Virtual Refrigerant Charge Sensor

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ABSRACT

Studies have shown that more than 50 percent of all air conditioners suffer from improper charge or air flow problems causing them to operate 10 to 20 percent less efficiently than expected. Utilities in California have developed incentive programs to encourage HVAC service contractors to tune up residential and small commercial air conditioners. A significant aspect of these programs involves refrigerant charge verification. In addition, Title 24 of the California code requires refrigerant charge verification for new installations and retrofits.

This paper presents a method for determining refrigerant charge using low-cost, non-invasive measurements (i.e., surface mounted temperature measurements). The method could be used as part of a protocol for verified service providers (VSPs) in California AC diagnostic tune-up or refrigerant charge, air flow (RCA) verification programs. Ultimately, the method could be embedded within a portable virtual refrigerant charge gauge for a technician's use or permanently installed on the AC unit. The accuracy of the virtual refrigerant charge sensor method is evaluated in this paper using laboratory data for a number of different systems and over a wide range of operating conditions with and without the presence of other faults. Seven different systems are considered, including a window unit, residential split systems, and light commercial packaged systems employing either fixed orifice expansion devices or thermostatic expansion valves and R-22 or R-410a as the refrigerant. The virtual refrigerant charge sensor is shown to have good performance in terms of accuracy and robustness and has the potential to be easily implemented and installed.

Introduction

Refrigerant charge is one of the most problematic issues for HVAC&R systems. Improper charge faults can be introduced during initial installation or developed during routine operation. Numerous case studies conducted by various independent investigators (Proctor and Downey, 1995; Cowan, 2004; Li and Braun, 2006b) concluded that more than 50% of the packaged air conditioning systems in the field were improperly charged due to improper commissioning or leakage. Proper refrigerant charge is essential for a system to operate efficiently and safely. Another study sponsored by the American Council for an Energy-Efficient Economy (ACEEE) concluded that improper charging of air conditioners and poor maintenance could increase energy use in homes by 20% and waste 17,600 Terawatt-hour of energy nationwide every year (Neme, 1999). There is a direct linkage between CO_2 production (global warming) and energy efficiency, and between refrigerant leakage and ozone depletion. The Montreal Protocol was designed in 1987 and substantially amended in 1990 and 1992 to protect the stratospheric ozone layer. Freon is a chlorofluorocarbon (CFC) that will damage the Earths protective ozone layer if released into the atmosphere. The laws governing CFC's now do not allow HVAC&R contractors to add Freon to a leaky system. They are first required to find and fix the leak, or they may lose their license.

In order to determine charge level with current practice, a technician generally evacuates the system and weighs the removed charge. This method is very time-consuming and costly because it involves 1) removing existing mineral oil and recovering existing refrigerant, 2) evacuating the system using a deep vacuum, and 3) weighing in refrigerant and fresh mineral oil. In order to adjust an existing refrigerant level during operation with refrigerant recovery, a charging chart is often used. However, this method doesn't provide information on charge level and is unreliable and can lead to the system being overcharged or undercharged. Some other charge fault detection and diagnostics tools require pressure sensors, which are not only very costly and but also tend to introduce leakage to the system due to invasive pressure sensing (Li and Braun, 2006b).

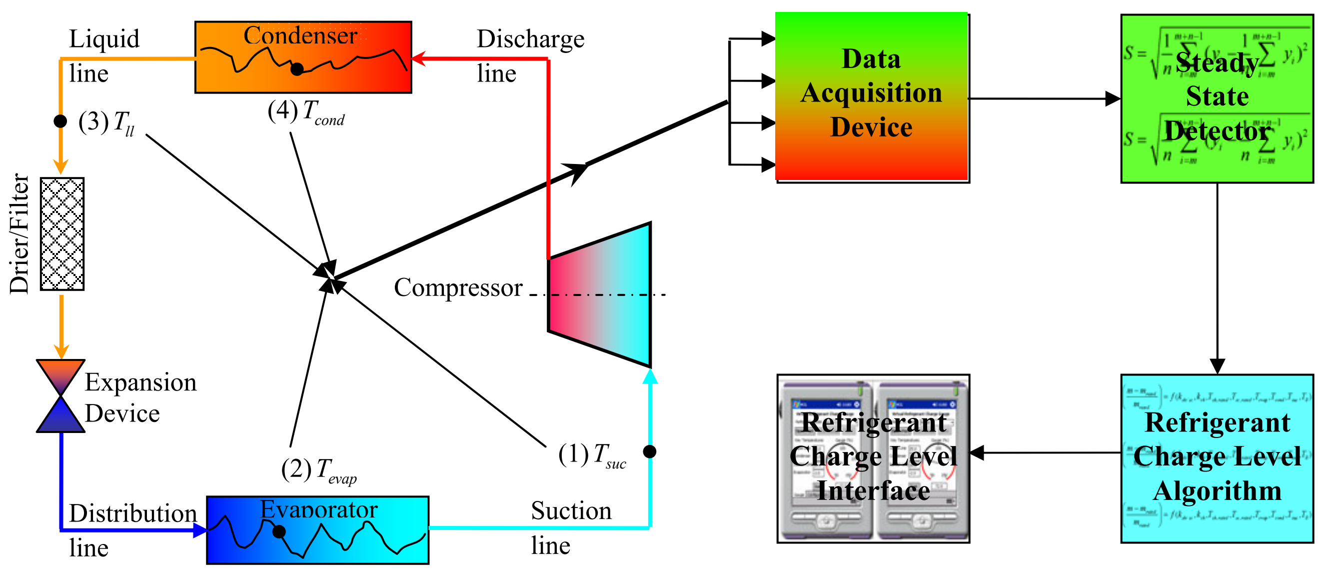
Li and Braun (2006a) proposed a method of obtaining refrigerant charge level using low cost non-invasive measurements (externally mounted temperature measurements) during operation. The invention could be used as part of a permanently installed control or monitoring system to indicate charge level and/or to automatically detect and diagnose low or high levels of refrigerant charge. It could also be used as a standalone tool by technicians in order to determine existing charge and during the process of adjusting the refrigerant charge. The current paper presents an extensive performance evaluation and prototype demonstration of this technology. Five different types of systems are used for evaluation and demonstration, which covers systems of both small and large capacities from a window unit to residential split systems and to light commercial packaged systems, using both fixed orifice expansion devices and thermostatic expansion valves, and using both R-22 and R-410a. The evaluation and demonstration verify that the virtual refrigerant charge gauge has very good performance in terms of accuracy and robustness and can be easily implemented and installed in terms of both hardware and software.
There are some patents related to refrigerant charge diagnosis. Most of the methods qualitatively indicate whether the system charge is below or above acceptable limits. A prior technology (Temple and Hanson, 2003) is able to determine system charge quantitatively but it requires relatively expensive pressure measurements and significant training data to fit a model and has not been tested extensively. What is more, methods for measuring pressure are highly invasive. Installation of pressure sensors requires fittings that can artificially incur refrigerant leakage. The uniqueness of the method presented in the current paper is that it can obtain refrigerant charge levels using low-cost surface-mounted temperature sensors only without disturbing the system, using readily available manufacturers' data and limited training data for implementation, and with the existence of other system faults.

Brief Description of the Virtual Refrigerant Charge Gauge

A typical vapor compression refrigeration cycle system is illustrated in Figure 1. The system generally consists of a compressor, a condenser, an expansion device and an evaporator. Typically, a filter/drier is also used. The various components are connected together via a conduit, usually copper tubing. Four surface-mounted temperature sensors are used to monitor the system as indicated in Figure 1. Measurements include suction line temperature (T_{suc}), liquid line temperature (T_{ll}), condensing temperature (T_{cond}), and evaporating temperature (T_{evap}). As illustrated in Figure 1, the virtual refrigerant charge gauge consists of four basic components: a data acquisiton device, a steady-state detector, a charge derivation algorthm, and a display interface.

The data acquisition device needs to provide four temperature measurements, which could range from a simple data acquisition board for a standalone tool to a sophisticated onboard instrumentation for a chiller system FDD application.

Figure 1. Measurements and Scheme of the Virtual Refrigerant Gauge



Since the charge gauge algorithm is based on steady-state operating conditions, a steady-state detector is used to filter out the transient data. A combined slope and variance steady-state detection algorithm (Li and Braun, 2003) is used. This algorithm computes the slope (k) of the best-fit line (Equation (1)) through a fixed-length sliding window of recent measurements and standard deviation (S) thereof using Equation (2). If both of the slope and deviation are smaller than corresponding thresholds (k_{th} and S_{th}), the system reaches steady state. The sliding window is specified by the number (n) of data points (y_m, y_{m+1}, …, y_{m+n-1}) and sampling time (τ).

$$y_i = a + k(i-m)\tau, \qquad i = m, m+1, ..., m+n-1 \tag{1}$$

$$S = \sqrt{\frac{1}{n}\sum_{i=m}^{m+n-1}(y_i - \frac{1}{n}\sum_{i=m}^{m+n-1} y_i)^2} \tag{2}$$

The refrigerant charge level algorithm, as shown in Equation (3), is the core of the virtual refrigerant charge gauge and essentially a simplified first-principle model of refrigerant charge inventory for vapor compression cycle equipment. The algorithm relates the four measurements and five constants to the system charge level in terms of deviations from rated (nominal) charge.

$$\left(\frac{m - m_{rated}}{m_{rated}}\right) = f(k_{sh/sc}, k_{ch}, T_{sh,rated}, T_{sc,rated}, T_{evap}, T_{cond}, T_{suc}, T_{ll}) \tag{3}$$

where m is the actual total charge, m_{rated} is the nominal total refrigerant charge, $k_{sh/sc}$ and k_{ch} are two constants characteristic of a given system, $T_{sc,rated}$ and $T_{sh,rated}$ are liquid line subcooling and suction line superheat at rated conditions, respectively. The three constants: m_{rated}, $T_{sc,rated}$ and $T_{sh,rated}$ can be readily obtained from the technical data provided by manufacturers. $k_{sh/sc}$ and k_{ch} can be either trained using a couple of data points or initially preset as generic default values and further fine-tuned using real data. The other four inputs on the right side are measurements from the data acquistion device and steady-state detector. The algorithm is derived based on physical analysis of the vapor compression cycle system rather than from an empirical data regression so it is independent of other faults and operating conditions and applicable to systems having either fixed or variable-area expansion devices.

The refrigerant charge display interface is a means by which the virtual refrigerant charge gauge provides readings to users. It could be a PDA or pocket PC which is most applicable to tools used by service technician, or a LCD, or a pointer-dial display.

Algorithm Evaluation and Demonstration Prototype

Algorithm Evaluation

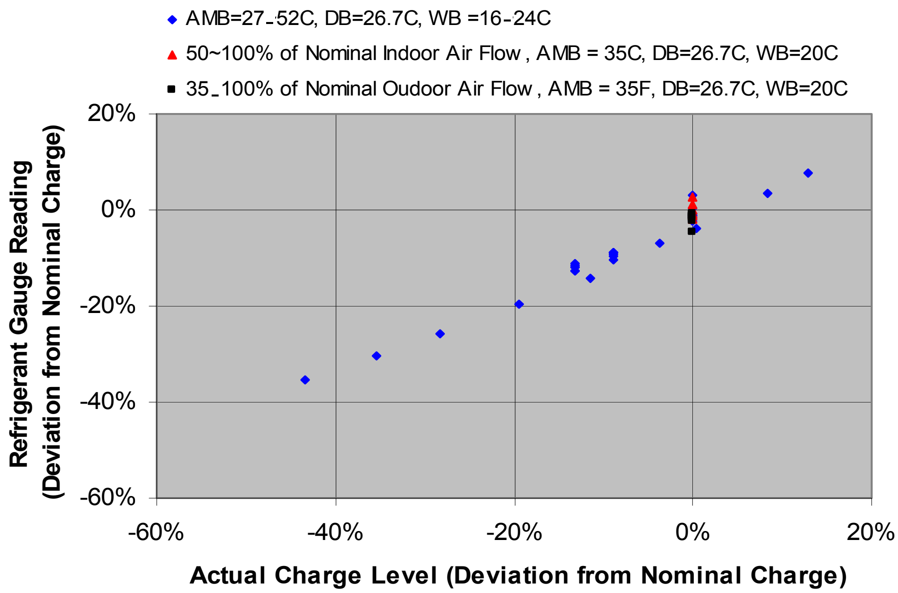
Four different types of systems are used to evaluate the algorithm depicted in Equation (3). The evaluated systems are chosen to cover both residential split units and light commercial packaged units, both fixed orifices and thermostatic expansion valves, and both R-22 and R-410a.

System I

System I is a 3-ton split air conditioner for residential application with a fixed orifice (FXO) as the expansion device and using R410a as the refrigerant. The nominal charge of this system is 6.3 lb. The data was orginally collected for the investigation of system modeling by Shen and Braun (2004). This data set covers 48 testing conditions with 1) refrigerant charge levels ranging from 57% to 113%, 2) ambient temperatures (AMB) ranging from 27 to 52 °C, 3) indoor air wet bulb temperatures (WB) ranging from 16 to 24 °C, 4) indoor air flow rates ranging from 50% to 100% of its nominal value, and 5) outdoor air flow rates ranging from 35% to 100% of its nominal value.

As shown in Figure 2, the virtual refrigerant charge level gauge has very good performance in terms of accuracy and robustness. The gauge reads accurately and reliably under a large variation of ambient driving conditions. Under nominal charge level, there is an uncertainty of ±5% even under severe faulty conditions such as low indoor or outdoor air flow rates.

Figure 2. Virtual Refrigerant Gauge Performance for a Split, FXO and R410a System

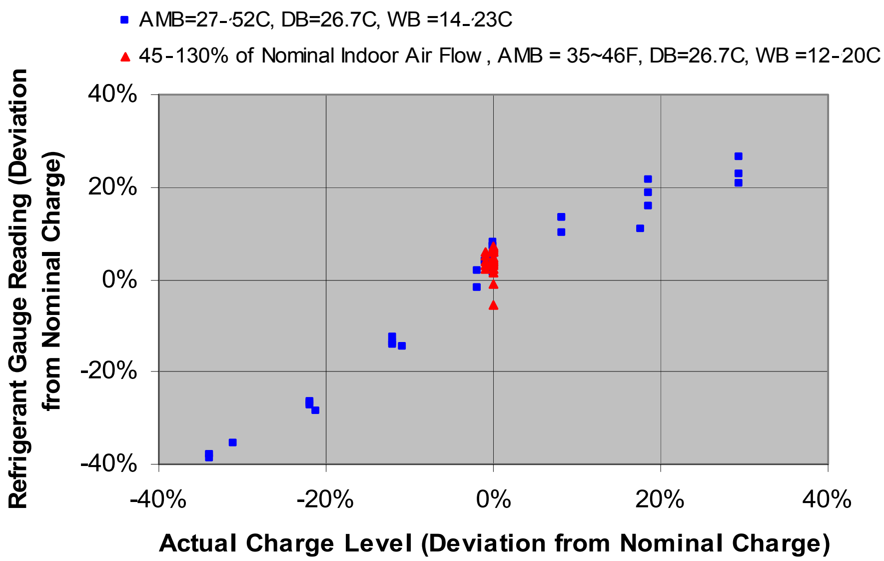


System II

System II is a 3-ton residential packaged air conditioner with a FXO as the expansion device and using R410a as the refrigerant. Its nominal charge is 7.15 lb. Data was orginally collected for investigation of system modeling by Shen and Braun (2004). This data set covers 73 testing conditions with 1) refrigerant charge levels ranging from 58% to 130%, 2) ambient temperatures ranging from 27 to 52 °C, 3) indoor air wet bulb temperatures ranging from 12 to 23 °C, and 4) indoor air flow rates ranging from 45% to 130% of its nominal value.

As shown in Figure 3, the virtual refrigerant charge level gauge has good performance in terms of accuracy and robustness. The gauge reads accurately and reliably under a large variation of ambient driving conditions. Under nominal and high charge levels, there is an uncertainty of ±7% even under severe faulty conditions such as low indoor air flow rates.

Figure 3. Virtual Refrigerant Gauge Performance for a Packaged, FXO and R410a System

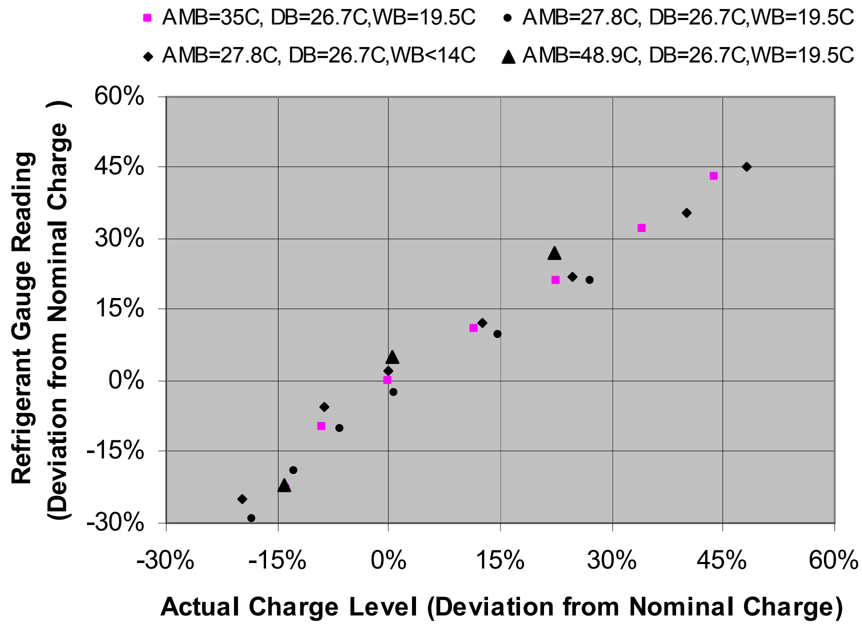


System III

System III is a 5-ton packaged rooftop air conditioner for light commercial application with a TXV as the expansion device and using R22 as the refrigerant. The nominal charge of this system is 11 lb. The data was orginally collected for the investigation of charge inventory system modeling by Harms (2002). This data set covers 24 testing conditions with 1) refrigerant charge levels ranging from 78% to 148%, 2) ambient temperatures ranging from 27.8 to 48.9 °C, and 3) indoor air wet bulb temperatures ranging from 14 to 19.5 °C.

As shown in Figure 4, the virtual refrigerant charge level gauge has good performance in terms of accuracy and robustness. Overall, the gauge reads accurately and reliably under all the testing conditions with an uncertainty of ±5%.

Figure 4. Virtual Refrigerant Gauge Performance for a Packaged, TXV and R22 System

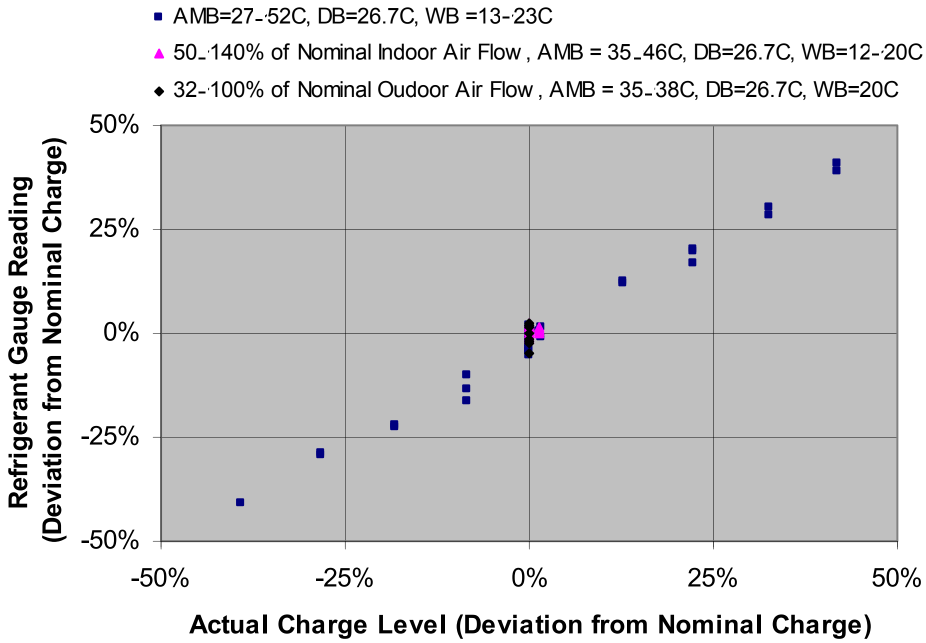


System IV

System IV is a 3-ton split air conditioner for residential application with a TXV as the expansion device and using R410a as the refrigerant. The nominal charge of this system is 6.41 lb. The data was orginally collected for the investigation of system modeling by Shen and Braun (2004). This data set covers 70 testing conditions with 1) refrigerant charge levels ranging from 61% to 141%, 2) ambient temperatures ranging from 27 to 52 °C, 3) indoor air wet bulb temperatures ranging from 12 to 23 °C, 4) indoor air flow rates ranging from 50% to 140% of its nominal value, and 5) outdoor air flow rates ranging from 32% to 100% of its nominal value.

As shown in Figure 5, the virtual refrigerant charge level gauge has excellent performance in terms of accuracy and robustness. The gauge reads accurately and reliably under a large variation of ambient driving conditions. Under nominal charge level, there is an uncertainty of ±4% under severe faulty conditions such as low indoor or outdoor air flow rates.

Figure 5. Virtual Refrigerant Gauge Performance for a Split, TXV and R410a System



Prototype Demonstration

A prototype of the virtual refrigerant charge gauge was developed to demonstrate the holistic implementation of the virtual refrigerant charge gauge.

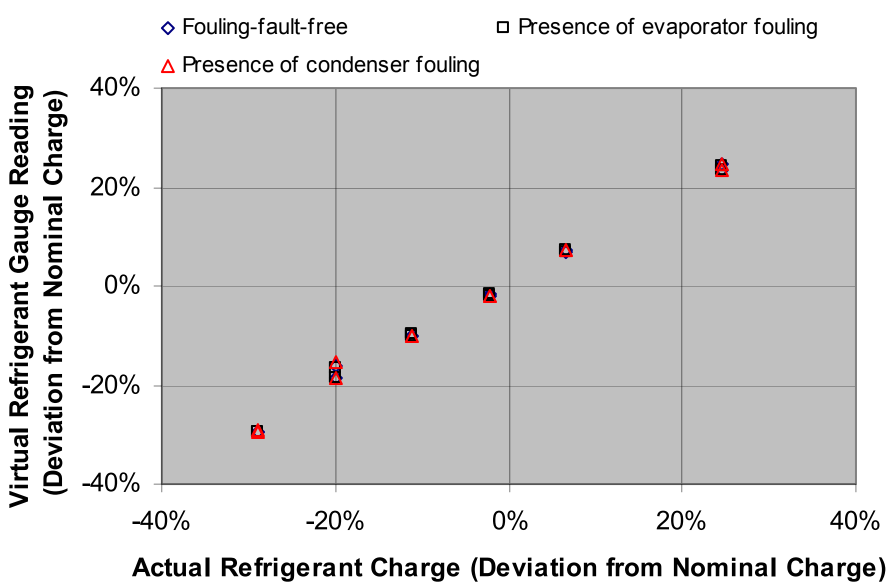
For the sake of mobility, a small window air-conditioner was chosen for the demonstration. The system has a cooling capacity of 5200-BTU, uses R-22 as refrigerant, and uses a fixed orifice as an expansion device. The nominal charge is 9 oz and its rated subcooling and superheat are 6.7 °C and 4.5 °C, respectively.

As shown in Figure 6, four thermocouples are mounted on the outer surface of the refrigerant tubing and insulated by sticky foam. Temperature measurements are acquired by a simple commercially-available acquisition board. Algorithms for steady-state detector and charge level derivation algorithm are implemented in a pocket PC. Refrigerant can be recovered from the system using a refrigerant recovery machine and can be weighed in using a scale. The gauge readings are displayed on the pocket PC as well.

Figure 7 shows the gauge readings vs. actual charge levels. This system could only operate under charge levels ranging from 70% to 130% of nominal charge level without shutting down due to low or high pressure cutouts. For each charge level, simulated evaporator and condenser fouling were introduced to the system to test its robustness. Evaporator and condenser fouling were simulated using paper. A total of 36 test points were collected and plotted in Figure 7. It can be seen that the charge gauge reads very accurately under various operating and faulty conditions.

Figure 6. Implementation of a Holistic Demonstration Prototype

Figure 7. Virtual Refrigerant Gauge Performance for a Window, FXO and R22 System



Conclusion

An extensive performance evaluation and a prototype demonstration of the virtual refrigerant charge gauge were performed. The virtual gauge requires determination of five parameters. Three of them, m_{rated}, $T_{sc,rated}$ and $T_{sh,rated}$, can be readily obtained from the technical data provided by manufacturers. The other two of them, $k_{sh/sc}$ and k_{ch}, can be either trained using a couple of data points or initially preset as generic default values and further fine-tuned using real data. Generally speaking, the gauge with default parameters has an accuracy of ±9% when the system charge level is within the range from 75% to 125% but the accuracy can degrade down to ±15% when the system charge level is out of the above range. With fine-tuned parameters, the global accuracy of the gauge can be improved up to ±5%.

In this paper, five different types of systems were used for evaluation and demonstration, which covers systems of both small and large capacities from a window unit to residential split systems and to light commercial packaged systems, using both fixed orifice expansion devices and thermostatic expansion valves, and using both R-22 and R-410a. Through the evaluation and demonstration, it is verified that the virtual refrigerant charge level gauge 1) has very good performance in terms of accuracy; 2) is very robust against both variations in operating conditions and impacts of other faults; 3) can be easily implemented at low costs in terms of both hardware and software; and 4) is generic for different types of systems. The gauge could be used as part of a permanently installed control or monitoring system to indicate charge level and/or to automatically detect and diagnose low or high levels of refrigerant charge. It could also be used as a standalone tool by technicians in order to determine existing charge and during the process of adjusting the refrigerant charge.

Acknowledgement

This work was co-supported by the California Energy Commission (CEC), U.S. Department of Energy (DOE), Purdue Research Foundation, and University of Nebraska-Lincoln.

NOMENCLATURE

AMB	= Ambient Temperature	S_{th}	= Threshold for S
DB	= Dry-bulb Temperature	T_{cond}	= Condensing temperature
k	= Slope of the best-fit line	T_{evap}	= Evaporating temperature
k_{ch}	= Empirical constant	T_{ll}	= Liquid line temperature
$k_{sh/sc}$	= Empirical constant	$T_{sc,rated}$	= Rated subcooling
k_{th}	= Threshold for k	$T_{sh,rated}$	= Rated superheat
m	= Actual total charge	T_{suc}	= Suction line temperature
m_{rated}	= Nominal total charge	τ	= Sampling time
n	= Number of data points	$y_{m,m+1,\ldots,m+n-1}$	= Data points
S	= Standard deviation	WB	= Wet-bulb temperature

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