Commission, 2011.

[10] M. Farzad; and D. L. O'Neal., "The Effect of Improper Refrigerant Charging on the Performance of a Residential Heat Pump with Fixed Expansion Devices (Capillary Tube and Short Tube Orifice)", *29th Intersociety Energy Conversion Engineering Conference*, pp. 92 I - 926, 1994.

[11] W. Kim and J. E. Braun, "Impacts of Refrigerant Charge on Air Conditioner and Heat Pump Performance", *International Refrigeration and Air Conditioning Conference*, *Paper 1122* , 2010.

[12] C. Neme, J. Proctor, and S. Nadel, "Energy Savings Potential from Addressing Residential Air Conditioner and Heat Pump Installation Problems", prepared for the American Council for an Energy-Efficient Economy (ACEEE), 1999.

[13] T. Downey and J. Proctor, "What Can 13,000 Air Conditioners Tell Us?", in American Council for an Energy-Efficient Economy (ACEEE) Conference, 2002.

[14] J. Tomczyk, *Troubleshooting An Undercharge of Refrigerant*, (2010). Available: http://www.achrnews.com/articles/troubleshooting-an-undercharge-of-refrigerant

[15] J. Tomczyk, *The Professor: Checking on Refrigerant Overcharge*, (2010). Available: http://www.achrnews.com/articles/the-professor-checking-on-refrigerant-overcharge

[16] J. Tomczyk., *Diagnosing A Restricted Liquid Line Can Be Tricky*, (2002). Available: http://www.achrnews.com/articles/diagnosing-a-restricted-liquid-line-can-be-tricky

[17] L. Yang, J. E. Braun, and E. A. Groll, "The Impact of Evaporator Fouling on the Performance of Packaged Air Conditioners ", presented at the International Refrigeration and Air Conditioning Conference, Paper 687 , 2004.

[18] R. Isermann, "Process Fault Detection Based on Modeling and Estimation—A Survey", *Automatica, vol. 20,* pp. 387, 1984.

[19] M. G. McKellar and D. R. Tree, "Steady State Characteristics of Failures of a Household Refrigerator " , *International Refrigeration and Air Conditioning Conference. Paper 78*, 1988.

[20] L. A. Stallard, "Model Based Expert System for Failure Detection and Identification of Household Refrigerators", Master's thesis , Mechanical Engineering, Purdue University, 1989.

[21] J. Braun and H. Li, "Automated Fault Detection And Diagnostics Of Rooftop Air Conditioners For California ", prepared for the Architectural Energy Corporation, August 2003.

[22] H. T. Grimmelius, J. Klein Woud, and G. Been, "On-line Failure Diagnosis for Compression Refrigeration Plants", *International Journal of Refrigeration, vol. 18*, pp. 31-41, 1995.

[23] M. Stylianou and D. Nikanpour, "Performance Monitoring, Fault Detection, and Diagnosis of Reciprocating Chillers ", *ASHRAE Transactions, vol. 102*, pp. 615-627, 1996.

[24] Y. Jia and T. A. Reddy, "Characteristic Physical Parameter Approach to Modeling Chillers Suitable for Fault Detection, Diagnosis, and Evaluation", *Journal of Solar Energy Engineering, vol. 125*, pp. 258-265, 2003.

[25] M. Yoshimura and N. Ito, "Effective Diagnosis Methods for Air-Conditioning Equipment in Telecommunications Buildings," in *Telecommunications Energy Conference Proceedin., Eleventh International*, *Vol 2*, pp. 21.1/1-21.1/7, 1989.

[26] T. M. Rossi and J. E. Braun, "A Statistical, Rule-Based Fault Detection and Diagnostic Method for Vapor Compression Air Conditioners", *HVAC&R Research, vol. 3*, pp. 19-37, 1997.

[27] B. Chen and J. E. Braun, "Simple Fault Detection and Diagnosis Methods for Packaged Air Conditioners", in *International Refrigeration and Air Conditioning Conference, Paper 498*, 2000.

[28] H. Li and J. E. Braun, "Decoupling Features and Virtual Sensors for Diagnosis of Faults in Vapor Compression Air Conditioners", *International Journal of Refrigeration, vol. 30*, pp. 546-564, 2007.

[29] P. R. Armstrong, C. R. Laughman, S. B. Leeb, and L. K. Norford, "Detection of Rooftop Cooling Unit Faults Based on Electrical Measurements", *HVAC&R Research, vol. 12*, pp. 151-175, 2006.

[30] S. Katipamula and M. R. Brambley, "Review Article: Methods for Fault Detection, Diagnostics, and Prognostics for Building Systems—A Review, Part I", *HVAC&R Research, vol. 11*, pp. 3-25, 2005.

[31] *Virtjoule*, (2014), Available: http://www.virtjoule.com/

[32] Pacific Northwest National Laboratory, *Smart Monitoring and Diagnostic System*, (2013). Available: http://buildingsystems.pnnl.gov/building/smds.stm

[33] Sensus MI, *Automatic Early Detection of Machine Faults Diagnosis Indicating the Cause of the Fault* (2014). Available: http://sensusmi.com/en/index.php?option=com_content&task=view&id=5&Itemid=62

[34] ClimaCheck, *ClimaCheck Solutions* (2014). Available: http://www.climacheck.com/?p=2

[35] H. Li and J. E. Braun, "Development, Evaluation, and Demonstration of a Virtual Refrigerant Charge Sensor", *HVAC&R Research, vol. 15*, pp. 117-136, 2009.

[36] J. B. Watt, "Development Of Empirical Temperature And Humidity-Based Degraded-Condition Indicators For Low-Tonnage Air Conditioners", Master's thesis, Mechanical Engineering, Texas A&M University, 1997.