Using Charge Determination Design of Experiments to Develop Refrigerant-based Heat Pump System Charge Models

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ABSTRACT

Refrigerant based heat pump systems are becoming an integral system in electric vehicle architectures due to their high efficiencies in providing heating and cooling to people and components within the car. An important component in heat pump systems that determines optimal efficiency is the amount of refrigerant (referred to as refrigerant charge). As such, the capability to model refrigerant charge helps quantify the health status of the heat pump system, whereby the lack or overabundance of refrigerant in a heat pump refrigerant system leads to various other component failures, e.g., liquid slugging, compressor overheating, material fatigue in heat exchanger, and degraded/stuck expansion valves. In designing a heat pump system, engineers need to perform a set of design of experiments to determine an optimal refrigerant charge based on a set of performance metrics in the presence of certain noise factors. This optimal refrigerant charge provides conditions where the heat pump system operates efficiently in both heating and cooling, in addition to facilitating operational conditions that will not lead to secondary component degradation or damage. The search for optimal refrigerant charge is classified as refrigerant charge determination, whereby engineers incrementally increase the refrigerant in the heat pump system in operation of heating/cooling and collect data about performance metrics. Some of the key performance metrics used to determine efficiency of a heat pump system include i) compressor inlet superheat temperature, ii) condenser outlet subcooled temperature, iii) compressor high side pressure, iv) compressor low side pressure, v) condenser outlet pressure, and vi) condenser quality estimate. Furthermore, this process follows design of experiments concepts and is performed for both heating and cooling modes of operation. In this paper, we leverage refrigerant charge determination as a training data source to develop refrigerant charge models, where several performance metrics are health indicators used as model inputs and the amount of refrigerant added to the heat pump system are ground truth refrigerant charges used as model outputs. In this paper we develop regression models to estimate the total refrigerant charge, which is used to classify different states of refrigerant based on levels of performance degradation corresponding to specific refrigerant charge thresholds. We trained a robust linear regression model using this charge determination data and found that the worst-case estimation error was less than 10% with respect to the refrigerant charge ground truth.

1. INTRODUCTION

Refrigerant heat pump systems are a prevalent technology used for in-vehicle heating, ventilation, and air conditioning (HVAC) and electric vehicle battery and electronics thermal conditioning. Vehicle-based heat pump technology offers several different benefits by improving energy efficiency, extending driving range, and enhancing cabin comfort as outlined by Antonijevic and Heckt (2004) and Qi (2014). Tesla first introduced heat pump technology in its Model Y sport utility vehicle, first launched in 2020. Following that release, numerous car manufacturers have employed this technology to their electric vehicle offerings including Audi e-Tron, BMW iX3, Hyundai Ioniq 5, Kia EV9, Nissan Leaf, Mercedes-Benz EQS, Volkswagen ID4, and GMC Hummer EV, to name a few. To effectively capitalize on this technology for electric vehicle designs, an integral design process in heat pump systems that directly impacts system performance is the determination of operational refrigerant charge in the system.

Operational refrigerant charge is the amount of refrigerant required to achieve sufficient heating or cooling provided through all the heat exchangers in the heat pump system. The

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amount of refrigerant charge plays a critical role in balancing thermal demands and ensuring that the refrigeration cycle and its control components operate within design conditions. For example, conditions when refrigerant charge is too low, insufficient amounts of mass flow through the system may lead to decreased amount of thermal transfer between low to high pressure side heat exchangers, which results in limiting heat rejection from the heat pump system. On the other hand, overabundance of refrigerant charge may enable operating conditions on the system that can potentially damage components e.g., compressor liquid slugging, stuck expansion valves, thermal instability, vacuum loss of heat exchangers, to name a few. Prolonged exposure to either over or undercharge refrigerant conditions will lead to component damage and/or may result in potential refrigerant leaks.

To assess the operational refrigerant charge in the system, a series of heating or cooling tests are performed after initial design or installation of a heat pump system. Traditional instrumentation within heat pump systems includes temperature and pressure sensors placed across each main component to estimate heat transfer and thermal stability of the system under a variety of ambient conditions necessitating specific customer or vehicle thermal demands. The objective of these tests is to measure the behavior of specific thermal conditions to assess the minimum and maximum range of refrigerant charge that provides sufficiently high heating or cooling thermal energy.

In this paper, we leverage the framework developed for refrigerant charge determination to develop and train a refrigerant charge model that estimates the percentage of active refrigerant in a heat pump system used for either heating or cooling. The novelty of utilizing performance metrics from refrigerant charge determination for the purpose of refrigerant charge estimation is to utilize a standard modeling framework built around vehicle develop practices. A similar approach that is primarily data driven, utilizes a neural network based refrigerant charge estimation model developed for air conditioning system in Son et al. (2018). In addition, a hybrid refrigerant charge fault model is developed for use with data center air conditioning systems in Xu et al. (2019). Furthermore, a series of virtual refrigerant charge sensors were designed using model-based methods to estimate refrigerant charge under varying operating conditions for air conditioning system in Li et al. (2009), Kim et al. (2013), and Kim et al. (2014).

To aid in our development, first in section 2, we summarize the method of refrigerant charge determination tests used to obtain an operational refrigerant charge for a heat pump system. Next in section 3, we develop a set of health indicators and a refrigerant charge model using characteristics from the charge determination tests. Illustrative experimental results are included in Section 4 that shows the efficacy of the refrigerant charge model using data from the charge determination tests. Finally, some concluding remarks are given in section 5.

2. REFRIGERANT CHARGE DETERMINATION TESTS

Refrigerant charge determination tests are a series of design of experiments, whereby the refrigerant charge (measured in grams) in a heat pump system is varied from a low to high value while operating the heat pump system in either heating or cooling mode of operation at a specified high thermal load. Typically used thermal load conditions will include vehicle technical specifications on worst case ambient conditions. To induce high cooling load, high value air flow is imparted on both the evaporator and external condenser heat exchangers under hot ambient conditions. Similarly, to induce high heating load, a high value air and/or coolant flow is imparted on a condenser heater and chiller heat exchanger under cold ambient conditions.

To measure heat pump thermal behavior, the heat pump system is mechanized with absolute pressure and temperature sensors that are sampled digitally at various locations within the refrigerant architecture (see Figure 1 for detailed locations). Digital readouts of temperature and pressures used in conjunction with detailed thermophysical properties of refrigerant, estimated using REFPROP from Lemmon et. al. (2018), provides estimates of refrigerant superheat temperatures, subcooled temperatures, saturation temperatures, entropy, enthalpy, and vapor quality estimates. Furthermore, accurately representing heat pump thermal behavior at varying refrigerant charge levels requires operating these tests under the realistic system level controls in place, i.e., the expansion valves, refrigerant flow valves, and electric compressors are controlled normally under these thermal load conditions.

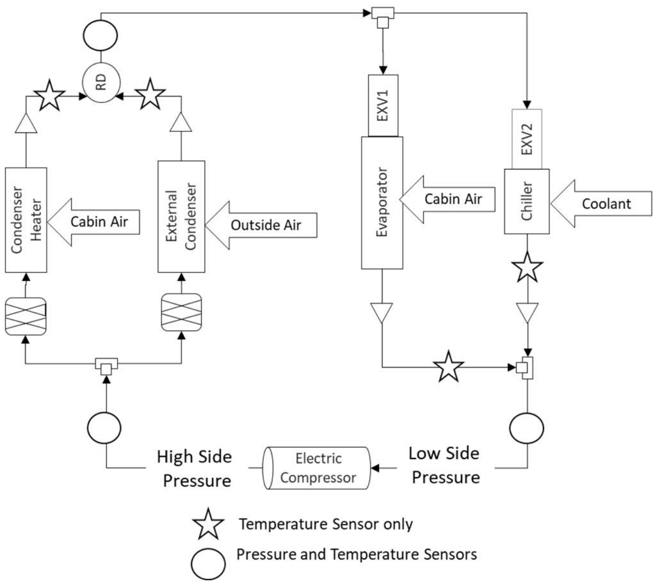

Figure 1. Heat pump architecture and instrumentation.

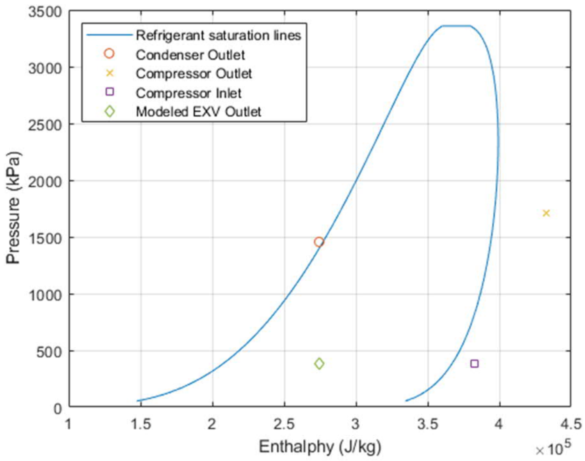

Figure 2. Heat pump pressure and enthalpy diagram.

Referring to the pressure and enthalphy diagram in Figure 2, in all modes of operation, the electric compressor takes at the suction side, low-temperature and low-pressure (also called low side pressure and temperature) refrigerant vapor from the discharge of the evaporator/chiller heat exchanger and compresses the refrigerant to raise its discharge pressure and temperature (also called high side pressure and temperature). This compressed refrigerant is transferred to either of the two condenser heat exchangers as seen in Figures 1 and 2. The expansion valves are typically controlled to regulate the superheat temperature flowing into the compressor, such that the valve opens more to reduce superheat temperatures as seen in Figure 2. Furthermore, the ability to maintain a specific high side and low side saturation temperatures through the different heat exchangers indicates the ability to provide sufficient heating or cooling from the heat pump system.

Analyzing refrigerant charge relies on the principles of superheat and subcooling. Superheat temperature refers to the increase of the refrigerant temperature above its saturation temperature. Superheat temperatures are defined for refrigerant operating within the superheated vapor region. Subcooling temperature, on the other hand, refers to the decrease of the refrigerant temperature below its saturation temperature. Subcooling temperatures are defined for refrigerant that operates in the compressed liquid region.

Initially when the refrigerant charge is minimal the amount of subcooled temperature is minimal, which implies that the amount of compressed liquid refrigerant entering the expansion valve is negligible. As more refrigerant charge is added into the system, the subcooled temperature increases to the point where enough subcooled temperature has developed such that it can supply enough compressed liquid into the expansion valve to operated effectively. The more refrigerant added to the system will subsequently increase the subcooled temperature, but at the risk of going beyond a certain point where highly pressurized refrigerant can exhibit thermal instability due to an excess amount of stored energy. Further downstream of the subcooled temperature, the superheat temperature behaves in the opposite way. As the refrigerant charge starts at the minimum amount, the superheat temperature is very high and is reduced as more refrigerant charge is added to the heat pump system. Overcharging the refrigerant beyond a specific point will cause the superheat temperature to vanish, such that this condition will cause saturated liquid to enter the suction side of the compressor. This effect is called liquid slugging and under prolonged exposure to this condition can cause severe damage to the electric compressor.

The overlapping conditions where the subcooled and superheat temperatures reach some nominal value and the heating or cooling air temperatures reaches a target value is considered the operating refrigerant charge range, as outlined in SAE J3023. This range of refrigerant allows the system designer to charge the system to yield the optimum amount of refrigerant to provide sufficient heating and/or cooling through the heat pump system. The minimum amount of refrigerant in this overlapping region is considered the optimal refrigerant charge, with some small added refrigerant beyond this value to be the operational refrigerant charge to account for any minute refrigerant leaks that is inherent in any vacuum system.

3. HEALTH INDICATORS AND REFRIGERANT CHARGE MODELING

In this section, a regression modeling framework is outlined that uses health indicators designed around the refrigerant charge determination metrics. These metrics are then used as regressors in a regression model that provides a percentage estimate of refrigerant charge, where the operational charge was determined from the charge determination design of experiments. Furthermore, the refrigerant charge percentages are partitioned into refrigerant classes based on varying levels of heat pump system performance.

3.1. Regressor Health Indicators

The metrics used in section 2 to determine optimal refrigerant charge include superheat temperature at the suction side of the compressor and the subcooled temperature at the discharge side of the condensers. These metrics are prime candidates for health indicators to estimate refrigerant charge. In the absence of sufficient subcooled temperatures (i.e., subcooled temperatures very close to zero), we make use of an additional health indicator denoted as the expansion valve (EXV) quality estimate. This health indicator is a dynamic model estimate for the refrigerant quality at the discharge portion of the expansion valve. It has inputs of compressor mass flow, expansion valve orifice area, and the pressure difference between inlet and outlet of the expansion valve.

To further enhance the set of health indicators, we make use a physiological analogy between refrigerant systems and human circulatory systems. In a circulatory system, the case where there is an insufficient amount of blood, the primary symptom is low blood pressure at the upstream portion of the heart. Conversely, in the case where there is an overabundance of blood, the primary symptom is high blood pressure at the upstream portion of the heart. In the context of a refrigerant system, the electric compressor acts as the "heart" of the system, where the high side pressure normalized with the low side pressure can indicate the refrigerant charge level in the heat pump system under specific conditions of use. Note that, this normalized pressure called pressure ratio is also used to denote operating conditions for the electric compressor.

To understand the behavior of each of health indicators used for regression modeling, Table 1 provides qualitative signs of when refrigerant is considered undercharged (low refrigerant compared with operational charge with noticeable thermal load deficiency) and overcharged (high refrigerant compared with operational charge with noticeable thermal load deficiency). In the undercharge state, both condenser outlet subcooled temperature and compressor pressure ratio are considered at a minimum value and will transition to maximum value in the overcharge state. Conversely, the compressor inlet superheat temperature and the expansion valve refrigerant quality are at maximum value in undercharge state and transitions to minimum value in the overcharge state.

Table 1. Health indicator refrigerant charge behavior.

Health Indicator	Undercharge Behavior	Overcharge Behavior
Compressor Inlet Superheat Temperature	High	Low
Condenser Outlet Subcooled Temperature	Low	High
EXV Refrigerant Quality	High	Low
Compressor Pressure Ratio	Low	High

3.2. Refrigerant Charge Regression Model

The refrigerant charge model used in this framework is a linear regression model that uses health indicators as regressor inputs (Figure 3 depicts the current regression model framework). The choice of uzing a linear regression model is to provide a well understood framework to show feasibility of estimating refrigerant charge, where the focus of this paper is to motivate the choice of health indicators based on traditional vehicle testing practices. In addition, the regression model will include a constant regressor term that will represent the nominal refrigerant charge percentage at the operational charge. Each of the other regressor terms are offset to prescribed valves to adjust for this operational refrigerant charge. The regression model output is a percentage of the refrigerant charge that is normalized with respect to the operational charge of the heat pump system.

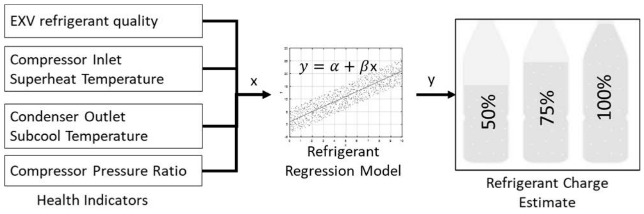

Figure 3. Refrigerant regression model framework.

Training of this regression model employs the use of health indicator data obtained from the refrigerant charge determination tests. Each of the charges added to the system at certain intervals are considered the ground truth refrigerant charge (see Table 2 for details). As refrigerant is added in situ to the heat pump system, significant component transient dynamics are introduced such that the refrigerant system requires sufficient time to settle to a steady state condition. In Figure 4, most of the transient response behaviors occur during the first couple of minutes after refrigerant has been added to the system, such that all health indicators sampled prior to the next refrigerant charge insertion is considered in steady state. In this effort, the health indicators are sampled for training just prior to changes in refrigerant charge.

Table 2. Refrigerant charge events.

Time (min)	Refrigerant Charge Added (%)	Time (min)	Refrigerant Charge Added (%)
0	38	60	78
6	44	66	81
12	50	70	84
17	56	74	88
23	59	78	91
29	63	83	94
36	66	88	97
43	69	92	100
51	72	97	103
55	75		

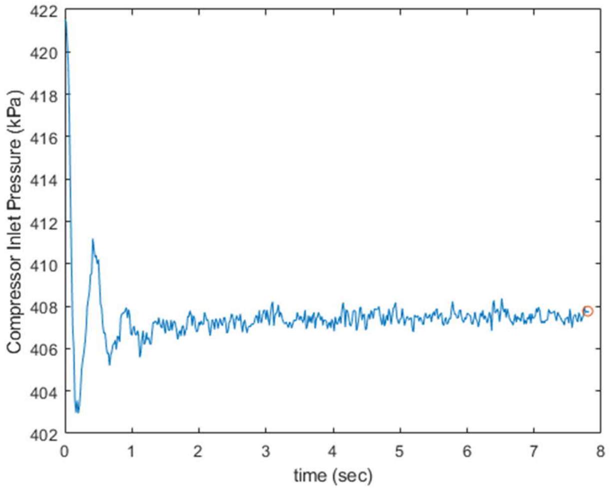

Figure 4. Sample refrigerant insertion time history.

4. EXPERIMENTAL RESULTS

The refrigerant charge determination tests performed in this paper include only cabin cooling tests at 40-degree Celsius ambient conditions. Alternatively, cabin heating charge determination tests are similarly performed with the exception that the controlled air temperature is with respect to the condenser heater instead of the evaporator. Both types of tests still involve monitoring the subcooled temperatures at the discharge side of the condensers.

This refrigerant charge determination test included 19 changes of refrigerant in the heat pump system with time intervals in operation of at least four minutes between charges as denoted in Table 2. Furthermore, the evaporator air temperature and condenser outlet subcooled temperature were monitored throughout the increases in refrigerant charge to ensure that the target air temperature has been reached with a minimum amount of subcooled temperature from the condensers as seen in Figure 5. Refrigerant was inserted past the point where the subcooled temperature has reached a suitable condition while still maintaining a target evaporator air temperature.

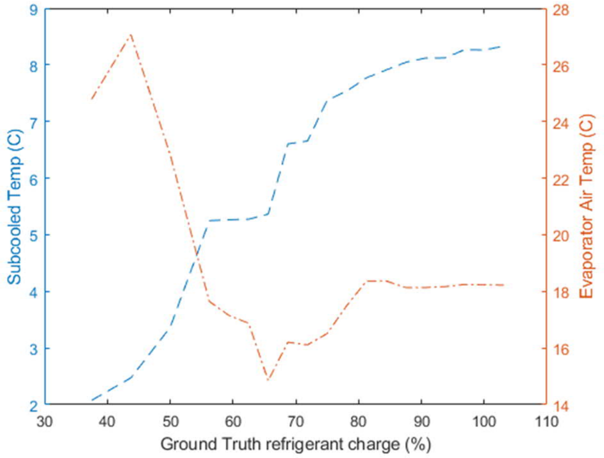

Figure 5. Subcooled temperature and evaporator air temperature vs ground truth refrigerant charge.

In this paper, the performance of the refrigerant charge regression model is evaluated based on estimation accuracy. Figure 6 shows the regression estimate in a box and whisker plot, such that the estimate matches closely to each corresponding ground truth refrigerant. A detailed evaluation of regression error with respect to refrigerant ground truth is seen in Figure 7, such that the mean regression error for any refrigerant level in these tests were bounded within 10% error. Furthermore, in the range of 72% to 103% refrigerant charge, the mean regression errors are bounded to within 5% error.

Note that from the heat pump system performance in Figure 5, healthy refrigerant class is between 85% to 103% based on the heat pump system's ability to achieve a target evaporator air temperature and enough subcooled temperature has developed. In the range of 55% to 85%, while the evaporator air temperature is within target, the subcooled temperature is reduced at each lower refrigerant level, such that degraded subcooled temperature will impact performance of other components within the heat pump system. This range of refrigerant charge is classified as degraded refrigerant. Below the 55% refrigerant charge, the evaporator air temperature is not providing sufficient cooling and subcooled temperatures are insufficiently low, such that prolonged exposure to these conditions can lead to component damage. This range of refrigerant charge is classified as undercharged refrigerant.

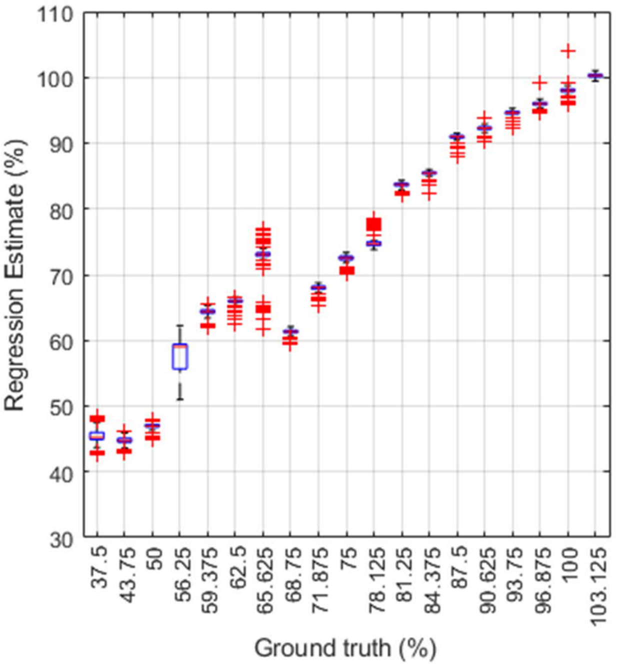

Figure 5. Regression estimate vs ground truth.

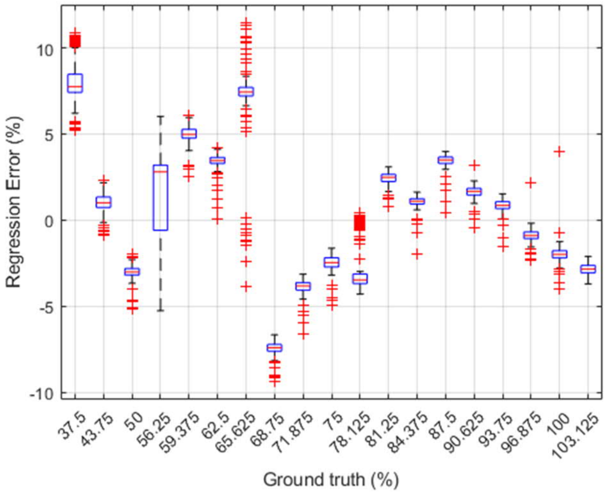

Figure 6. Regression error vs ground truth.

5. CONCLUSION

In this paper, we designed a framework for refrigerant charge estimation exploiting a commonly used process called refrigerant charge determination that is required during the design of a heat pump system. The metrics to evaluate heating or cooling system performance are used as health indicators and are regressors in a refrigerant charge regression model. This model estimates the percentage of refrigerant in the heat pump system under certain operational conditions. Experimental studies of the charge determination tests show that the regression model exhibits estimation errors of less than 10% throughout the range of refrigerant levels tested. Furthermore, the system performance responses of the charge determination tests are used to classify refrigerant classes of healthy, degraded, and undercharge refrigerant levels. In this paper, we acknowledge that more complex modeling methods can potentially extract better estimation performance compared with linear regression techniques, and that future work can be conducted to survey several modeling methods for additional comparisons.

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