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Development and Experimental Evaluation of an Automated Charge Testing Methodology for Domestic Refrigerators

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ABSTRACT

Optimizing the refrigerant charge in a vapor compression cycle can lead to improvements in system performance and energy savings. Manufacturers often perform extensive experimental charge testing under different operating conditions to determine the optimal system charge of a certain product. However, the current de-facto industry standard procedure for performing such evaluation involves repeated charging and evacuating of equipment which is a time-consuming effort. In this work, an automated charge testing device and method were developed to perform a charge optimization for domestic refrigerators with the unit operating. This device consists of a combination of three solenoids to isolate a small calibrated volume of liquid refrigerant. This calibrated volume is typically around 2cc and allows a very small amount of refrigerant, usually less than 5 grams based on the density of liquid, to be charged into a unit with consistent accuracy and repeatability. This work also includes the development of a methodology for utilizing the device including software that automatically operates the device to charge the unit with additional refrigerant, collects and compares performance data, and detects when the optimal charge is reached to end the experiment. With the developed methodology, the entire procedure can be performed without human interaction saving a great amount of time and effort compared to conventional charge testing methods.

1. INTRODUCTION

Proper refrigerant charge inventory is essential to ensure adequate performance of vapor compression equipment. Determining the optimal charge of vapor compression equipment is an important part of the design process for manufacturers. There are two common approaches that are employed to estimate optimal charge level: 1) use of a detailed charge-sensitive system model that is developed and validated for the specific unit and 2) testing of the unit under different charge levels to collect enough data to generate a relationship between performance and charge level. Typical charge testing approaches include repeated evacuation and charging of equipment, requiring significant time and cost. There has been some previous work related to development of automated adjustment of refrigerant charge, but nothing currently exists that can automatically, accurately, and repeatably determine the optimal charge for small refrigerators while they are operating continuously in a laboratory setting.

Lifson, Taras and Dobmeier (2006) patented an invention that was used to add or remove refrigerant from a storage cylinder to the system while a unit operates in the field. It monitors the performance of the cycle based on temperatures and pressures within the system or ambient temperature and decides if the system has the optimal amount of charge. The storage device adds or removes refrigerant based on measured pressure within the system. This device was invented for optimizing the refrigerant charge while the equipment is in operation in the field. It is intended to be a part of the system. It was not designed for accurately determining optimal charge in a laboratory testing environment.

Kang, Luo and Galante (2009) patented an invention for an automatic service device. This invention includes a refrigerant supply tank connected to an air conditioning system by a series of two valves to either add or remove refrigerant from the system. A controller decides whether to add or remove refrigerant from the system based on various system performance indicators, such as evaporator superheat and condenser subcooling, that are determined using an array of temperature and pressure measurements. This invention is intended for technicians in the field to adjust charge levels for an air conditioning unit during service. It is not sufficiently accurate to determine optimal levels in a laboratory setting for small domestic refrigerators.

Patil et. al (2016) developed a methodology for training a virtual refrigerant charge sensor in rooftop units. The virtual refrigerant charge sensors use an empirical model that uses system measurements of suction superheat, liquid-line subcooling and evaporator inlet quality to predict the charge level in the system. During the development and experimentation of the methodology, refrigerant charge addition was controlled automatically using a solenoid valve at the suction side of the system and an electronic weighing scale. The use of a scale worked well due to the relatively large amount of refrigerant in a rooftop unit compared to a typical refrigerator. For a domestic refrigerator, the refrigerant charge is normally less than 200 grams and the charge increment step for determining the charging curve has to be approximately 5 grams or less to generate a meaningful relationship between charge and performance. Due to the small amount of refrigerant for each addition, a typical method of using a scale to control the amount of refrigerant entering the system may not achieve the required level of accuracy.

In this work, a charging device that can accurately and consistently add refrigerant to the system and a method that utilizes the device to automatically determine the optimal charge of the system are developed. The device adds refrigerant in increments of less than 5 grams considering the usually small amount of refrigerant charge in typical refrigerators. This paper describes the automated charging system and includes example results from automatic charge determination experiments performed on domestic refrigerators with both variable-speed and fixed-speed compressor controls.

2. DEVICE HARDWARE DEVELOPMENT

The charging system uses a combination of three solenoid valves to create and isolate a calibrated volume, as shown in **Figure 1**. A refrigerant tank is connected to the device via a liquid line and a vapor return line. *Solenoid 2* is connected to the liquid side of the refrigerant tank while a vapor return line is connected to *solenoid 1*. Once *solenoid 1* and *2* are both open, and *solenoid 3* is closed, liquid refrigerant will flow into the calibrated volume and the vapor will escape through the solenoids. Once the calibrated volume is filled, *solenoid 1 and 2* will close and *solenoid 3* will open to suction. Liquid refrigerant contained in the calibrated volume will be charged into the system. Since during operation, the suction pressure of a normal refrigerator will be significantly lower than the saturation pressure of liquid refrigerant at room temperature, all the liquid refrigerant will be vaporized and charged into system with only vapor refrigerant of equal volume left. This sequence of solenoid valve operation is termed "*a pulse*" for this device. With the calibrated volume ensuring consistency, each pulse should charge the same amount of refrigerant into the system.

This approach uses a constant calibrated volume to promote accuracy and consistency in the charging process since it would be challenging to accurately measure and directly control the weight of refrigerant using a scale for this application. While the volume is fixed in this approach, the varying density of the refrigerant must be addressed. Ensuring that the calibrated volume is filled entirely with liquid is imperative to the performance of the device. In addition, the effect of temperature on density should be accounted for.

To ensure the calibrated volume is filled with liquid, a vapor return line is required. The calibrated volume is around 2cc and the diameter of the tubes used are 1/8" copper tube. If only two solenoids were used to connect the refrigerant tank and the unit, the remaining vapor in the calibrated volume after each pulse would be trapped in the device and prevent liquid from filling the entire calibrated volume. Using a vapor return line with the geometry shown in **Figure 1**, the vapor lock problem can be effectively solved and the consistency of the device can be ensured. A photo of the actual three-solenoid device attaching to the charging port of the system is shown in **Figure 2.**

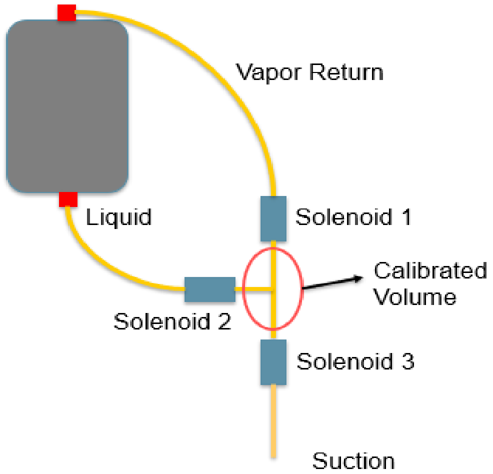

Figure 1: Schematic of the three-solenoid valve device

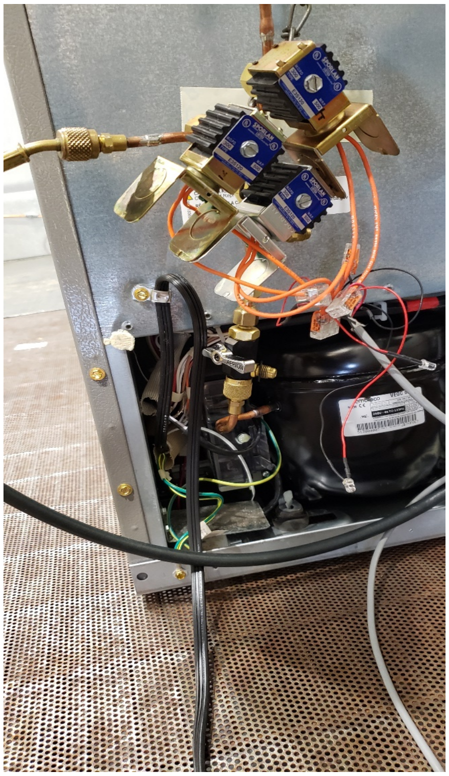

Figure 2 Photo of the three-solenoid valve device and calibrated volume attached to the charging port of a system.

In order to account for the volume in the lines between *solenoid 3* and the unit, an experiment was designed to determine and calibrate the actual amount of liquid refrigerant charged into the unit. An evacuated tank is connected to downstream of *solenoid 3* and refrigerant is charged into this tank. The tank is kept in an ice bath to further increase the pressure difference once some refrigerant has entered the tank. The experimental set up and illustration is as shown in **Figure 3**. After pulses, the hand valve on the tank is closed and the tank is taken for weight measurement. Then the tank is evacuated again for a next set of experiments. For a single pulse, some of the refrigerant will be lost while filling up the evacuated lines connecting to the device. For two consecutive pulses, the second pulse should not have this problem and all the refrigerant should be charged into the tank. By finding the difference between the weight addition of first and second pulses, an accurate estimate of the refrigerant charged for each pulse can be determined and the amount lost through the lines can be determined as well. This experiment can further validate the volume calibration as well as account for the vapor weight loss in the lines in the actual experiment. The length of connection in this experiment is similar to that used for the refrigerator charging setup.

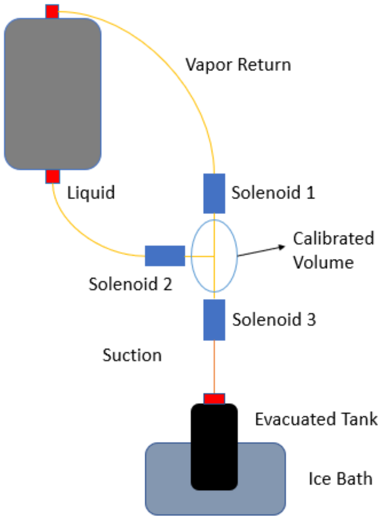

Figure 3: Schematic of experimental setup for volume calibration

3. CONTROL AND SOFTWARE LOGIC

The developed device requires appropriate control logic and software to enable automated operation. Besides controlling the solenoid valves, an algorithm was implemented to automatically determine whether the total amount of refrigerant in the system reaches an optimal level. Thus, the system uses online measurements to evaluate the performance of the refrigerator throughout the testing period. The performance indicator used in this approach is power consumption. While other indicators such as the COP of the system could be used, power consumption is equivalent to COP when the refrigerator interior is maintained at the desired set point cabinet temperature.

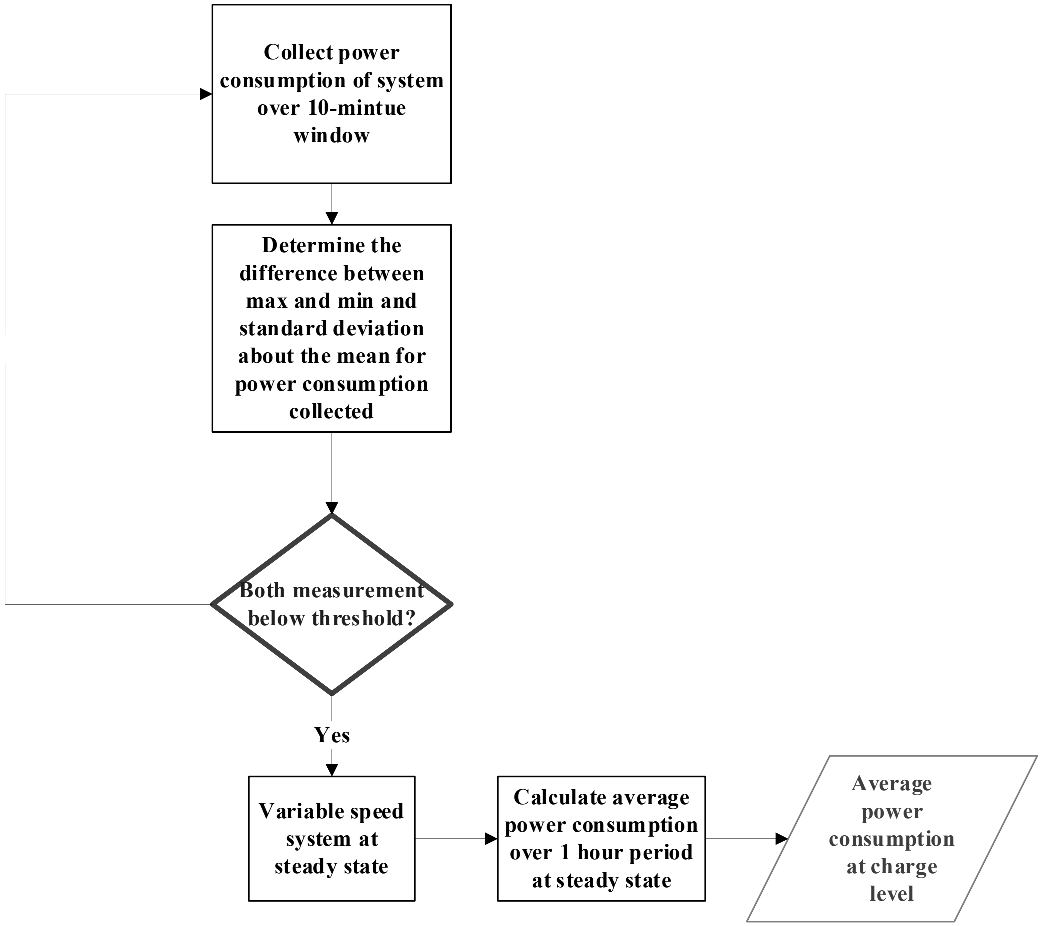

Figure 4 Variable-speed unit steady-state detector and data collection process flowchart

The process of determining steady-state operation for a system with a variable-speed compressor is shown in **Figure 4**. Steady-state operation is determined by analyzing the power consumption over a moving window of 10 minutes using a 1-second sampling interval. The difference between the maximum and minimum values within the window along with the standard deviation about the mean are compared to a threshold value. When both indicators are within the threshold, the system is considered to be at steady-state. For a unit with a variable-speed compressor, the power consumption determined at steady-state is directly used in the process of determining the charge level that minimizes power consumption (maximizes COP) .

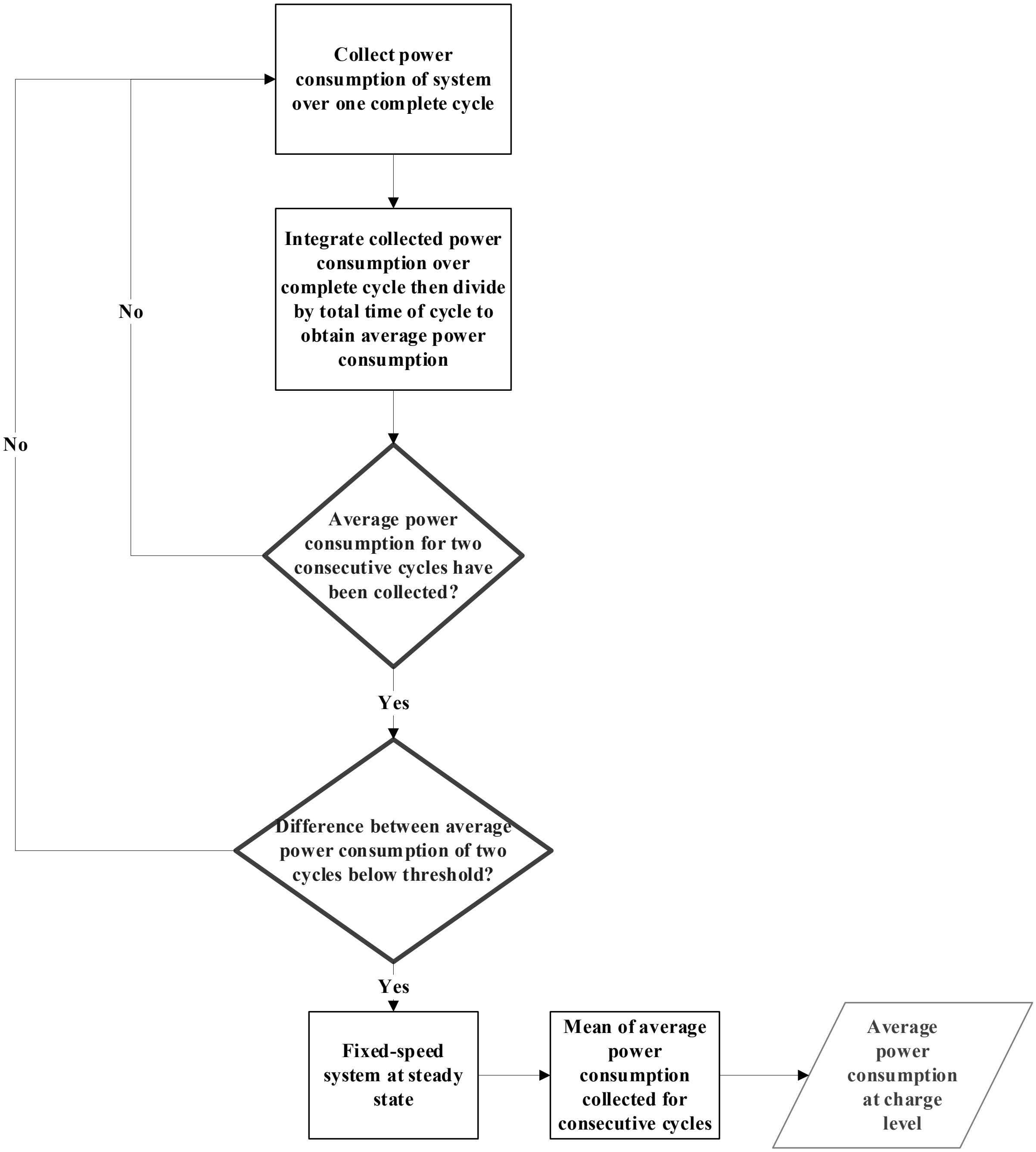

Figure 5 Fixed-speed unit steady-state detector and data collection process flowchart

If the unit has a fixed-speed compressor with on/off control, the power consumption of the unit needs to be determined for the entire cycle for an accurate and meaningful comparison at different charge levels. The process for determining a fix-speed system at steady-state is shown in **Figure 5**. The integral of power consumption over a complete cycle including when the compressor is off and on is first calculated. This integral of power consumption is then divided by the total time of this cycle to obtain the average power consumption. Average power consumption for successive on/off cycles are compared to identify quasi-steady-state behavior and then steady results are used in the process of determining the charge level that minimizes power consumption.

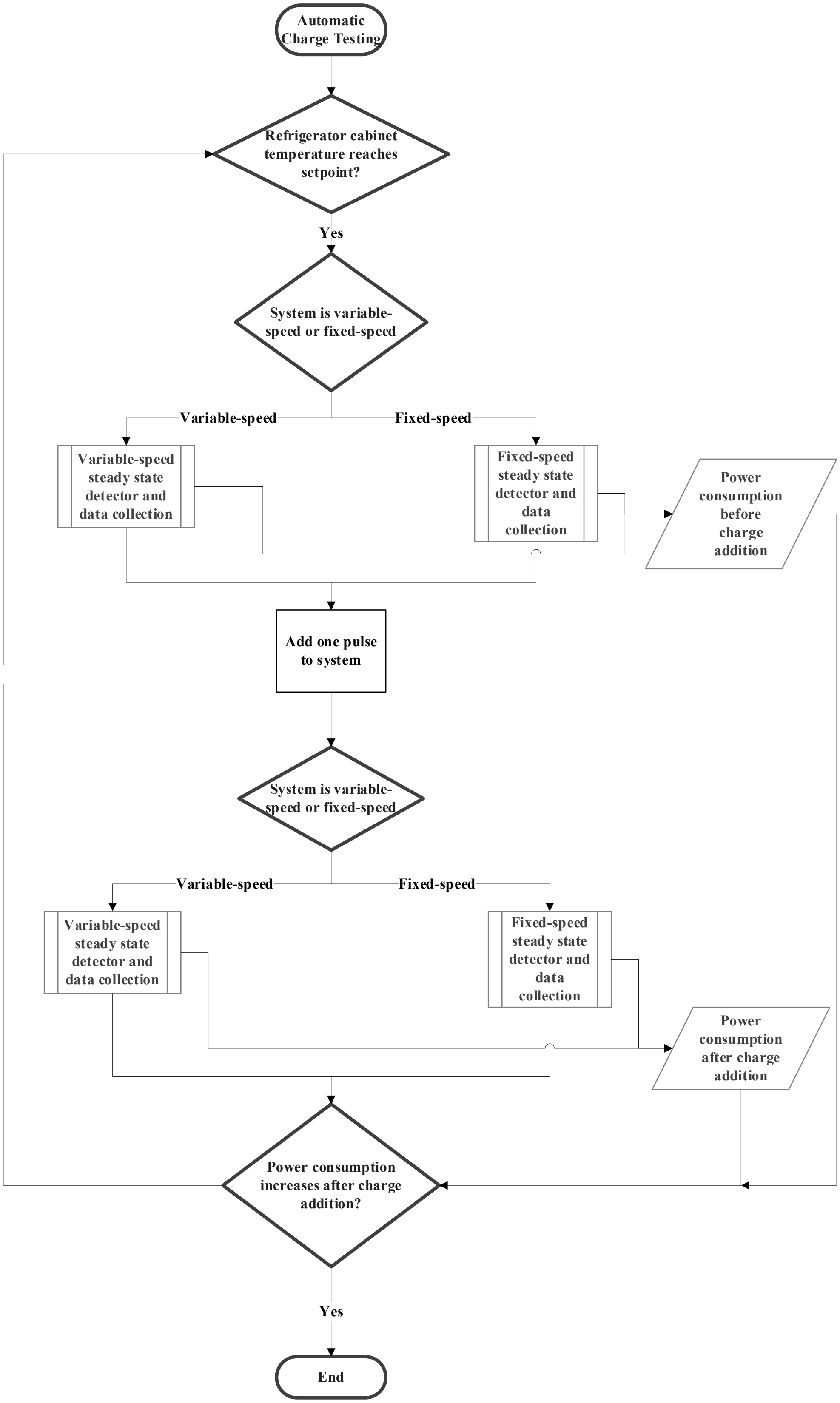

Figure 6 Automatic charge testing software flowchart

The complete software logic for automatic charge testing methodology is shown in **Figure 6**. The software uses logic described in **Figure 4** and **Figure 5** to determine whether system is at steady-state for both fixed-speed and variable-speed systems. The charge testing should only start once the refrigerator cabinet temperature has reached setpoint. Once cabinet temperature is at setpoint, the software will use the appropriate steady-state detector to collect power consumption data of the unit at steady-state.

The performance of the system should improve as the refrigerant charge increases from the low initial charge towards the optimal charge. Furthermore, as the charge increases beyond an optimal level, the performance of the unit should deteriorate with charge. Using this logic, the system software performs comparisons of the steady-state power consumption after each pulse of refrigerant with that of the previous charge level. If the steady-state performance of the system is still increasing, then the process of increasing charge continues. However, if the steady-state performance starts to decrease, then the optimal charge is reached and charge testing is stopped.

4. EXPERIMENTAL RESULTS

4.1 Unit with Variable Speed Control

An implementation of the automated charging systems was first tested for a variable speed R134a domestic refrigerator. Before using the device to charge the unit and carry out automatic charge testing, an experiment calibrating the weight of refrigerant per pulse described in the previous section was performed. Experimental results are shown in **Table 1** for three sets of experiments. For each experimental set, the device performed one, two and three pulses into the evacuated tank separately, and the weight of the tank after the pulses was measured. From the experimental results, the first pulse corresponded to approximately 4.23 grams of refrigerant while the second and third pulses were both 4.50 grams. This shows that the lines before the connection to the device and the unit hold around 0.27 grams of refrigerant as vapor. Furthermore, this experiment showed that the device charges 4.50 grams of R134a per pulse.

It should be noted that during the development of the device, a more direct determination of the charging volume was difficult. Since the charging volume is only around 2cc, a typical method of using water or another liquid at atmospheric pressure to fill the volume did not work because the surface tension of the liquid was sufficient to hold up the liquid against its weight and prevent it from filling the volume. Therefore, the charge per pulse data was used as a basis for the automatic charge testing.

Table 1: Cumulative Mass Injected into Tank

Pulse #	Cumulative Mass Injected (grams) into Tank		
	One Pulse	Two Pulses	Three Pulses
1	4.2	8.7	13.2
2	4.3	8.8	13.2
3	4.3	8.7	13.3
Mean (grams)	4.23	8.73	13.23
Addition (grams)	4.23	4.50	4.50

Figure 4 shows a plot of steady-state power consumption as a function of refrigerant charge level for a 26 cubic foot (736.24 liter) R134a refrigerator having a variable-speed compressor. The nominal charge for the refrigerator is 155 grams (5.5 oz). The plot shows the expected trend of increasing system performance as the refrigerant charge level approaches the optimal charge. Since the cabinet temperature remained constant at each charge level, the power consumption decreased as the charge approached the optimum. Each pulse added 4.5 grams of refrigerant to the unit and the software collected the steady-state data at each charge level. As data is collected, the software decides whether system is at optimal charge to end the experiment or not.

Although **Figure 7** illustrates the process for determining the optimal refrigerant charge, the experiment was ended prematurely because of the limited time available for the human supervision that was needed for this trial run. The system was subsequently fully automated and could be operated without human supervision.

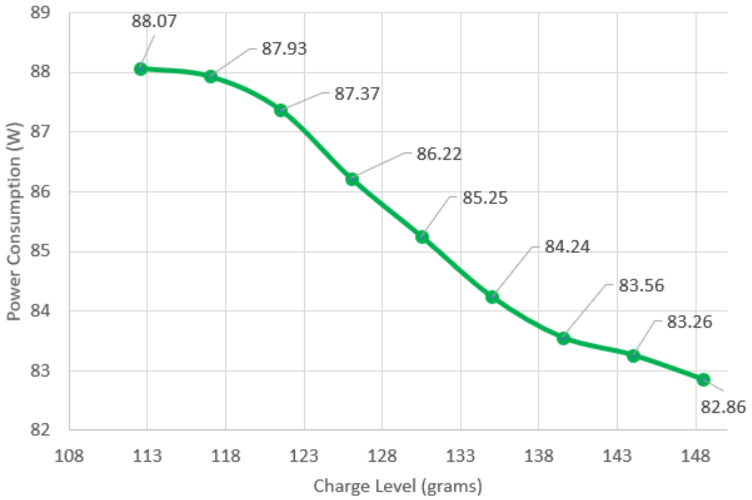

Figure 7: Power Consumption versus refrigerant charge for R134a unit

4.2 Unit with on/off control

The device and methodology were also tested on a domestic refrigerator having on/off compressor controls running R600a (isobutane). **Figure 8** shows the average power consumption for each complete on/off cycle as a function of refrigerant charge for a 22 cubic foot (622.97 liter) R600a refrigerator having a fixed-speed compressor with on/off control. For detection of steady-state operation with on/off control, the software detection compares data for two complete cycles. This particular unit has a nominal isobutane charge level of 58.5 grams. The charge amount for each pulse was determined using the calibration procedure to be 1.6 grams per pulse and this data was used in the charge determination experiment. As can be seen in **Figure 8**, the optimal charge occurs near the nominal charge at a value of about 57 grams. The red line in **Figure 8** is a curve fit determined from the data.

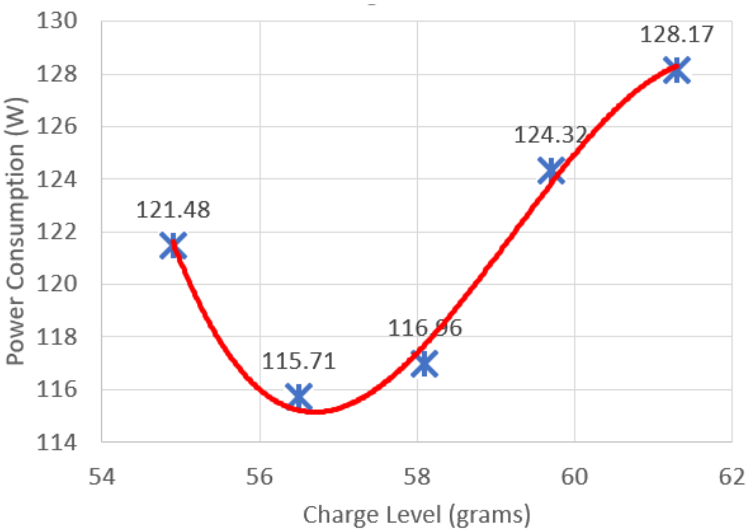

Figure 8: Power Consumption versus refrigerant charge for Isobutane Unit

Figure 9 shows time variation of power consumption during a portion of the automated charge testing. The power consumption is shown in red, while the charge level is in blue. The results show two complete cycles at a single charge level along with transitions between charge levels. Since the unit has a fixed speed compressor with on/off control, the performance of the unit at this charge level is determined by the average power consumption of one complete cycle, calculated by dividing the integral of power consumption over the time of the entire cycle.

Figure 9: Power consumption versus time of the Isobutane unit at a particular charge level

5. CONCLUSIONS

An automatic charging device and methodology were developed that can automatically add refrigerant charge, evaluate performance, and determine optimal refrigerant charge. The charging device pulses a fixed volume of liquid refrigerant while the unit is in operation. The intervals between pulses are dictated by a determination of steady-state performance at each charge level. The overall approach is much faster than current methods for determining optimal charge that involve evacuating, charging, and testing performance for individual charge levels.

Future work should be done to improve the accuracy of the device. In particular, the T-shaped calibrated volume device was constructed by soldering small copper pipes and its volume was only inferred from calibration experiments. A device with a prescribed volume could be manufactured using 3D metal printing. Additional work should also be carried out to more thoroughly validate the methodology for different refrigerators and refrigerants.

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