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Differential Mass Evacuation Sampling Method for Measuring Refrigerant Charge in Round Tube Plate Fin Heat Exchangers (ASHRAE RP-1785)

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ABSTRACT

Charge modeling tools require high-fidelity experimental validation data to tune their predictions. This study addresses this need through a novel, validated, refrigerant charge measurement method for obtaining high-fidelity experimental charge data in Round Tube Plate Fin Heat Exchangers (RTPF). The method determines refrigerant charge in an RTPF by measuring the mass difference to the dry RTPF weight with a custom designed Differential Mass Measurement Scale (DMMS). A validation of the differential mass evacuation sampling method was conducted four times by measuring the same amount of refrigerant (119 g) on the DMMS and a commercial refrigerant scale respectively and comparing each measurement with the other; the mean difference between the DMMS and refrigerant scale measurements was 2.7 ± 1.7 g at 95% confidence interval. In addition, measured charge was confirmed from repeated tests and showed 1.3% repeatability of the method. The validated method can allow collecting high-fidelity experimental charge validation data for a variety of testing conditions in a Round Tube Plate Fin Heat Exchanger (RTPF).

1. INTRODUCTION

Refrigerant charge in air conditioning and refrigeration systems directly affects efficiency and capacity of the systems (Poggi *et al.* 2008). Cowan (2004) found that optimizing refrigerant charge can reduce energy consumption in cooling mode by 5 to 11% for packaged rooftop air conditioning units installed in California. Refrigerant charge in an air conditioning and refrigeration systems can be predicted by charge modeling tools (Harms, 2002; Ding *et al.,* 2009; Jin *et al.,* 2016). The modeling tools must be experimentally validated to ensure their prediction accuracy. While the measurement is critical, the existing work in the open literature highlighting methods of charge measurement are relatively sparse, specifically for refrigerant charge measurement in Round Tube Plate Fin Heat Exchangers (RTPF) that are widely used in air conditioning and refrigeration systems (Yao *et al.,* 2004; Wen and Ho, 2009; Kim *et al.,* 2013; Cotton and Shabtay, 2017).

Researchers use two main methods for refrigerant charge measurements. The first is the online-measurement method, 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). The second method is the sampling-measurement method, which rapidly isolates the charge of a sample, and then measures the sample in subsequent additional steps. As an early compelling example for an online-measurement method, Miller (1985) studied charge migration of an outdoor unit of a heat pump by employing a dedicated differential mass measurement scale. His online-measurement method utilized a tare weight to offset for the weight of the unit leaving only the refrigerant charge as the residual weight. Charge migration was then measured by a load cell while the unit was operated in heating mode. His method enabled rapid measurements while operating the equipment *in-situ* at the expense of lower measurement accuracy than achievable with sampling methods. Miller reported an accuracy of

±0.05 kg for the charge of a 3-ton (10.5 kW) outdoor unit. Ding *et al.* (2009) investigated a quasi-online-measurement method. Refrigerant charge is moved to a connected sampling cylinder, and the cylinder is weighed to measure charge. The unique feature of this method is to re-use refrigerant, saving measurement time and refrigerant. Although the quasi-online-measurement method has comparable accuracy (0.64% of measured charge) to that of the sampling-measurement method, refrigerant and oil charge cannot be measured separately by this method.

Peuker (2011) experimentally investigated R134a refrigerant and oil charge of an automotive air conditioning system using the sampling-measurement method. He used a quick-closing valve method combined with a remove-and-weigh method and reported an accuracy of 10 g of measured refrigerant charge and 0.1 g of measured oil charge (*e.g.* 0.6% of 22 g of oil). The oil and refrigerant charge in the system are recovered by an evacuated sampling cylinder placed in liquid nitrogen as a recovery pump. Then the refrigerant charge is determined by removing the refrigerant, weighing the cylinder. The oil retention is obtained by filling liquid refrigerant and circulate it inside the sampling section and determining the oil concentration in the mixture.

Both the sampling-measurement methods and online-measurement methods have advantages; the online-measurement methods are fast but have limited accuracy while the sampling-measurement methods are accurate but time-consuming. Recently, Lee *et al*. (2020) proposed a new method providing a compromise between measurement accuracy and speed. That novel method uses a differential mass evacuation sampling process to separately obtain refrigerant and oil charge in a heat exchanger. The achieved accuracy is comparable to the sampling-measurement methods while the method is fast enough to accommodate the development of a large experimental validation database for charge simulation. Lee *et al.* (2020) also presented other critical apparatuses for implementing the measurement method such as a test section module which include a RTPF under test, also known as a Removable Heat eXchanger Charge Test module (RHXCT), and a Modular Duct Assembly (MDA). The related refrigerant conditioning loop can be found in Saleem *et al.* (2020).

The study presents repeatability and validation of the differential mass evacuation sampling method with a Round Tube Plate Fin Heat Exchanger (RTPF) in both evaporator and condenser mode with pure R410A refrigerant.

2. EXPERIMENTAL METHODOLOGY

The differential mass evacuation sampling method determines the charge in a Round Tube Plate Fin Heat Exchangers (RTPF) by measuring the difference to the dry RTPF weight with a custom designed Differential Mass Measurement Scale (DMMS). The following sections describe the related testing apparatuses and the method's operation steps. Further details on the methodology of the differential mass evacuation sampling method was previously presented in Lee *et al.* (2020).

2.1 Experimental Testing Apparatuses

The differential mass evacuation sampling method employs several key testing apparatuses. Charge samples are obtained using a Removable Heat eXchanger Charge Test Module (RHXCT) that includes the RTPF under test; and the RHXCT is equipped with pressure and temperature sensors, electronic expansion valves, Rapid Shut-off Valves (RSVs) on both inlet and outlet refrigerant pipes in the RHXCT for quick charge sampling. Figure 1 shows a simplified schematic of the RHXCT. Test conditions are provided using a refrigerant conditioning loop and a psychrometric chamber to provide fixed inlet air conditions. Inside the psychrometric room, the RHXCT is connected to a Modular Duct Assembly (MDA) which can deliver desired airflow to the RHXCT shown in Figure 2, and the Differential Mass Measurement Scale (DMMS) is used for determining the charge in the RHXCT.

Drawing inspiration from Miller (1985)'s differential mass measurement scale, an improved Differential Mass Measurement Scale (DMMS) is presented and shown in Figure 3. First, the refrigerant hoses and electrical lines are removed from the updated DMMS during the charge measurement process to eliminate external forces. This separation removes any line and instrumentation weight biases from the measurement. Second, as the length of the horizontal beam is increased, the torque applied to the center pivot increases for a fixed imbalance increases, reducing the measurement error caused by friction force at the center pivot. Accordingly, the DMMS utilizes a horizontal beam length maximized for available space. The apparatus space is protected from uncontrolled airflow due to HVAC systems and/or personnel. The center pivot is further improved by using four low-friction, self-aligning pillow block bearings that enable a rotating shaft, reducing hysteresis. Structurally, the four bearings connect the horizontal beam and the support frame; and a 12.7 mm shaft connects the four concentric bearings.

Third, Miller (1985) used a load cell with an accuracy of 50 g; this study employs a high accuracy load cell (HBM-S2M-10N) with a maximum capacity of 1,000 g, with a 0.02% full scale accuracy, translating to an accuracy of 0.2 g. Fourth, the load cell includes an internal mechanical overload protection mechanism to prevent loss of calibration. Additionally, a mechanical overload protector, two in-line permanent magnet disks holding up to 1 kg before separation, are used between the load cell and the horizontal beam to protect the load cell from mechanical damage. Lastly, the output signals of the load cell are amplified and converted to digital signals using an HX711 amplifier and an analogue to digital converter and then are sent to a LabVIEW program which saves and displays data. The load cell and signal processing units are calibrated *in-situ.*

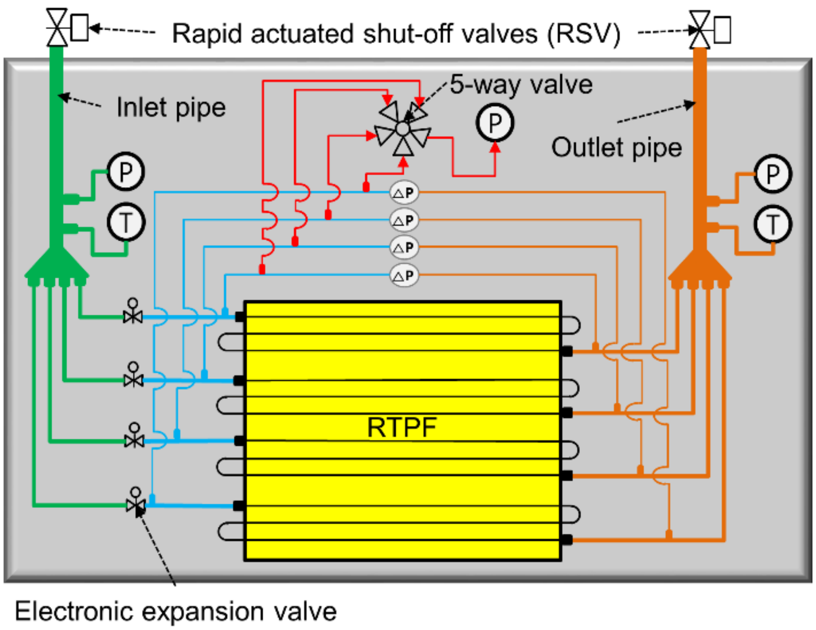
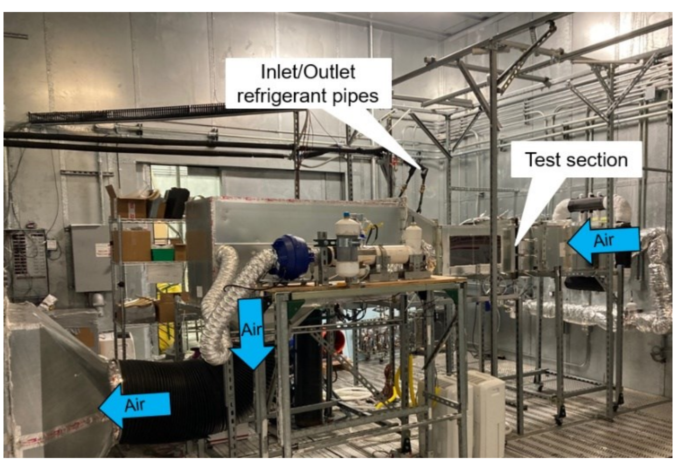


Figure 1: Simplified schematic of the removable heat exchanger charge test module (RHXCT) (modified from Lee *et al.,* 2020).



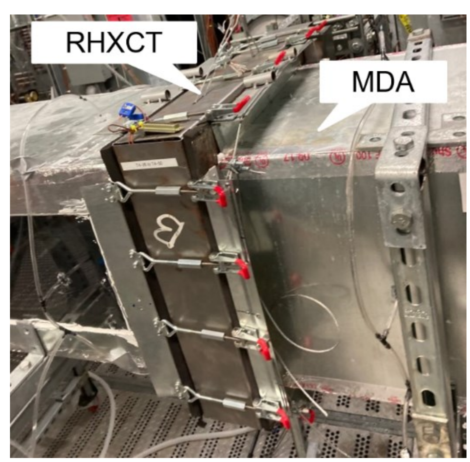


Figure 2: Modular duct assembly (MDA), (left) and the combined structure of the RHXCT and MDA, (right) (modified from Lee *et al.*, 2020)

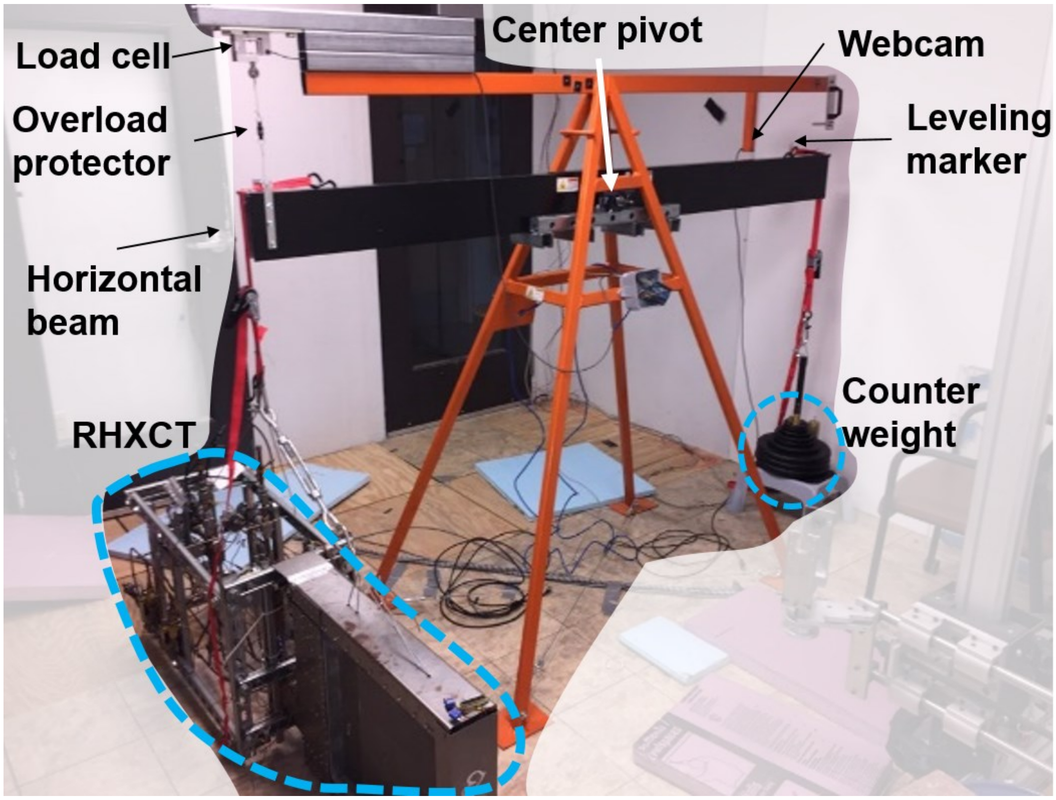


Figure 3: Differential Mass Measurement Scale (DMMS) with the removable heat exchanger charge test module located in the airflow guard space.

2.2 Operation Steps

The overall operation steps of the differential mass evacuation sampling method (Lee *et al.,* 2020) are presented in Figure 4.

(1) Prior to weighing the RHXCT, the RHXCT is evacuated and weighed by the DMMS. This process gives an initial differential weight of the RHXCT, which is the Tare Weight (Δm_{TW}): the difference between a counter weight and weight 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 steady state condition to allow refrigerant flow rates to stabilize. Once a desired test condition is reached and steady-state data acquisition is complete, the refrigerant charge in the RHXCT is sampled by simultaneously closing two Rapid Shut-off Valves (RSVs) 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 of the RHXCT in this step, is termed Charge Sampled Weight (Δm_{CW}). The total charge in the RHXCT, enclosed between the two RSVs, is determined by the difference between the Δm_{CW} and Δm_{TW}. The charge in the RTPF of interest (*e.g.* heat exchanger tubes and return bends) is acquired by removing auxiliary charge inside RHXCT from the total charge in the RHXCT.

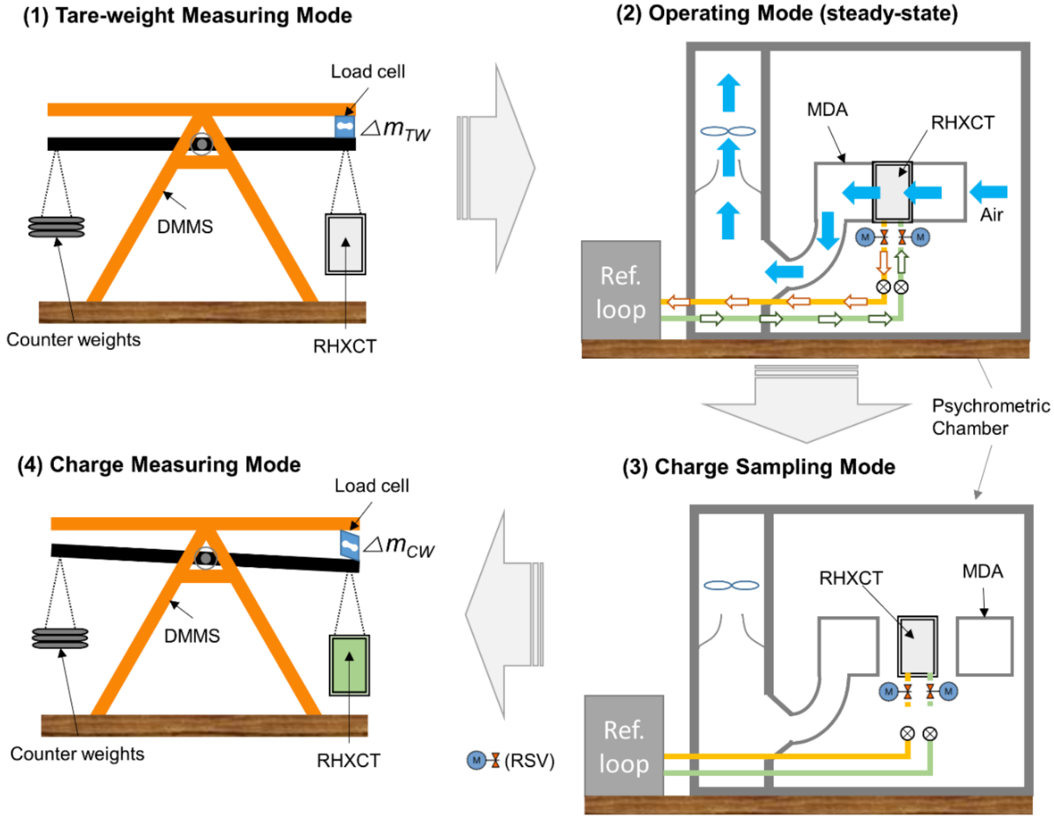


Figure 4: Schematic of measurement process to determine the DMMS's accuracy.
The movement of the horizontal beam is exaggerated for illustrative purposes.

2.3 Data Reduction

For evaporator mode, refrigerant mass flow rate ($\dot{m}_{ref}$) and outlet superheat (*SH*) were selected as the independent variables. To avoid undesirable charge errors by condensation, all evaporator tests were conducted under dry conditions without dehumidification, *i.e.* without condensation on the fins. The air inlet temperatures were maintained at 26.7 ℃ for the evaporator mode. The condenser tests use refrigerant mass flow rate ($\dot{m}_{ref}$), inlet superheat (*SH*), and outlet subcooling (*SC*) as the independent variables (Lee *et al.,* 2020). The air inlet temperatures were maintained at 21.1℃ dry bulb and 15.4℃ wet bulb temperature in the condenser mode. Primary heat exchanger testing variables are presented: the refrigerant side capacity, $\dot{Q}_{ref}$, air side capacity, $\dot{Q}_{air}$, outlet superheat, SH_{out}, inlet superheat, SH_{in}, outlet subcooling, SC_{out}, are expressed as

$$\dot{Q}_{ref} = \dot{m}_{ref} \cdot (h_{r,o} - h_{r,i}) \tag{11}$$

$$\dot{Q}_{air} = \dot{m}_{air} \cdot c_p \cdot (T_{db,i} - T_{db,o}) \tag{12}$$

$$SH_{out} = T_{r,o} - T_{r,sat,o} \tag{13}$$

$$SH_{in} = T_{r,i} - T_{r,sat,o} \tag{14}$$

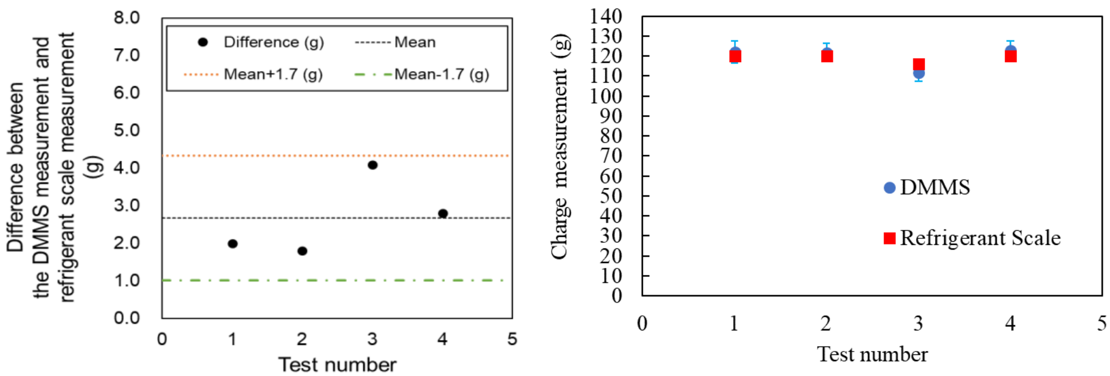
$$SC_{out} = T_{r,sat,o} - T_{r,o} \tag{15}$$

where $\dot{m}_{ref}$ is the refrigerant flow rate, $h_{r,o}$ is the refrigerant enthalpy at the RTPF outlet, $h_{r,i}$ is the refrigerant enthalpy at the RTPF inlet, $\dot{m}_{air}$ is the air flow rate, c_p is the specific heat at constant pressure of air-water vapor mixture, $T_{db,i}$ is the inlet air dry-bulb temperature, $T_{db,o}$ is the outlet air dry-bulb temperature, $T_{ref,o}$ is the refrigerant temperature at the RTPF outlet, $T_{r,sat,o}$ the saturated refrigerant temperature at the RTPF outlet, and $T_{ref,i}$ the refrigerant temperature at the RTPF inlet.

3. EXPERIMENTAL RESULTS

3.1 Validation of Differential Mass Evacuation Sampling Method

A validation of the differential mass evacuation sampling method was carried out by measuring the same amount of refrigerant on a commercial refrigerant scale (TIF9020A) and the DMMS respectively and comparing each measurement with the other. The whole charge measurement processes and comparisons were repeated four times to ensure credibility of the validation. The validation results are given in Figure 5. The mean difference between the measurements of the DMMS and the refrigerant scale was calculated using student-t distribution, the continuous probability distribution obtained from Excel's built-in TINV function; it was 2.7 ± 1.7 g at 95% confidence interval with respect to 119 g of the mean measured charge by the refrigerant scale. For further explanation, the DMMS has some advantages over the refrigerant scale; the DMMS can weigh up to 280 kg while the refrigerant scale weigh up to 100 kg. Moreover, the DMMS has higher accuracy; Lee *et al.* (2021) reported the DMMS's accuracy of 0.006% with 49.9 kg load, whereas the refrigerant scale has 0.5% accuracy with 100 kg. In this study, the validated charge measurement method is applied to measure charge of R410A refrigerant.



(a) difference between the DMMS measurement and refrigerant scale measurement

(b) charge measurement by DMMS and refrigerant scale

Figure 5: Validation result of charge measurement. The error bars indicate measurement uncertainties.

3.2 Energy Balance and Uncertainties

All tests fulfill the 5% energy balance requirement of ASHRAE Standard 33 (2016). Figure 6 shows the energy balance between refrigerant and air. Table 1 shows the uncertainties of all test data that are obtained by the uncertainty propagation calculations based on the analysis method presented by Taylor and Kuyatt (1994). The charge measurement uncertainties range between ±4.7~5.5 (g). A mean relative uncertainty of 1.0% with respect to measured charges was obtained and is considered sufficiently accurate for model validation purposes by the authors.

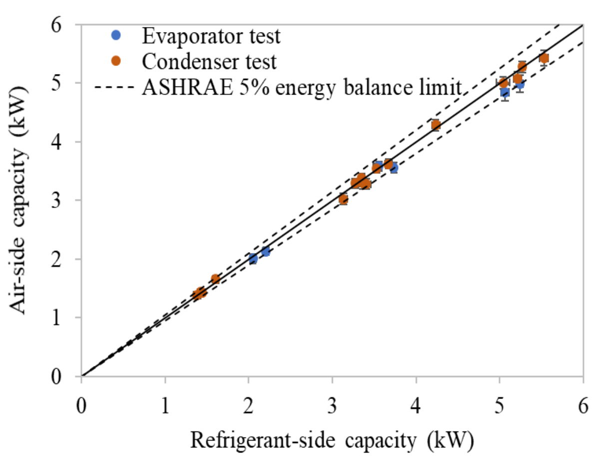


Figure 6: Air-side and refrigerant side capacity along with 5% energy balance limits.
The error bars indicate uncertainties of capacity obtained from the uncertainty propagation calculation.

Table 1: Maximum uncertainties of all shown experimental test results

Parameter	**Symbol**	**Uncertainty**
Pressure	P	±1.7 kPa
Temperature	T	±0.06 °C
Refrigerant mass flow rate	$\dot{m}_{ref}$	±0.05% of measured
Air mass flow rate	$\dot{m}_{air}$	±2.0% of measured
Refrigerant-side capacity	$\dot{Q}_{ref}$	±0.08 (kW)
Air-side capacity	$\dot{Q}_{air}$	±0.14 (kW)
Evaporator RTPF charge	$m_{ref,RTPF,eva}$	±4.9 (g)
Condenser RTPF charge	$m_{ref,RTPF,cnd}$	±5.5 (g)

3.3 Repeatability of Charge Measurements

The repeatability of charge measurement in condenser and evaporator mode were evaluated by repeatedly testing the same test points as shown in Table 2 and Table 3. The test results show an absolute charge difference of 11.0 g from the repeated tests, which is equivalent to 3.1% of repeatability of measured charge in evaporator mode. In condenser mode, 13.1 g of absolute charge difference was found from the repeated tests, equivalent to 1.3% repeatability of measured charge.

Table 2: Repeatability of evaporator mode.

Variable	**Unit**	**Test number 4**	**Repeated test on test number 4**	**Absolute difference**
$\dot{m}_{ref}$	kg/hr	75.8	75.8	0.0
$\dot{m}_{air}$	kg/s	0.437	0.435	0.0
$\dot{Q}_{ref}$	kW	3.56	3.56	0.0
$\dot{Q}_{air}$	kW	3.58	3.45	0.1
SH_{out}	K	11.0	11.0	0.0
$m_{ref,RHXCT}$	g	355	345	11.0

Table 3: Repeatability of condenser mode.

Variable	**Unit**	**Test number 19**	**Repeated test on test number 19**	**Absolute difference**
$\dot{m}_{ref}$	kg/hr	56.6	56.6	0.0
$\dot{m}_{air}$	kg/s	0.310	0.311	0.0
$\dot{Q}_{ref}$	kW	3.40	3.40	0.0
$\dot{Q}_{air}$	kW	3.28	3.29	0.0
SH_{in}	K	25.5	25.5	0.0
SC_{out}	K	6.7	6.8	0.1
$m_{ref,RHXCT}$	g	971	984	13.1

4. CONCLUSION AND FUTURE WORK

The presented charge measurement method is considered highly accurate and reliable for obtaining R410A experimental charge validation data for evaluating/tuning charge models on various testing conditions by the authors.

A novel differential mass evacuation sampling method was presented. Testing apparatuses were developed for the method include charge sampling and weighing systems, as well as refrigerant and airside conditioning setups.

The novel differential mass evacuation sampling method allows quick charge measurement within an hour after charge sampling. The separation of the test section occurs in an instant due to the quick clamps on airside duct and the shut-off valves on the refrigerant pipes, followed by an immediate weight measurement by the DMMS, thus making charge measurement simple and fast, as needed for building an extensive charge measurement database for model validation purposes. The method was validated with an error of 2.7 ± 1.7 g at 95% confidence interval with respect to 119 g of the mean measured charge by a refrigerant scale. Furthermore, the method was proven to have high-accuracy, 1.0% of relative uncertainty with respect to measured charge and 1.3% of repeatability of measured charge in condenser mode for the entire testing-sampling-measurement process.

Future work will include conducting experimental tests on refrigerants with various oil and refrigerant circulation rates for various sizes and circuitries of heat exchangers; moreover, the developed differential mass evacuations sampling method allows measuring mass changes in not only a heat exchanger but also other system components or entire systems.

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NOMENCLATURE

c	*specific heat (kJ/kg-K)*
h	*enthalpy (kJ/kg)*
m	*mass (g)*
$\dot{m}$	*mass flow rate (kg/hr)*
P	*absolute pressure (kPa)*
$\dot{Q}$	*capacity (kW)*
SH	*outlet superheat for evaporator mode, inlet superheat for condenser mode (K)*
SC	*subcooling (K)*
T	*temperature (°C)*
u	*uncertainty of mass measurement (g)*
V	*volume (ml)*
x	*quality (-)*

Subscript

air	*air*
AUX	*auxiliary*
atm	*atmosphere*
cnd	*condenser mode*
CW	*charge sampled weight of RHXCT*
db	*air dry bulb*
dry	*dry condition without refrigerant*
eva	*evaporator mode*
i,	*in, inlet*
liq	*liquid state*
m	*mass*
o,	*out, outlet*
p	*constant pressure*
r,	*ref, refrigerant*
rel	*relative*

RHXCT	*removable heat exchanger charge test module*
RSV	*rapid shut-off valve*
RTPF	*round tube plate fin heat exchanger*
sat	*saturated*
tot	*total*
tp	*two-phase state*
TW	*tare weight of RHXCT*
vap	*vapor state*
wb	*air wet bulb*
Δ	*difference between two values*

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