Differential Mass Measurement Scale for Measuring Refrigerant Charge and Oil Retention of Round Tube Plate Fin Heat Exchangers (ASHRAE RP-1785)

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ABSTRACT

During the product development process of split-system air-conditioning units, simulation models are widely used by manufacturers to predict equipment performance. Model-based development allows manufacturers to reduce the number of experiments prior to product launch, reducing product development cycle time and cost. However, the current models struggle to predict performance for reversible heat pump systems because of inaccurate predictions of refrigerant charge and oil retention. This is due to a lack of validation data for R410A charge models. This study provides high-quality reference data for refrigerant and oil charge measurements in residential fin-tube heat exchangers operating with R410A. This high-quality reference data will allow tuning of simulation models to improve charge prediction accuracy. As a result, the data will enable enhanced simulation model development with better charge and performance prediction capabilities, reducing product development cost for our industry. A key component, the Differential Mass Measurement Scale (DMMS) with 0.006% of relative accuracy of 49.9 kg tare weight of a heat exchanger test module, to implement this method is presented.

1. INTRODUCTION

Refrigerant charge plays a major role in determining operating efficiency and behavior of air-conditioning and refrigeration systems (ACRS). It is critical to know the precise refrigerant charge in specific components of a system under a specific operating condition. During the system operation, the refrigerant charge inventory primarily migrates between the evaporator and the condenser. Knowledge of refrigerant charge in heat exchangers is therefore critical to minimize input power and maximize capacity of ACRS (Poggi *et al.*, 2008). Simulation programs employ void fraction correlations to predict refrigerant charge in ACRS (Jiang *et al.*, 2006). A fair number of the void fraction models (*e.g.* Hughmark (1962), Taitel and Dukler (1976), and Cioncolini and Thome (2012)) depend on empirical correlations including dimensionless parameters acquired from the experimental data. For this reason, a high-fidelity experimental validation database is necessary for the improvement of the charge simulation's accuracy. The validation is accomplished by comparing the measured charge masses with those predicted by the simulation.

Most charge measurement methods can be divided into two classes. The first is the sampling measurement method (SM), which isolates the charge of a sample (*e.g.* heat exchanger) within a very short period followed by determination of the charge in the sample through differential weighing or similar method. The second method is the online measurement method (OM), where the charge is directly measured in-situ either indirectly by transient measurement and integration of inlet and outlet mass flows or directly by weighing the change of mass of a system or component(s). Both have been studied in the literature and each have method has advantages that our work attempts to combine.

Peuker (2011) proposed the SM utilizing an evacuated sampling cylinder, a flushing method, and a mix and sample method. The oil and refrigerant charge in the system are recovered by employing an evacuated sampling cylinder placed in liquid nitrogen as a recovery pump. The refrigerant and oil charge are determined respectively by removing the refrigerant and weighing the cylinder. The flushing method and the mix and sample method are employed for determining oil charge. His flushing method utilizes a solvent to flush and remove oil from the test section. This method has an accuracy of 1.4 g (1.4% of the 100 g of oil charge) with multiple consecutive flushes. The mix and sample method requires to fill refrigerant and circulate it inside the section in which oil remains to remove the oil from the section. The mass of oil is then calculated by measuring the well-mixed oil concentration. The accuracy of this method is 0.1 g (0.6% of the 22 g oil of charge). This method requires at least 12 hours of testing time per data point but is stated to provide an accuracy of 0.3% (4.2 g) of the 1,245 g charge.

As an early example for an online measurement (OM) method, Miller (1985) experimentally investigated charge migration of an outdoor unit of a heat pump by using a dedicated differential mass measurement scale. This OM method used a tare weight to compensate for the weight of the unit leaving only the refrigerant charge as the residual force. Charge migration was then measured by a load cell while the unit was operated in heating mode. Miller (1985) achieved ±50 g (±0.1 lb) of accuracy in the charge mass measurement for a 3-ton (10.5 kW) outdoor unit. This method allows fast measurements in (almost) unmodified equipment but has over an order of magnitude less absolute accuracy compared to Peuker (2011)'s method.

Ding *et al.* (2009) suggested a quasi-OM method. Refrigerant charge is moved to a connected sampling cylinder, and the cylinder is weighed to determine charge. In contrast to Peuker (2011), the measured refrigerant is re-used by the refrigeration system. This process decreases measurement time and saves refrigerant. While the quasi-OM has good accuracy (0.64% of measured charge), refrigerant and oil charge cannot be measured separately by this method. In addition, Ding *et al.* (2009) compared both the OM and SM methods: the SM needs greater time compared with the OM (300 minutes compared against *in-situ*), and has higher accuracy with an order of 0.11% of measured charge by the SM; on the other hand, the OM is an almost instantaneous and convenient method but has low accuracy within an order of 10% of measured charge.

In summary, the SM methods are accurate but slow while the OM methods are fast but have limited accuracy. A better compromise between accuracy and speed of the measurement method is needed to determine refrigerant and oil charge cost-effectively for the purpose of charge model validations. This study presents a novel measurement method to obtain separate refrigerant and oil charge in heat exchangers with an accuracy similar to the SM methods that can be collected fast enough to accommodate the development of a large experimental validation database for charge simulation of 3 ton (10.5 kW) capacity split systems. This experiment requires several key components: 1) a Removable Heat Exchanger Charge Test module (RHXCT), 2) a Differential Mass Measurement Scale (DMMS), 3) a Modular Duct Assembly (MDA) inside a psychrometric chamber, and 4) a pumped oil and refrigerant conditioning loop. This work presents details of the Differential Mass Measurement Scale (DMMS), the vital device to implement the differential mass sampling method, while the remaining components of the experimental setup is described in Lee *et al.* (2020).

2. DIFFERENTIAL MASS EVACUATION SAMPLING METHOD

This section presents the differential mass sampling method that determines the charge in a sample heat exchanger by measuring the difference to the dry heat exchanger weight with a specially designed Differential Mass Measurement Scale (DMMS). The method can provide the benefits of both, the OM and SM methods by isolating and quickly separating the heat exchanger in steady-state operation to be measured using the DMMS. Additionally, this method measures refrigerant and oil charge in the heat exchanger separately using a multi-step evacuation process to determine both. Furthermore, it does not include multiple and complicated mixing steps which result in long measurement times. Moreover, the refrigerant and air-side experimental apparatus are designed to be maintained in a stand-by mode while charge measurements are performed, further increasing experimental speed.

Figure 1 describes the experimental apparatus used for this method. It is composed of three types of components. The first are devices for providing test conditions such as a refrigerant and oil conditioning loop and an air-side conditioning apparatus (*e.g.* psychrometric room). The second are devices for obtaining charge samples, the Removable Heat eXchanger Charge Test module (RHXCT), and the third is a differential mass measurement scale for determining the charge in the heat exchanger. Details on the DMMS are presented the following sections.

2.1 Test Procedure for Pure Refrigerant Charge

In this section, the simplified operation steps of the differential mass evacuation sampling method for pure refrigerant (oil-free) are described:

(1) Prior to weighing the RHXCT, the RHXCT is evacuated and weighed by the DMMS. This process gives the initial differential mass of the RHXCT, Δm_{dry}, which is the tare weight: the difference between a counterweight and mass of the RHXCT.

(2) The Modular Duct Assembly (MDA) is prepared in a psychrometric chamber. The MDA can deliver desired flow rate, temperature, and humidity of air to the RHXCT. The RHXCT is connected to the MDA and operated at a designed condition to allow refrigerant and oil flow rates to stabilize. Once a desired test condition is reached and steady-state data acquisition is complete, the refrigerant charge in the heat exchanger is sampled by simultaneously closing two Pneumatic actuated Rapid Shut-off Valves (PSVs) on the RHXCT's inlet and outlet.

(3) The RHXCT is disconnected from the MDA. Subsequently, the separated RHXCT is weighed again using the DMMS, after any condensate on the surface has evaporated. The measured differential mass is Δm_{start}. By subtracting Δm_{dry} from Δm_{start}, the total mass of refrigerant, m_{ref}, enclosed between the two PSVs can be obtained. This can be expressed as

$$m_{ref} = \Delta m_{start} - \Delta m_{dry} \tag{1}$$

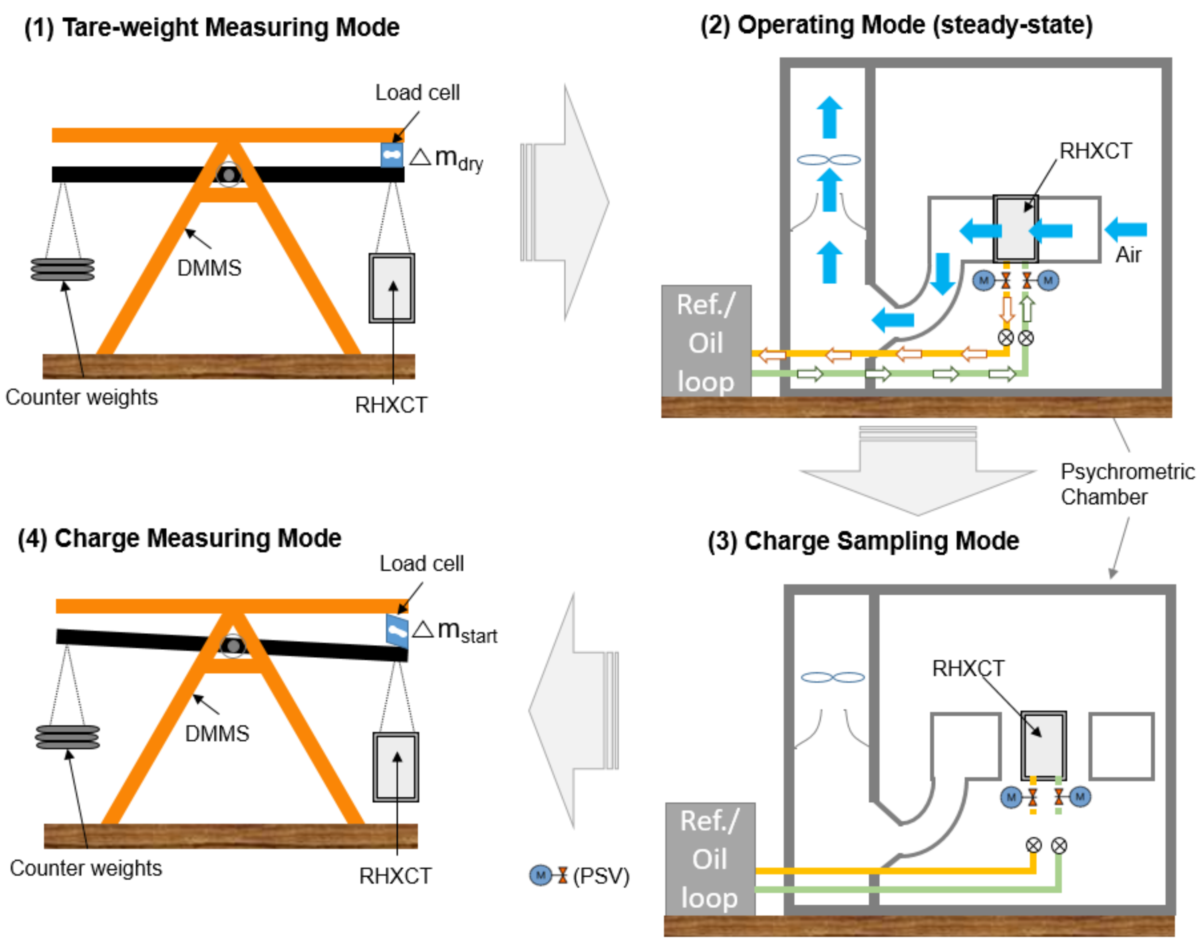

Figure 1: Schematic of the charge measurement process for pure refrigerant

2.2 Test Procedure for Pure Refrigerant and Oil Charge

The detailed operation steps of the differential mass evacuation sampling method for refrigerant and oil charge are as follows:

(1) Prior to weighing the RHXCT, oil in a separator is drained and the RHXCT is flushed with two phase pure refrigerant to remove any residual oil from previous experiments. Then, to measure the exact amount of refrigerant charge and oil retention in a heat exchanger, the RHXCT is evacuated and weighed by the DMMS. This process eliminates the effect of remaining oil residue on the tare differential weight of the RHXCT, and gives the initial differential mass of the RHXCT, Δm_{dry}.

(2) The RHXCT is connected to the MDA and operates at a designed condition to allow refrigerant and oil flow rates to stabilize. Once a desired test condition is reached and steady-state data acquisition is complete, the refrigerant charge and oil retention in the heat exchanger are sampled by simultaneously closing the PSVs on the RHXCT's inlet and outlet.

(3) The RHXCT is disconnected from the test section by disconnecting the refrigerant and electrical connections and unclamping the RHXCT from the MDA.

(4) The separated RHXCT from the test section is weighed again using the DMMS, after any condensate on the surface has evaporated. The measured differential mass is Δm_{start}. By subtracting Δm_{dry} from Δm_{start}, the total mass of refrigerant and oil, $\Delta_{mref\&oil,tot,start}$, enclosed between the two PSVs can be obtained. This can be expressed as

$$m_{ref\&oil,tot,start} = \Delta m_{start} - \Delta m_{dry} \tag{2}$$

(5) The refrigerant is recovered by connecting a recovery machine, leaving only the oil mass in the RHXCT. The refrigerant-oil mixture passes through the coalescent oil separator inside the RHXCT to ensure that only pure refrigerant is recovered. Thereafter, the RHXCT is evacuated by using a vacuum pump. Minimum pressure at the end of the evacuation process is set higher than the vapor pressure of the oil; the exact value will be determined based on the oil which will be used in the test. This will ensure that all oil remains in the RHXCT. During the evacuation process, water condensate might be generated on the surface of the RHXCT; therefore, fans are utilized to blow air toward the RHXCT to reduce condensate generation and evaporate any condensate prior to the next step.

(6) After completing the refrigerant recovery, the DMMS is utilized to measure Δm_{end}. By subtracting Δm_{dry} from Δm_{end}, the mass of oil, the refrigerant that is dissolved in the oil, and the residual refrigerant in the vapor state are determined,

$$m_{ref\&oil,tot,end} = \Delta m_{end} - \Delta m_{dry} \tag{3}$$

(7) $m_{ref\&oil,tot,end}$ contains the actual oil mass, the mass of refrigerant dissolved in the oil ($m_{ref,solub}$), and the mass of refrigerant within the test section $m_{ref,sh}(V_{tot}, T, P)$ at the given total volume of all components of the test section as well as given pressure and temperature. Thus, the actual oil mass can be expressed as

$$m_{oil} = m_{ref\&oil,tot,end} - m_{ref,solub} - m_{ref,sh}(V_{tot}, T, P) \tag{4}$$

In this study, we anticipate that $m_{ref,solub}$, $m_{ref,sh}(V_{tot}, T, P)$ are neglected due the negligible solubility of refrigerant in oil at low evacuation pressure and negligible mass of superheated refrigerant. Therefore, the actual oil mass can be simplified as follows:

$$m_{oil} \approx m_{ref\&oil,tot,end} \tag{5}$$

(8) The refrigerant mass is determined by subtracting the oil mass (m_{oil}), from the total initial mass of refrigerant and oil ($m_{ref\&oil,tot,start}$):

$$m_{ref} = m_{ref\&oil,tot,start} - m_{oil} \tag{6}$$

3. DIFFERENTIAL MASS MEASUREMENT SCALE (DMMS)

Miller (1985) used a Differential Mass Measurement Scale (DMMS) to weigh a combined mass of refrigerant and oil in an outdoor unit (5.7 kg of the target charge level). An entire outdoor unit was suspended from one side of the horizontal beam of the DMMS, with a counterbalance to offset the weight on the other side. The small balance change due to the refrigerant and oil charge migration was measured by a load cell with an accuracy of 0.05 kg, on the outdoor unit side of the horizontal beam. Drawing inspiration from Miller (1985)'s DMMS, an improved DMMS is presented as illustrated in Figure 2.

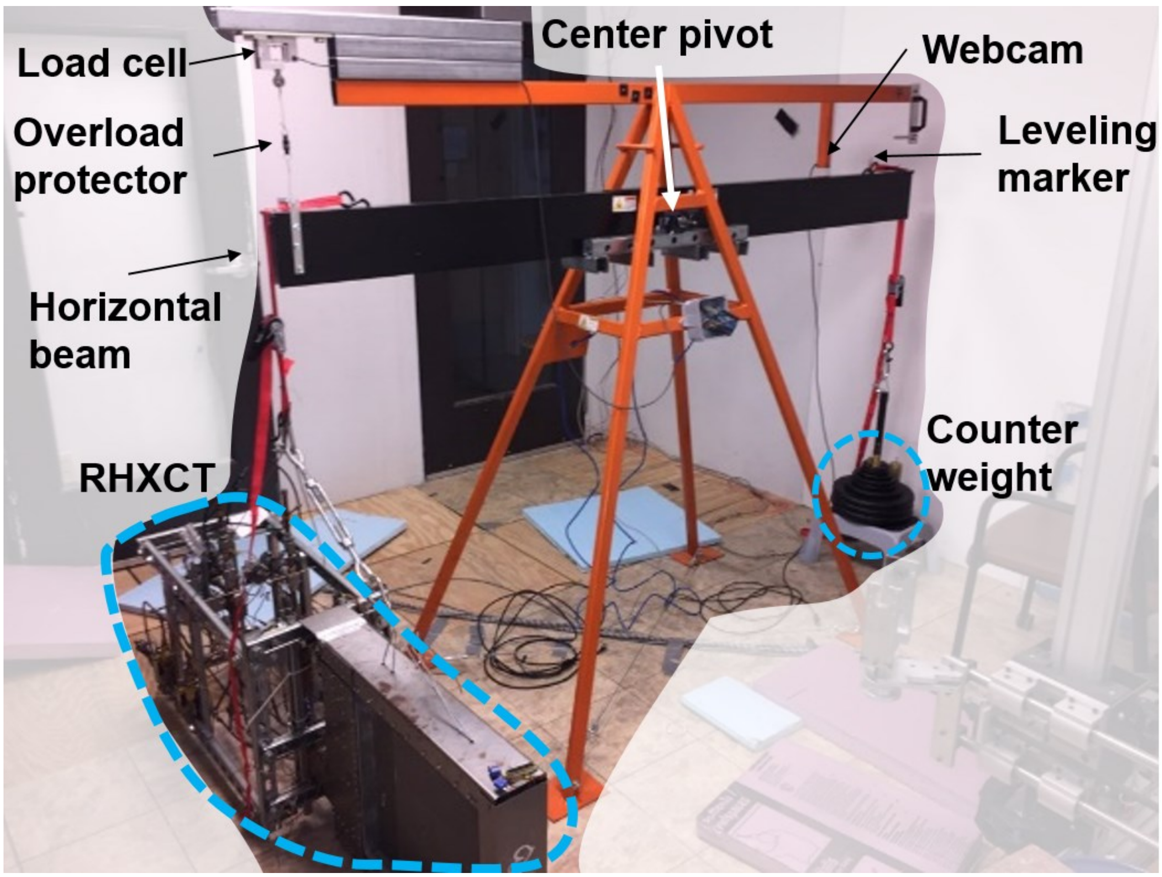

Figure 2: Picture of the DMMS with the RHXCT within thermal guard space (lower room of experimental office building within Oklahoma State University Building Airflow and Contaminant Transport Laboratory).

First, the refrigerant hoses and electrical lines are removed from the updated DMMS during the charge measurement process to improve the accuracy. This separation removes any line and instrumentation weight biases from the measurement. Second, as the length of the horizontal beam increases, the torque applied to the center pivot increases, which reduces the measurement error caused by the friction force of the center pivot. Accordingly, the updated DMMS utilizes a horizontal beam of a length maximized for the given thermal guard space size. Third, the DMMS employs a high accuracy load cell (HBM-S2M-10N) with an internal mechanical overload protection mechanism. Its maximum capacity is 1,000 g, with a 0.02% full scale accuracy, translating to an accuracy of 0.2 grams. An additional secondary overload protector, two in-line permanent magnet disks holding up to 1 kg before separation, is used between the load cell and the horizontal beam. The output signals of the load cell are amplified and converted to the digital signals using an HX711 amplifier and DA converter and then are sent via an Arduino to a LabVIEW program which saves and displays data.

4. RESULT

The accuracy of the DMMS was obtained by comparing with a standard mass. The standard mass is regarded as an anticipated approximate refrigerant charge (200 g, for evaporator mode) for the first heat exchanger under test. The details of the heat exchanger and the test conditions can be found in Lee *et al.* (2020). Figure 3 illustrates the process to acquire the accuracy of the DMMS as follows:

(1) Two weights were suspended from each side of the DMMS, and 200 g of the standard mass was added onto the weight on the load-cell side. The calibration of the load cell was performed with the 200 g of the standard mass.

(2) With the RHXCT and the counterbalance suspended from the DMMS, the tare weight (Δm_1) was measured by the load cell after the beam was leveled.

(3) Thereafter, to simulate the real charge measurement process, the RHXCT was unloaded from the DMMS and re-loaded to the DMMS.

(4) Subsequently the standard mass (200 g) was added onto the RHXCT. The charge weight including the tare weight (Δm_2) was measured by the load cell after the beam was leveled. The final charge (*e.g.* change of mass) was then calculated by subtracting the measured Δm_1 from the measured Δm_2.

(5) The process from (2) to (4) was repeated four times, and its result is illustrated in Figure 4.

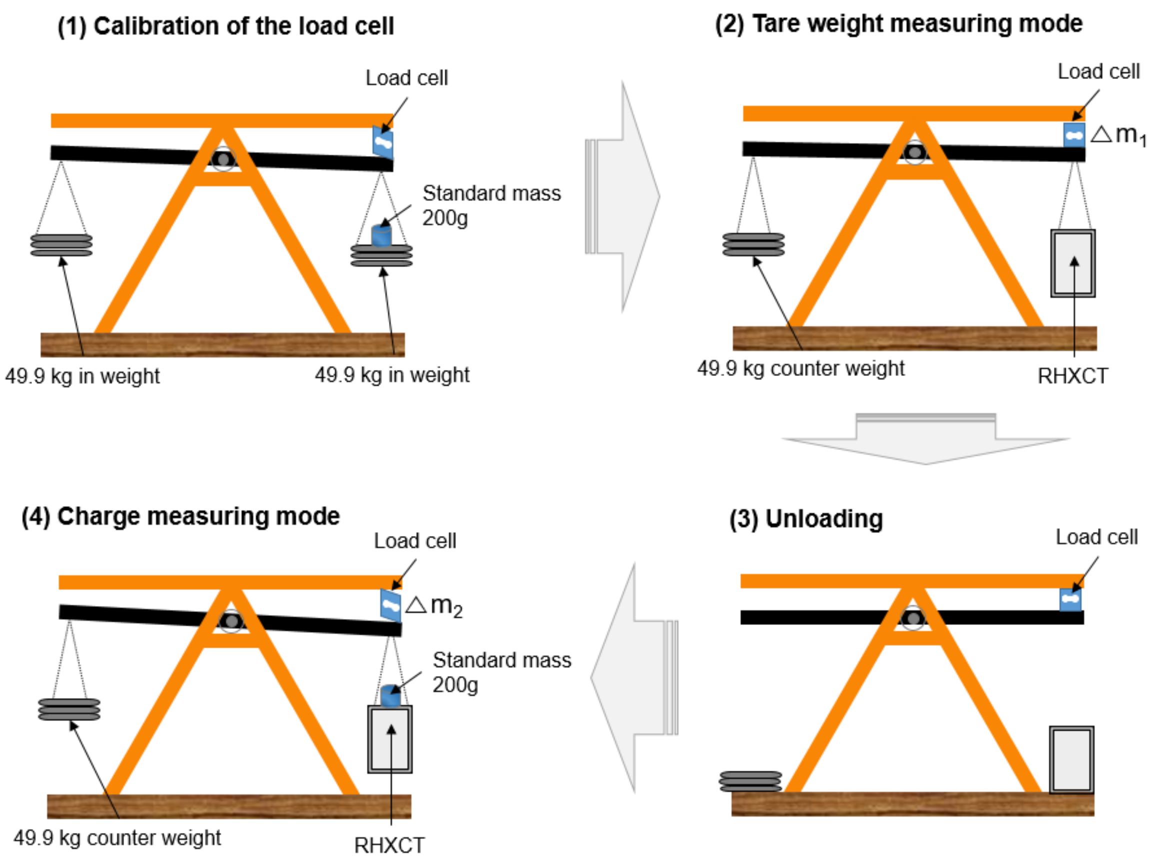

Figure 3: Schematic of measurement process to determine the DMMS's accuracy. The slope of the beam is exaggerated.

The mean value of the reading using student-t distribution, 201.0 ± 3.1 g @95%CI, of the DMMS was compared to the standard mass (200 g) as shown in Figure 4. The maximum absolute error of the DMMS was 3.2 g (1.6% of the relative error with 200 g of the known standard mass), translating to a 0.006% of relative accuracy of 49.9 kg tare weight of the RHXCT.

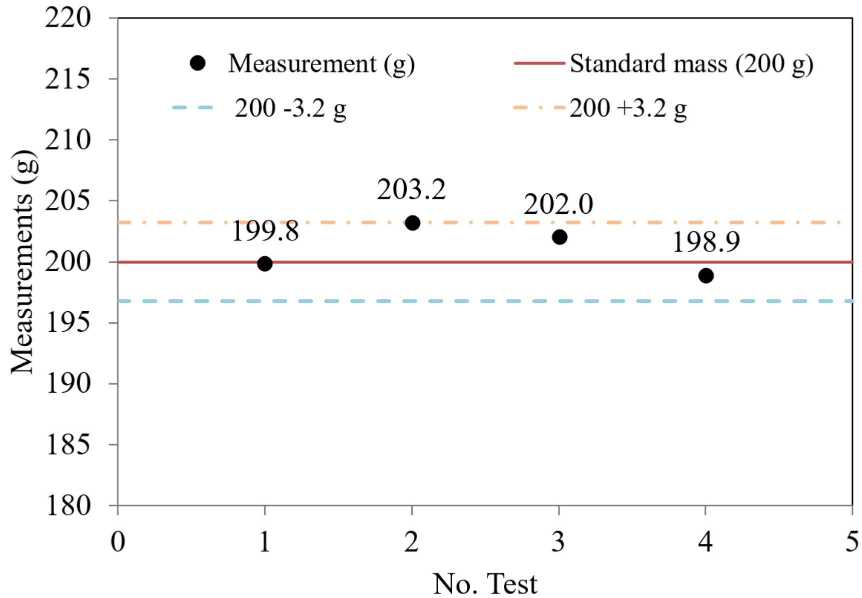

Figure 4: The measurements of the DMMS with the added known mass (200 g) after reloading the RHXCT

5. CONCLUSION AND FUTURE WORK

The differential mass evacuation sampling method is presented that can quickly capture high-fidelity charge measurements for experimental validation of the charge simulation. This method embraces the advantages of the existing charge measurement methods (OM and SM) such as independent charge determination of refrigerant and oil and simple/fast measurement to accommodate large number of data points. The principal component, the Differential Mass Measurement Scale (DMMS), was developed. Due to high accuracy of the load cell (0.02% full scale accuracy) and simple and robust mechanism of the DMMS, it can produce continuous accurate charge measurements with 0.006% of relative accuracy of the 49.9 kg tare weight of the RHXCT. The presented differential mass evacuation sampling method and the differential mass measurement scale will be applied to measure charge of pure refrigerants and refrigerants with various oil circulation rates as part of ASHRAE RP-1785.

NOMENCLATURE

m	mass
P	pressure
T	temperature
V	volume

Subscripts

dry	dry condition without oil and refrigerant
end	at the end of the oil retention and refrigerant charge measurement
oil	POE oil
ref	refrigerant
sh	superheated vapor

solub	solubility
start	at the start of the oil retention and refrigerant charge measurement
tot	total
Δ	difference between two values

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