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IMPROVING THERMAL INSULATION OF COMPRESSOR COOLING CAPACITY MEASUREMENT VESSEL THROUGH HEAT LEAKAGE FACTOR REDUCTION

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Abstract. The use of a vessel for measuring the cooling capacity of compressors is widely employed in the industry, but heat exchange between the vessel and the external environment can generate errors in the measurement. It is essential to reduce the thermal exchange of the vessel with the environment in which it is installed and accurately measure this heat exchange, known as the heat leakage factor (W/°C). This vessel must be thermally insulated and maintained in an environment with controlled temperature and ventilation, minimizing heat exchange with the external environment, which can result in errors of the mass flow measurement, used in the calculation of thermal capacity of the compressor being tested. The present work aims to reduce the thermal exchange of the vessel and accurately measure this heat exchange, through measurements using calibrated thermocouples on the surface of the vessel and environment where the vessel is installed, it is possible to identify possible problems that contribute to the increase of the heat leakage factor, such as a high delta temperature or a large dispersion in temperature around the vessel, leading to an insufficient calibration of the heat leakage factor. A measurement was also performed according to the standard characterizing the current loss factor, and based on the results obtained, a new proposal for enclosing the vessel was designed, improving the thermal insulation of the vessel, reducing points where there was heat exchange by conduction outside the vessel, reducing the speed of the external air, homogenizing the temperature of the airflow with a system of perforated plates. The results obtained were quite significant, with a reduction of approximately 83% in the loss factor, which demonstrates the effectiveness of the new proposal. It was also possible to improve the measurement loop around the vessel, representing the average temperature around more coherently, ensuring that the calibrated loss factor will be smaller, more stable, and reliable.

Keywords: Calorimeter, heat transfer, thermal insulation, refrigeration, instrumentation.

1. INTRODUCTION

Among all household appliances, refrigerators consume the most energy in the world accounting for around 30% of the total energy consumption (APEC Energy Working Group 2018). The IIR estimates that the total number of refrigeration, air conditioning and heat pump systems in operation worldwide is approximately 3 billion, including 1.5 billion of domestic refrigerators. (IIR 2015). Electricity consumption for refrigeration and air conditioning has been increasing over the last few years in both developed and developing countries. The refrigeration sector (including air conditioning) consumes about 17% of the overall electricity used worldwide (IIR 2015).

The most common compressor used in residential refrigeration is the reciprocating compressor. This component consumes most, if not all, of the energy required by the system, and therefore, improving its performance is one of the main issues for system designers (Negrão et al. 2011).

Refrigerant compressors are relatively complex products that require a wide range of tests to be performed for both product development and quality control. Among these tests, the performance test stands out. Its objectives are to measure the refrigerating capacity, active power consumption, isentropic efficiency and the coefficient of performance (COP) of the compressor (Flesch e Normey-Rico 2010).

To ensure standardized test procedures, international standards such as ISO-917 (ISO 1989), EN 13771-1 (CEN 2016), and ANSI/ASHRAE 23 (ANSI/ASHRAE Standard 23 2019) have been established. These standards define topological characteristics of the refrigeration system, measurement uncertainty limits, and control requirements.

The normative requirements are not sufficient to meet all the needs of compressor testing, especially in the field of research and development (R&D), where the gains from product modifications are generally incremental and below the tolerances specified by the standards. In addition, there is no global standard with traceability in the international system of measurements for cooling capacity. Therefore, there may be significant variations between different test panels, technologies, and laboratories (Rossetto 2014).

To measure with quality some parameters are very important, among which we can mention: control of pressures, control of ambient temperatures of the compressor, control of the return temperature to the compressor, measurement of temperatures correctly and measurement of mass flow. According to the standard there are five main methods for mass flow measurement:

Calorimetric methods:

- Method A: Secondary fluid calorimeter on the suction side
- Method B: Dry system refrigerant calorimeter on the suction side
- Method C: Condenser/Gas Cooler calorimeter on the discharge side, water cooled

Flow meter methods:

- Method D: Refrigerant gas flow meter
- Method E: Refrigerant flow meter in the fluid line entering the expansion device

The secondary fluid calorimeter consists of a direct expansion coil or a set of coils in parallel serving as a primary evaporator. This evaporator is suspended in the upper part of a pressure tight and heat-insulated vessel. A heater is located in the base of this vessel, which is charged with a volatile secondary fluid so that the heater is well below the liquid surface. The refrigerant flow is controlled by either a manual or a constant-pressure expansion device, which shall be located close to the calorimeter. The expansion device and the refrigerant pipes connecting it to the calorimeter shall be insulated to minimize the heat gain (CEN 2016).

The calorimeters (Component F in Figure 1b) operate by an energy balance. The refrigerant fluid is pumped by the compressor and passes through a valve, which expands the fluid and causes the cooling effect. As the fluid enters the calorimeter, an internal resistance provides heat ($\dot{Q}$). Temperature and pressure measurements are taken at the inlet and outlet of the calorimeter, allowing to determine the inlet and outlet enthalpies (h_5 and h_6, respectively) (Figure 1a). The heat exchange factor with the surroundings must be determined (F), and the temperatures of the calorimeter and the surroundings must be measured to correctly compensate for the exchanges with the surroundings (t_{bs} and t_{amb}). With this information known, we can calculate the mass flow rate ($\dot{m}$) using the following equation (CEN 2016):

$$\dot{m} = \dot{Q} + F\frac{T_{amb}-T_{bs}}{h_6-h_5}.$$ (1)
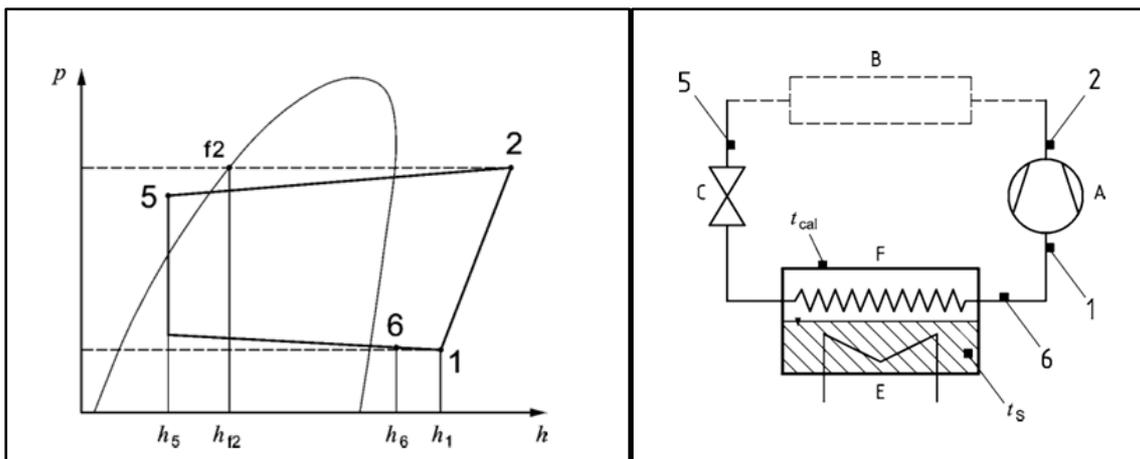

Figure 1a. pressure versus enthalpy diagram.   Figura 1b. Diagram circuit

As a standard procedure, calorimeters should be calibrated to determine the heat loss factor F (W/°C). This factor determines the rate of heat transfer between the calorimeter and the surroundings. For calibration, the temperature of the calorimeter and the surroundings should be approximately 15°C apart (CEN 2016). Once equilibrium is reached, it is possible to calculate the thermal loss to the surroundings and make the necessary compensations. Ideally, this value should

be very close to zero. However, if this value becomes high, errors in compensation can occur, which may be significant in industry standards. Initially, a value of 2.1W/°C was obtained when measuring this parameter.

The ambient temperature measurement in the current calorimeter under study is conducted using four Pt100 temperature transducers distributed in different positions around the calorimeter (at 90° angles from each other and positioned at different heights). However, typically, these four transducers are connected in parallel and measured by a single acquisition channel, representing the average ambient temperature. If there is a presence of temperature gradients in the calorimeter environment, compensating for temperature using the thermal loss correction factor may not be sufficient to account for all the thermal energy exchanges between the calorimeter and its surrounding environment (ROSSETTO, 2014).

Several characteristics of calorimeters have been investigated by various authors. Some researchers have focused on studying errors related to electrical characteristics (Barbosa, Fúlvio Queiroz 2006), general errors of pressure control, pressure measurement, and fluxometer (Rossetto 2014), as well as control strategies (Flesch e Normey-Rico 2010). However, no specific attention has been given to the thermal exchange between the calorimeter and the surrounding environment. Recognizing this gap in the existing literature, the present study aims to evaluate thermal exchanges, specifically considering radiation and convection mechanisms.

2. METHODOLOGY

When evaluating the initial calorimeter, see Fig. 2, some points were identified that can be modified to ensure a lower loss factor and greater stability.
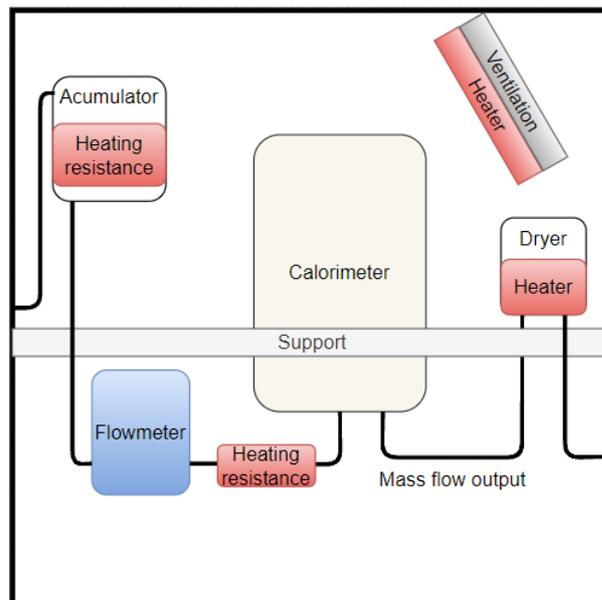

Figure 2. Initial calorimeter configuration.

To evaluate the current panel situation, thermocouples were installed at various points on the surface of the calorimeter, in the surrounding environment, and at specific locations such as near the fluid container, close to the heating sources, and at the bottom of the box. These points were selected to gain insights into the current conditions and to demonstrate their potential contribution to increased heat exchange.

To improve the accuracy of the instrumentation, both thermocouples were calibrated in a silicone bath to ensure thermal stability. A calibrated PT100 sensor was used for this purpose. The thermocouples were calibrated within a range of 2°C above and below the target value (32.2°C).

In order to evaluate the performance of compressors, calorimeter tests were conducted. These tests involved controlling various parameters such as condensing temperature, evaporating temperature, suction line temperature, ambient temperature, compressor shell temperature, as well as the airspeed, during those tests temperatures of calorimeters and surrounding were monitored.

After monitoring 122 tests with the instrumented temperature points, the following distribution was observed around the calorimeter (Figure 3), the median was slightly above the temperature, which is not necessarily a problem because it can be compensated, but some points were considerably above, such points may represent a problem in the calibration of

the loss factor, because when calibrating the calorimeter such points are not at the temperatures measured during the test, the calibration is performed without fluid flow inside the calorimeter, which represents a condition slightly different from the actual test condition. Such points should be modified, reducing differences in the calibration and during the tests performed on the panel.

Another point that drew attention was that in some tests the average of the four measurement points of the initial proposal was 32.2°C, but when placing more instrumentation points a greater temperature gradient was noticed between the top and bottom of the vessel, where above it was warmer by resistance and below it was colder, were atypical test conditions but showed that they should have more points for temperature control, or redesign the box so that such an effect cannot happen, ideally both.
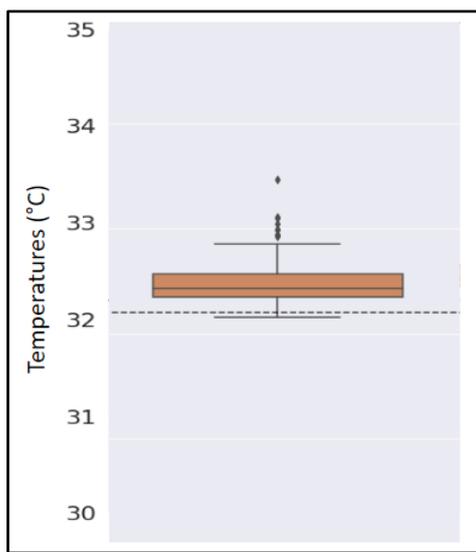

Figure 3. Distribution of temperatures around the initial Vessel.

The initial proposal vessel included some pipes that could be removed and repositioned outside the pressure vessel. These pipes were used for installing a pressure gauge, gas charging inside the vessel, and visualizing the internal fluid. The main issue with these pipes is that they would act as fins, intensifying heat exchange and acting as barriers to air flow.

The initially constructed pressure vessel lacked thermal insulation. If the temperatures of the environment and the vessel were the same, there would be no heat exchange. However, if there is a stable temperature differential between them, it is possible to compensate appropriately according to the standard. Nevertheless, maintaining temperatures very close and highly stable poses a significant challenge.

Inside the box where the calorimeter is installed, there were areas with significantly higher temperature differentials compared to the surrounding environment and the calorimeter itself. These areas included an oil separator wrapped in a heating element. The heating element was used to maintain controlled temperature within the box, but it caused issues such as hindering airflow and temperature homogenization. Additionally, these components contributed to increased heat exchange and undesired radiation emitted directly onto the calorimeter.

To improve airflow and reduce the effective thermal exchange area due to fins, all the piping was reassessed. The pipes used for pressure measurement, fluid level, and inlet/outlet were kept with minimal size, while the rest of the pipes were positioned outside the controlled temperature box. Equipment that was previously inside the box was also relocated to avoid obstructing airflow, resulting in a visually improved environment within the box.

Another action taken was the insulation of the entire pressure vessel and necessary piping for the proper functioning of the calorimeter. By insulating these components, resistance to heat exchange was added. The effectiveness of this heat exchange reduction is directly related to the quality and thickness of the insulation material used.

Initial calculations were performed (Table 1) using Eq. (2), where ε is the emissivity, σ is the Stefan-Boltzmann constant ($5.670374419 \times 10^{-8}$ W / (m² x K⁴)), A is the area of vessel (m²), T_s and T_a are the surface temperature and room temperature (K). Small temperature differences between the calorimeter and components within the box, as well as the box itself, can contribute to thermal losses due to radiation. These temperature differences, when converted to Kelvin and

raised to the fourth power, become significant for the study. To address this issue, all hot components were removed from close proximity to the calorimeter. This includes the oil separator wrapped in a heating element, the ambient heater, and the resistances in the inlet and outlet pipes, which were also moved away from the pressure vessel.

$$q = \varepsilon \, \sigma A \, (T_s^4 - T_a^4) \tag{2}$$

Table 1. Initial calculations to check the importance of radiation.

Ambient temperature (°C)	Surface temperature (°C)	Área (m²)	Emissivity	Heat flux (W)
32	32.00	0.25	0.95	0.00
33	32.00	0.25	0.95	-1.54
34	32.00	0.25	0.95	-3.09
33	32.00	0.25	0.97	-1.57
34	32.00	0.25	0.97	-3.16
33	32.00	0.25	0.99	-1.60
34	32.00	0.25	0.99	-3.22

To get around the ventilation problem and to be able to remove the resistance from inside the box, a box was built with perforated plates at the top and bottom, in this way it was possible to take the resistance and fans to a side duct, in this way the air is forced to enter from above and is suctioned at its base, making the ventilation more uniform, the ventilation was adjusted as low as possible, aiming to maintain a balance between better temperature uniformization and maintaining a low ventilation, avoiding the increase of the convective coefficient (h).

After all the changes the current configuration was reached (Figure 4), which consists of a much cleaner appearance, lower temperature differences inside the box through the reduction of heat sources and a better homogenization through the redesign of the ventilation and heating system, another point was the addition of thermal insulation in the calorimeter.
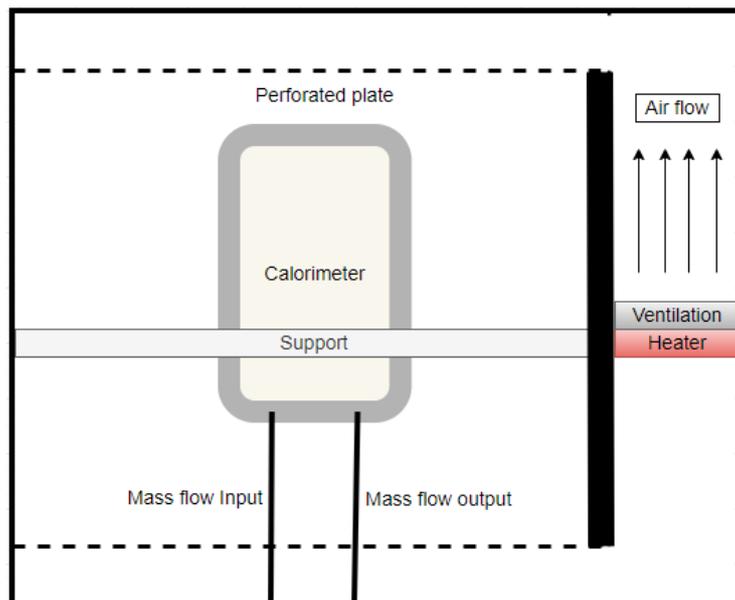

Figure 4. Final configuration of Calorimeter.

3. **CONCLUSION**

In the present work it was observed that standards are often not sufficient in industry, where gain is often incremental and methods more rigorous than the standard should be used in characterizing product improvements. At the start of the study the measured loss factor was 2.1W/°C, which may not necessarily lead to measurement errors as these losses will be compensated for in the test mathematically.

When instrumenting the points with thermocouples, points that had not been observed were observed, such as a possible instability in some tests and that radiation can be quite important for the heat exchange levels in question. It was also possible to verify some points that could visibly be improved, such as reducing the heat exchange area, thermal insulation for the calorimeter and improving the layout inside the box, improving ventilation and consequently reducing the temperature gradient inside the box.

After the improvements made, the loss factor was reduced to 0.36W/°C, representing 83% less, which will help in the stability of the tests, improving repeatability and reproducibility. Another point is that with the new configuration reduces the possibility of instability in some tests, where the average of the points around the box was correct, but the gradient was high, with the current configuration the air is forced to circulate throughout the box. Another conclusion is that the increase of measurement points around the vessel and an analysis of the difference between them will contribute to reducing uncertainties.

4. REFERENCES

ANSI/ASHRAE Standard 23. 2019. "Methods for Performance Testing Positive Displacement Refrigerant Compressors and Compressor Units".

APEC Energy Working Group. 2018. "Refrigerator/Freezer Energy Efficiency Improvement in the APEC Region: Review of Experience and Best Practices". https://www.apec.org/publications/2018/12/refrigerator-freezer-energy-efficiency-improvement-in-the-apec-region. Accessed 28 May 2023.

Barbosa, Fúlvio Queiroz. 2006. "Redução das incertezas nas medições de grandezas elétricas em uma bancada de ensaios de desempenho de compressores". UFSC - Mechanical Engineering Postgraduate Program.

CEN. 2016. "Compressors and Condensing Units for Refrigeration. Performance Testing and Test Methods Refrigerant Compressors".

Flesch, Rodolfo C.C., e Julio E. Normey-Rico. 2010. "Modelling, Identification and Control of a Calorimeter Used for Performance Evaluation of Refrigerant Compressors". *Control Engineering Practice* 18 (3): 254–61.

IIR. 2015. "The Role of Refrigeration in the Global Economy". https://iifiir.org/en/fridoc/the-role-of-refrigeration-in-the-global-economy-2015-138763. Accessed 05 Jun 2023.

ISO. 1989. "ISO 917 - Testing of Refrigerant Compressors". Switzerland.

Negrão, Cezar O.R., Raul H. Erthal, Diogo E.V. Andrade, e Luciana Wasnievski Da Silva. 2011. "A Semi-Empirical Model for the Unsteady-State Simulation of Reciprocating Compressors for Household Refrigeration Applications". *Applied Thermal Engineering* 31 (6–7): 1114–24. https://doi.org/10.1016/j.applthermaleng.2010.12.006.

Rossetto, João Paulo Rossetto. 2014. "Análise de fontes de erro na medição de vazão mássica em ensaios de compressores de refrigeração". UFSC - Federal University of Santa Catarina - Mechanical Engineering Postgraduate Program.

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