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Bo Shen
Purdue University

James E. Braun
Purdue University

Eckhard A. Groll
Purdue University

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Validation of Methods for Tuning System Charge Predictions in Unitary Equipment

Bo Shen*, James E. Braun, Eckhard A. Groll
Purdue University
Ray W. Herrick Laboratories
140 S. Intramural Drive
West Lafayette, IN 47907, USA
*Corresponding Author, e-mail: shen1@purdue.edu

Abstract

To simulate the performance of unitary air conditioning and heat pumping equipment at design conditions, the amount of subcooling leaving the condenser is typically specified at design conditions and the required refrigerant charge necessary to achieve that subcooling is computed. For off-design conditions, the charge is fixed at the value determined for the design conditions and the amount of subcooling is estimated. Previous studies have shown that existing models do not predict the effect of off-design charge very well, even when tuned at design conditions. Four factors that cause the inaccuracies in charge prediction are identified in this paper, which are the unaccounted liquid volumes in the condenser, refrigerant dissolved in the compressor lubricant, inaccurate void fraction models, and an inaccurate estimate of the subcooled liquid length. Some of these factors lead to constant errors, while the others lead to errors that change with operating conditions. This paper presents a method for tuning parameters associated with a charge correction equation that requires data for two operating points. The approach uses a semi-empirical solubility relationship to predict the refrigerant dissolved in the lubricant, associates the variable charge errors with the subcooled liquid length, and considers all the other errors as a constant offset. The ability of a system model to predict off-design charge effects is significantly improved through the use of this tuning approach. This was confirmed though comparisons with measured results and predictions obtained from existing tuning approaches The tuning approach was tested for multiple units and different operating conditions.

1. Introduction

Accurate charge inventory modeling requires very specific knowledge of internal volumes, which are often not available. Therefore, refrigerant charge is typically tuned at a single point in order to allow predictions at off-design conditions. Generally, a tuning method involves adjusting some system parameters to make the simulation results match the measured performance at an operating condition, usually a design condition. Thus, the tuned parameters account for some uncertain system or device information. The tuning method should have some physical meaning; otherwise it will not extrapolate well to other operating conditions. An accurate performance prediction at off-design operating conditions must be based on a well-known system and an accurate simulation at design conditions. In this case, the tuning methods are more indispensable at off-design conditions.

Leroy et al. (2000) conducted a comprehensive simulation study of ten air conditioning units with the public-domain simulation model, PUREZ. In this paper, refrigerant charge was tuned in order to account for inaccuracies associated with the void fraction models and unknown system inner volumes. An inaccurate charge prediction may cause a phenomenon called “charge saturation”, where calculated cooling capacity and compressor consumption become insensitive to increases in system charge. A simple charge tuning method proposed by Leroy et al (2000) consisted of adjusting the system charge to match the simulated cooling capacity and measured value at one design operating condition. Another charge tuning approach evaluated by Leroy et al. (2000) involved tuning the air-side and refrigerant-side heat transfer coefficients of both the condenser and evaporator proportionally with a single multiplier, while the charge was tuned simultaneously, to match the measured cooling capacity and superheat degree together. Results of the model predictions using the tuned design charge and heat transfer coefficients were compared with measured performance as a function of charge level. For the off-design charge simulations, two different approaches were employed for adjusting the charge levels: 1) the tuned charge level was adjusted by the same absolute quantity as was done in the laboratory tests, and 2) the tuned charge level was adjusted by the same percentage as that associated with the laboratory tests. Both approaches did not properly account for the effect of charge on cooling capacity and compressor power. The authors suggested that tuning the system charge at one design condition was not sufficient to allow good performance predictions for other refrigerant charges.

Tuning the system charge by matching the cooling capacity at a single point does not properly account for the physics associated with the unaccounted charge. Harms et al (2002) suggested that subcooling is a much better criteria for tuning charge than cooling capacity. However, tuning the charge to match subcooling at a single point still doesn't give good results at off-design charges. As a result, a semi-empirical model is introduced in the current paper that characterizes the missing charge in terms of the operating conditions and two parameters that can be tuned using measurements at two points. This method provides excellent extrapolation of the effects of charge at off-design.

The simulation results presented in this paper were obtained using ACMODEL (see Rossi et al (1995), LeRoy et al (1997) and Harms et al (2002)). Thirteen void fraction models are incorporated within ACMODEL. For most of the results presented in this paper, the Baroczy (1965) model was used because it was recommended by Harms et al (2002). With respect to the compressor model, ACMODEL accepts ARI polynomial compressor equations. The compressor mass flow prediction is coupled with a simple correction for varying superheats. The mass flow is corrected by the ratio of the calculated suction gas density to standard suction gas density corresponding to the ARI standard test condition. With respect to the heat exchanger analysis, each tube is separated into small segments. The heat transfer is calculated with an effectiveness-NTU method. In addition, the heat transfer and pressure drop correlations of micro-fin tubes and specially configured airside fins are applied. This program can model multiple-row condenser and evaporator coils, and the airflow is assumed to mix after flowing across each row. The comprehensive method proposed by Braun et al. (1989) is used to model wet coils. ACMODEL can simulate both fixed area and adjustable area expansion devices. For fixed area expansion devices, the model of Kim and O'Neal et al (1994) is used. For adjustable area expansion devices, the measured superheat degree is specified directly.

ACMODEL has a charge tuning and heat transfer tuning mode as indicated in Figure 1. In ACMODEL's tuning mode, it is necessary to have design point measurements for suction pressure, superheat degree, discharge pressure and subcooling degree, and air-side boundary conditions. First, with given superheat degree, suction pressure and discharge pressure, the compressor model predicts the mass flow rate and discharge temperature. Then, the discharge pressure and temperature, and the mass flow rate are inlet conditions to the condenser model, while the suction pressure and temperature, and mass flow rate are inlet conditions to the evaporator model. Next, the air-side heat transfer coefficients are tuned with separate multipliers for evaporator and condenser to give an inlet enthalpy to the evaporator and outlet enthalpy from the condenser that match the value provided by the given degree of subcooling. After these calculations, the system charge is predicted by integration of the density over all internal volumes. The deviation between the actual charge and the simulated charge is used to obtain an unaccounted liquid volume in the liquid line. The unaccounted liquid volume and the heat transfer multipliers will be used as tuning factors for other cases. Tuning charge by an unaccounted liquid volume is similar to the idea of tuning charge by an absolute quantity, since the refrigerant liquid density is fairly constant. This is a traditional single point tuning method.

2. Description of equipment and laboratory tests

Most of the experimental results presented in this paper were obtained from a 2.5-ton R-22 split system (see LeRoy et al. (2000)), and a 5-ton R-22 packaged system (see Harms et al. (2002)) tested within the psychrometric rooms at the Herrick Labs. Both the units used a TxV expansion device. The 2.5-ton split system was investigated under standard operating condition A with varied charges, and the 5-tonb packaged system was investigated under conditions of A, B, C and HT with varied charges. Condition A, B, C and HT have indoor dry bulb temperature 80 °F. Condition A has indoor wet bulb temperature 67°F, and outdoor dry bulb temperature 95 °F. Condition B has indoor wet bulb temperature 67 °F, and outdoor dry bulb temperature 82 °F. Condition C has indoor wet bulb temperature less than 57 °F, and outdoor dry bulb temperature 82 °F. Condition HT has indoor wet bulb temperature less than 57°F, and outdoor dry bulb temperature 120 °F.

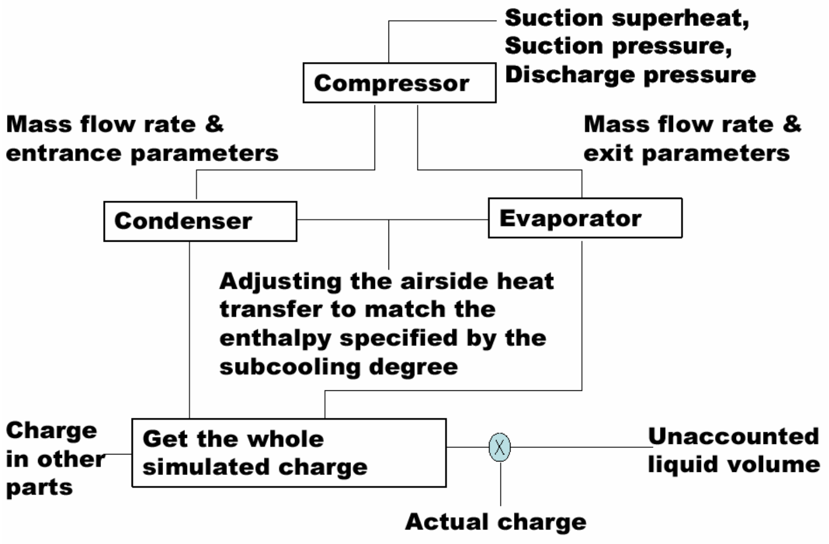

Figure 1: Logic of single-point charge tuning method

3. Two-point charge tuning method

Four primary factors cause errors in predicting charge inventory:

1. Inaccurate void fraction models: the actual void fraction depends upon the flow pattern, but most of the void fraction models were developed for a single flow pattern.
2. Unaccounted inner volumes: it is difficult to model all of the inner volumes, especially with respect to units that are tested in laboratories, since there are additional instruments installed. The most important inner volumes are located in the subcooled region, because of higher refrigerant density. Even small unaccounted for volumes in the subcooled region have a significant impact on the charge inventory.
3. Refrigerant dissolved in the compressor lubricant: the refrigerant dissolved in the lubricant can be as much as 10% of the total charge in a system with a reciprocating compressor.
4. Inaccurate heat transfer: an inaccurate ratio between single-phase and two-phase heat transfer volumes causes errors in charge predictions, since it impacts the liquid length in the condenser.

Figure 2 shows the effect of void fraction correlation on charge predictions for a 3.5-ton packaged unit (see Rossi et al (1995)). The differences are as large as 30%. However, the deviations are nearly constant. This suggests that a constant tuning factor can account for errors in void fractions. Similarly, unaccounted inner volumes in the subcooled region should be correctable with a constant factor. The amount of refrigerant that is dissolved in oil depends upon the operating conditions through the effect on equilibrium concentrations. Most of the oil resides in the compressor. Consider the solubility equation from Martz et al (1996) for R-22 and polyolester oil applied to the compressor oil with a low-side compressor shell.

$$x = \frac{P}{773 + 18.5T + 0.525T^2} \tag{1}$$

where P [kPa] is the suction pressure, T [°C] is the oil temperature evaluated at the compressor temperature, and x is the refrigerant solubility ratio of the refrigerant-oil mixture.

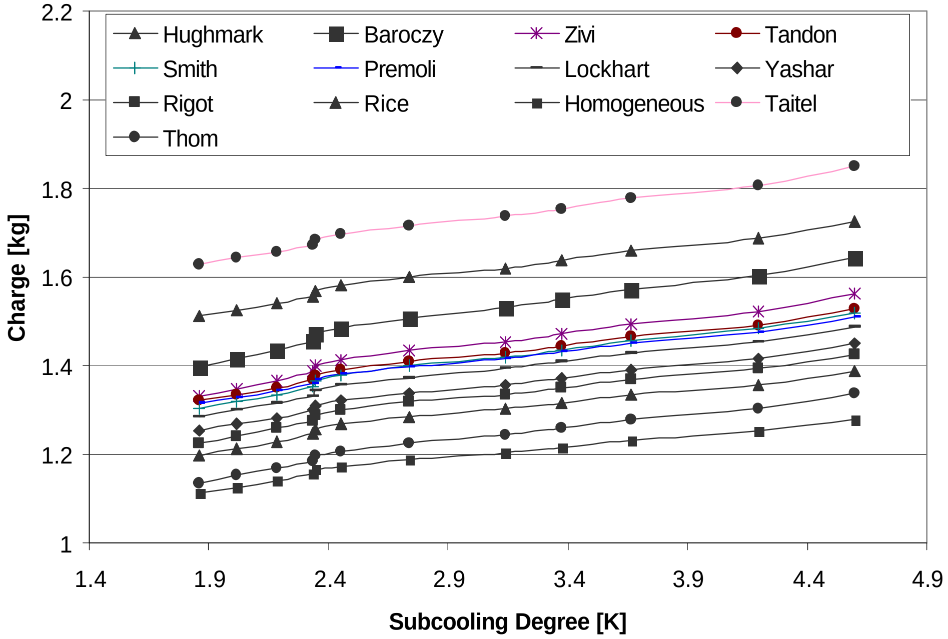

Figure 2: System charge predictions for different void fraction models applied to a 3.5-ton packaged unit

As mentioned, inaccurate liquid phase heat transfer causes errors in charge predictions, since it impacts the liquid length in the condenser. This factor would lead to errors that change with operating conditions. The dependence on liquid length is a significant effect and will be considered for a two-point tuning method.

The new two-point charge tuning method requires data for two operating points. The approach is intended to use a semi-empirical solubility relationship like equation 1 to predict the refrigerant dissolved in the lubricant, associate the variable charge errors with the subcooled liquid length, and consider all the other errors as a constant error.

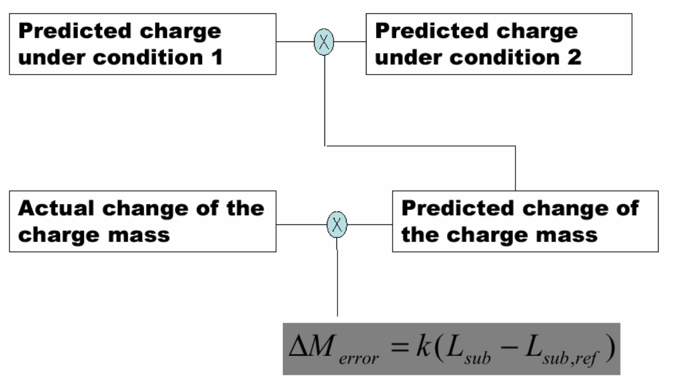

Figure 3: Logic of two-point charge tuning method (associate the variable charge errors to liquid length)

Equation 2 and Figure 3 present the logic of the two-point charge tuning method,

$$M_{tuned} = M_{untuned} + r_{ll} V_{tune,ref} + M_{oil,dissolved} + k(L_{sub} - L_{sub,ref}) \tag{2}$$

In equation 2, $M_{untuned}$ is the predicted refrigerant charge determined by integration of the density over all internal volumes. $M_{oil,dissolved}$ is an estimate of the mass of refrigerant dissolved in oil using a solubility equation, as shown in equation 3.

$$M_{oil,dissolved} = M_{oil} \frac{x}{1-x} \tag{3}$$

where M_{oil} is the oil inside the compressor shell. In addition, r_{ll} and $V_{tune,ref}$ are the liquid density and an additional volume that are assumed to be in the liquid line following the condenser. $L_{sub,ref}$ is a liquid length at a rated operating condition. Both $V_{tune,ref}$ and $L_{sub,ref}$ are determined at the same rated condition (Condition 1). k is a tuning constant accounting for the variable errors due to the liquid length. L_{sub} is a liquid length in condenser at any operating condition. M_{tuned} is the final charge prediction after tuning. Two tuning factors need to be determined in equation 2, $V_{tune,ref}$ and k, which requires two operating conditions for tuning. This tuning method was implemented within the ACMODEL tuning scheme.

For the first step of the two-point tuning method, after the air side heat transfers are adjusted to have the predicted subcooling degree match the measured value at a rated condition (Condition 1), the heat transfer multipliers, $L_{sub,ref}$, r_{ll} , $M_{oil,dissolved}$, untuned predicted charge $M_{untuned}$ are obtained at the condition. Then the unaccounted volume $V_{tune,ref}$ is adjusted so that the final predicted charge M_{tuned} matches the actual value at Condition 1.

In the next step, the assumed heat transfer multipliers and the unaccounted liquid volume $V_{tune,ref}$, the reference liquid length $L_{sub,ref}$ determined at Condition 1 are used in the system model. With the measured data at another condition (Condition 2), the new liquid length L_{sub} , $M_{oil,dissolved}$, untuned predicted charge $M_{untuned}$ and $r_{ll}V_{tune,ref}$ are obtained. Then, the proportionality constant k is adjusted so that the calculated charge M_{tuned} matches the measured value at Condition 2. After these two steps, the tuning factors $V_{tune,ref}$ and k in equation 1 obtained using two data points for a test unit can be used to predict refrigerant charge at other charge levels and operating conditions.

Figure 4 presents the charge mass as a function of subcooling degree of the 5-ton packaged system under condition A. With the traditional single-point tuning method, the charge model is tuned at the operating point **a**. With the new two-point tuning method, the charge model is tuned at operating points **a** and **b**. The new tuning method improves the charge prediction significantly. The predicted charge almost exactly matches the measured charge over a range of different subcooling degrees.

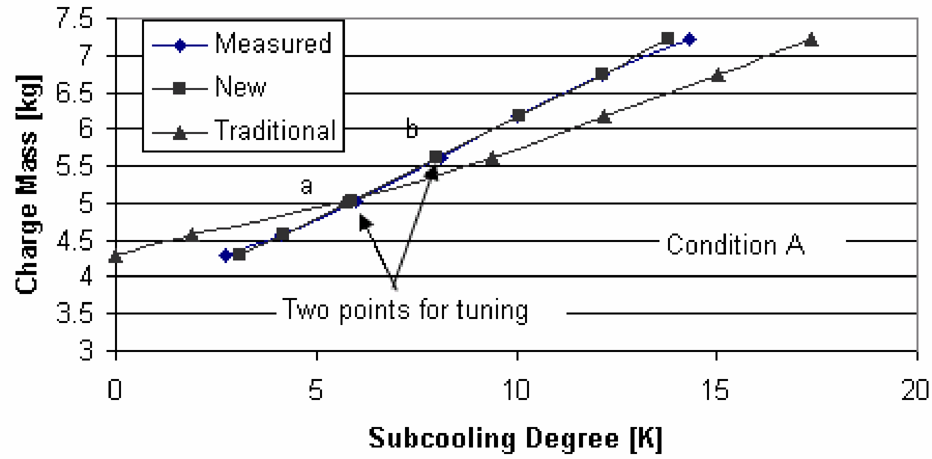

Figure 4: Charge mass as a function of subcooling degree in a 5-ton packaged unit under Condition A

A good tuning method should work well for multiple working conditions and units. Figures 5 and 6 present charge mass as a function of subcooling degree for the 5-ton packaged system under Condition C and Condition HT. The tuning factors of the single-point tuning method and the two-point tuning method were the same as obtained for Figure 4, i.e. no additional tuning was performed for Condition C and HT.

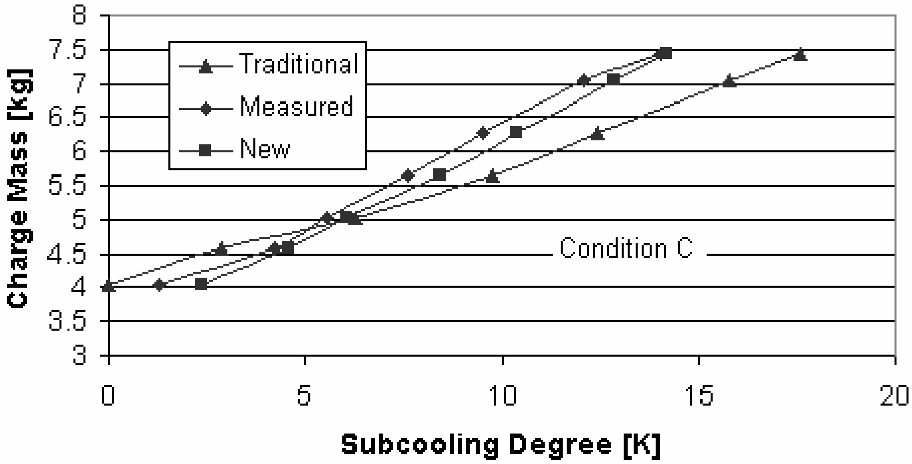

Figure 5: Charge mass as a function of subcooling degree in a 5-ton packaged unit under Condition C

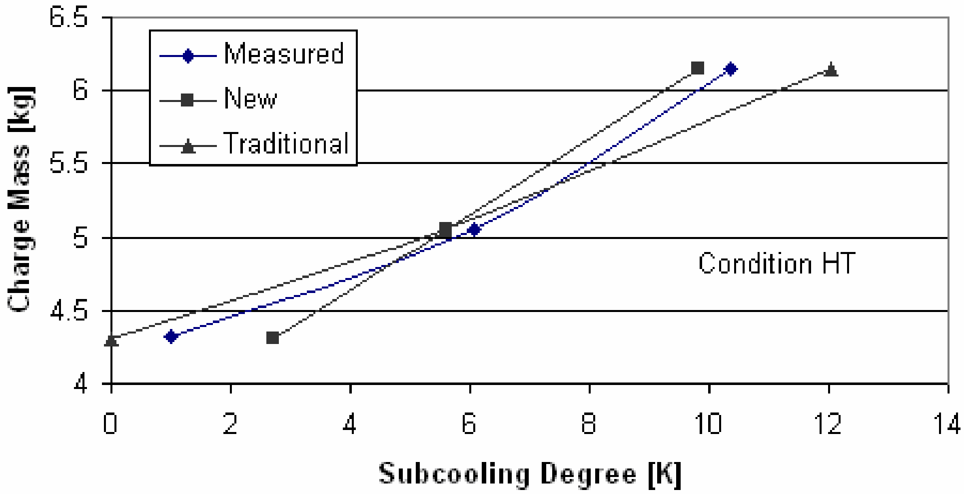

Figure 6: Charge mass as a function of subcooling degree in a 5-ton packaged unit under Condition HT

As shown in Figures 5 and 6, the two-point tuning method works well for different operating conditions when tuned at a single operating condition and two charge levels. The two-point tuning method improves the charge level predictions when compared to the single-point tuning method. The largest charge deviation at Operating Condition C reduced from 10% to 3%, and the largest charge deviation at Operating Condition HT reduced from 6% to 3%. The two-point tuning method should also work when tuned at the same charge level but two different operating conditions. In this case, inaccurate liquid length calculations lead to errors that change with operating conditions, even using the same charge. However, the effect of this method may be more apparent when tuned at different charge levels and the same operating condition.

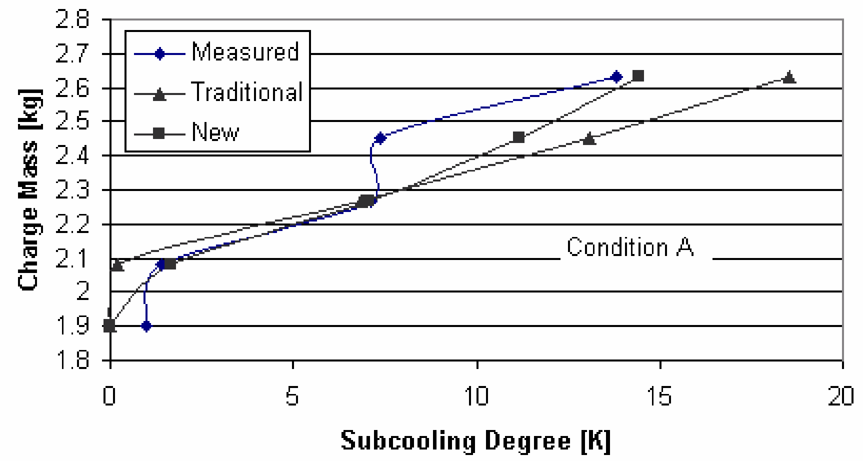

Figure 7: Charge mass as a function of subcooling degree in a 2.5-ton split unit under Condition A

Figure 7 presents charge mass as a function of subcooling degree for the 2.5-ton split unit under condition A. The two-point tuning method was better than the traditional single-point tuning method for predicting charge, especially at very high and very low subcooling degrees.

Improved charge mass predictions lead to better system performance predictions. Figure 8 shows the total cooling capacity as a function of charge mass for the 2.5-ton split system under condition A. In comparison to the traditional method, the two-point charge tuning method improves the cooling capacity prediction with the largest deviation reduced from 4.07% to 2.40%.

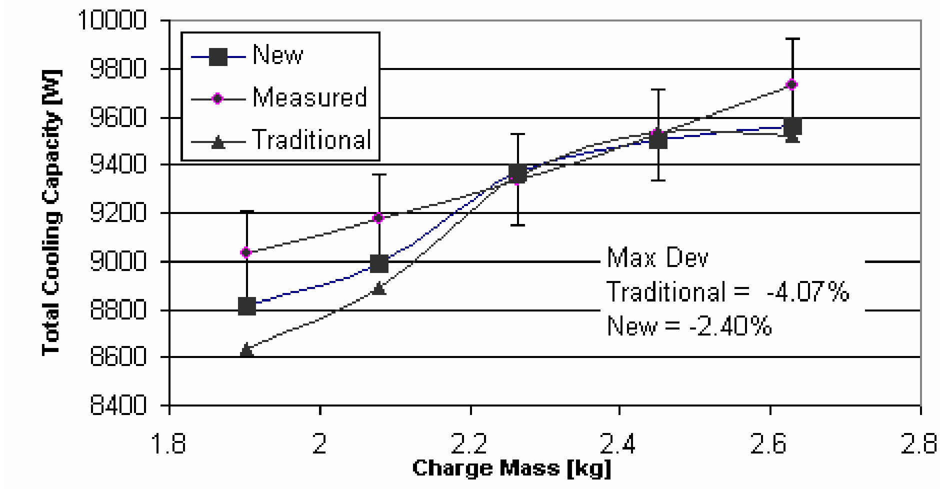

Figure 8: Cooling capacity as a function of charge mass in a 2.5-ton split unit under Condition A

4. Conclusions

The traditional methods for tuning refrigerant charge use a single design point, but do not extrapolate well for off-design charges. This paper presented a two-point tuning approach that more accurately accounts for missing inner volumes, the refrigerant dissolved in oil, and the variable charge errors due to the subcooled liquid length. The ability of a system model to predict off-design charge effects is significantly improved through the use of this tuning approach. The tuning approach was tested for multiple units and different operating conditions.

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