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ANALYSIS OF THE INFLUENCE OF THERMAL LOAD AND DOOR OPENING ON A REFRIGERATION TEACHING BENCH

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Abstract: The development of technologies that seek to reduce energy consumption in refrigeration systems is highly relevant today. Research on didactic refrigeration benches shows the importance of understanding how certain variables can influence the energy consumption of commercial refrigerators. Didactic refrigeration benches are equipment that can help to understand the effects of adverse operating conditions and how they impact on equipment efficiency. This study addresses the impact of door opening and thermal load on the refrigeration teaching bench in the thermal sciences laboratory at the University Center of Brusque - UNIFEBE. Experiments were carried out with and without thermal load, and with and without door openings. Opening the door on the bench resulted in a 3.67% increase in average energy consumption. The added thermal load contributed to an average increase of 6.7% in energy consumption. Due to the opening of the door, and the humidity that entered the system, there is an extra energy consumption of 28.75 kWh per year. Measured values and calculations showed an increase in energy consumption in the experiments carried out on the teaching bench related to the thermal load and door opening. The results highlight the importance of controlling energy consumption and reducing the frequency and time of door openings on refrigerators, contributing to the conscious and sustainable use of this equipment.

Keywords: Refrigeration; Teaching bench; Experiment; Consumption; Energy.

INTRODUCTION

The Second Law of Thermodynamics deals with heat transfer, where the tendency is to seek thermal equilibrium, which occurs naturally, where the body with the higher temperature transfers heat to the one with the lower temperature. In the case of refrigeration, the aim is to cool a particular environment, so for the cycle to happen, work is included in the system. The transformation of this energy makes it possible to change the physical state of the refrigerant, ensuring that heat is removed from the insulated environment. This simple concept is widely applied in our daily lives, in commercial, residential and industrial refrigeration (ÇENGEL; BOLES, 2006).

According to ABRAVA (2019), Brazil ranks sixth among the countries with the most expensive energy in the world. The Instituto Escolhas (2021) cites that refrigerators account for 31.9% of a household's consumption. It should be noted that these are essential goods, and are part of 98.1% of the country's properties. Thus, there are actions to mitigate this advance, based on the current implementation of regulations related to efficiency and performance, information contained in the Inmetro label.

The Brazilian Center for Energy Efficiency (2023) reports that the average monthly consumption of a 2-door *frost free* refrigerator is 56.88 kWh. Graphically, Fig. 1 shows the distribution of energy required according to the equipment used in a home.

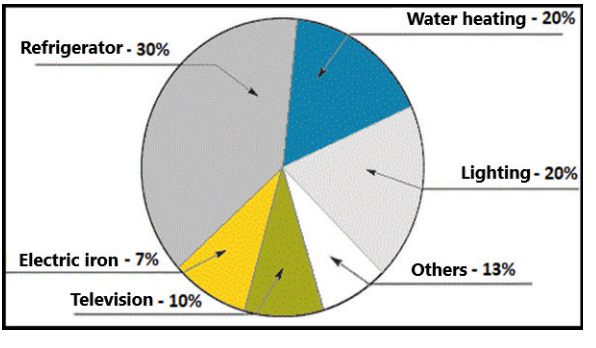

Figure 1 - Electricity Consumption in a Household

Source: EFLUF (2023).

It is true that any generation of work requires the release of energy, but there are also several other factors that interact with this process. In the case of equipment such as fridges, efficiency involves the habits of users. Agência Brasil (2023) points out that when refrigerators are used, the sides of the product must be kept away from other bodies in order to ensure adequate heat exchange, and they must have insulation rubber in good condition, as well as avoiding the ingress of hot air as much as possible.

The material of the object used in food storage also directly influences the efficiency of the refrigeration system. This is due to the variation in heat transfer capacity from one material to another. In the case of good thermal conductors, we have metal containers and also glass, meaning that as well as keeping food cold for longer, they reduce the workload of the refrigeration system compared to plastic containers (AGÊNCIA NACIONAL DE VIGILÂNCIA SANITÁRIA, 2015).

Changes in humidity in the internal environment have a significant impact on the energy consumption of a refrigerator, where these variations can occur both in conditions where the door remains closed and when the door is opened. However, in the open door condition, humidity transfer changes according to the number and duration of openings. Finally, it was found that the consumption of a refrigerator with door openings is 8% higher than the same refrigerator without openings (SAIDUR *et al.*, 2007).

When investigating the use of a domestic refrigerator in Bangladesh, it has been shown that energy consumption increases when the door is opened, with this figure varying by 7-30%, depending on the number of openings, compared to the closed door condition. In addition, it has been shown that temperature fluctuations inside the cabin due to door openings damage the quality of stored food (KHAN; AFROZ, 2014).

With a theoretical in-depth study of refrigeration procedures, based on practical tests aided by a didactic bench, this article aims to study how the variables thermal load and door opening impact on the increase in power consumption of refrigerators. In addition, it presents data that expands knowledge about the didactic refrigeration bench, facilitating its operation and the inclusion of future practical studies from the thermal sciences subjects taught at the UNIFEBE institution.

LITERATURE REVIEW

Refrigeration is based on removing heat from a body in order to reduce its temperature by transferring the heat to another body. Any physical or chemical phenomenon that occurs endothermically can be used to produce cold. However, it was with the advent of electricity that the first automatic refrigerator appeared (1918). And so, in 1928, based on the refrigerants developed by Mr. Thomas Midgely, there was a great advance in the refrigeration industry (MATOS, 2010).

VAPOR COMPRESSION REFRIGERATION SYSTEMS

The main way to build a refrigeration system is from the work done by a refrigerant, where it follows the compression stages, condensation, expansion and evaporation. Formulating a theoretical model of an ideal refrigeration cycle, we have the reverse Carnot cycle, Fig. 2, which is a purely reversible cycle, i.e. there are no losses. Initially, the fluid is compressed isentropically (1-2); there is an increase in pressure and temperature, so the amount of heat QH is expelled isothermally (2-3); there is isentropic expansion (3-4), where the pressure and temperature are reduced; and finally, there is isothermal absorption of heat from the body with the lowest temperature, with QL being the amount absorbed (4-1) (ÇENGEL; BOLES, 2006). This cycle is applied in a comparative way, where real cycles should be modeled to present the highest possible coefficient of efficiency (COP), seeking an increase in temperature during the condensation phase and a reduction in temperature during evaporation (STOECKER, 1985).

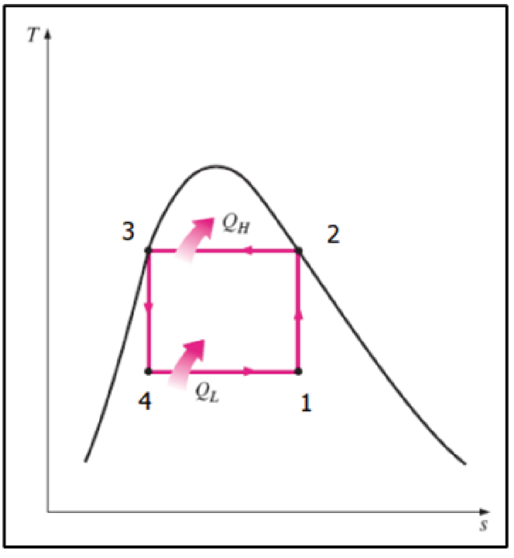

Figure 2 - Reverse Carnot cycle

Source: Çengel; Boles (2006).

The representation of the standard vapor compression refrigeration cycle in a T-s diagram is shown in Fig. 3, following the scheme presented earlier. On line 1-2, the fluid, which was in the saturated vapor state, is compressed isentropically until it reaches condensing pressure; in this transformation, the temperature of the refrigerant exceeds the external temperature of the system. Heat is then rejected to the environment at constant pressure, reaching point 3, where the refrigerant reaches the saturated liquid state. Expansion then takes place up to point 4, defined by the evaporation pressure, and in this segment of the cycle the fluid has a temperature lower than that of the refrigerated environment in question. Finally, the fluid receives heat at constant pressure until it reaches the saturated vapor state, point 1, closing the cycle (STOECKER, 1985).

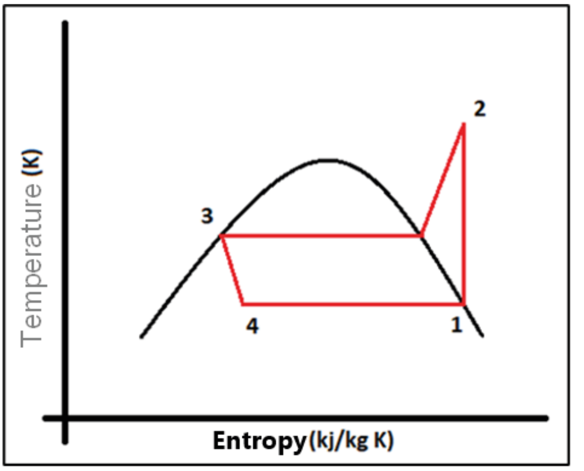

Figure 3 - Ideal Steam Compression Cycle

Source: Stoecker (1985).

However, in practice we are faced with the real refrigeration cycle, which is not reversible. It has substantial temperature differences in the heat exchangers due to losses related mainly to friction in the fluid flow tubes. As a result, the compressor and expansion valve do not act isoentropically. These variations can be seen in Fig. 4 (ÇENGEL; BOLES, 2006).

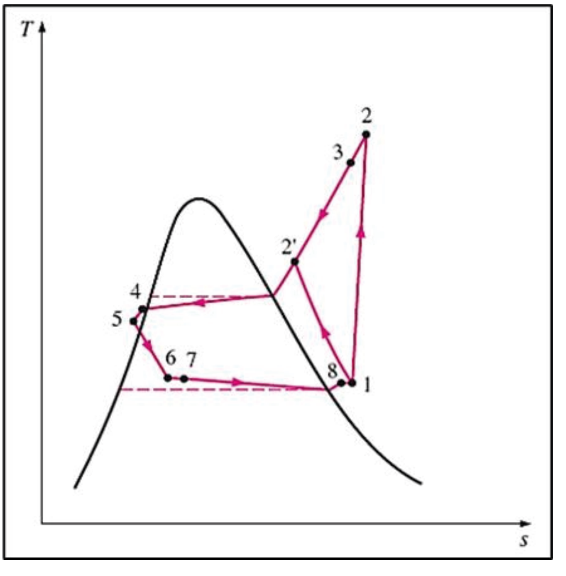

Figure 4 - Real refrigeration cycle

Source: Çengel; Boles (2006).

Figure 5 shows how the cycle works. The refrigerant enters the compressor, after compression it goes to the condenser with high pressure, where heat is transferred until the refrigerant becomes liquid, so it is expanded in the valves, its pressure reduces, and consequently, part of the liquid evaporates instantly (VAN WYLEN; SONNTAG; BORGNAKKE, 1995).

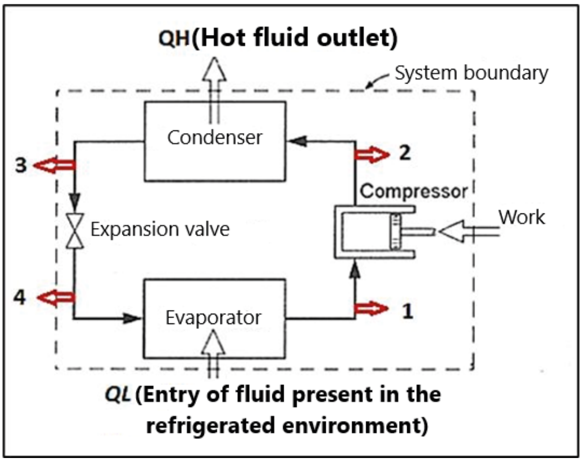

Figure 5 - Refrigeration cycle

Source: Van Wylen; Sonntag; Borgnakke (1995).

So there you have it:

1-2 Isentropic compression in the compressor;

2-3 Heat rejection at constant pressure in the condenser;

3-4 Isoenthalpic expansion in an expansion device;

4-1 Heat absorption at constant pressure in the evaporator.

For a refrigerator, the heat is absorbed by the freezer tubes, which act as an evaporator, and is dissipated to the environment by the rear coil, which serves as a condenser, Fig. 6 (ÇENGEL; BOLES, 2006).

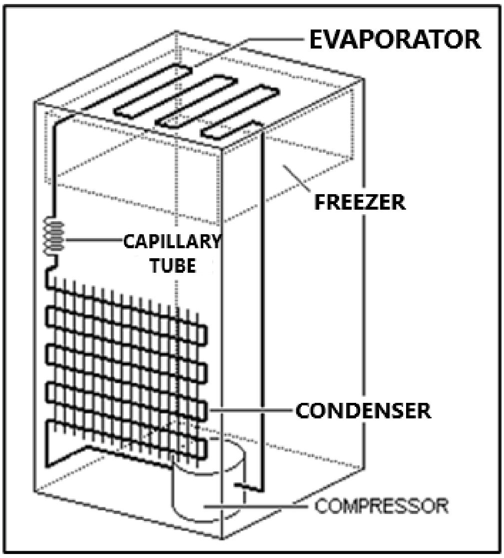

Figure 6 - Representation of a domestic refrigerator

Source: Çengel; Boles (2006).

RESIDENTIAL, COMMERCIAL AND INDUSTRIAL REFRIGERATION

Among the fields of refrigeration, the equipment is set up in a similar way. Residential refrigeration is limited to the manufacture of household refrigerators, freezers and air conditioners. Samsung (2023) reports that the temperature of a refrigerator varies, but its ideal working standard is 1°C to 7°C. For a freezer, on the other hand, due to the need to freeze the food, the equipment must have negative temperatures, in the range of -14°C to -25°C.

For commercial and industrial refrigeration, higher power is required to reach lower temperatures, where freezing and storage temperatures are between -5°C and -30°C. In these applications, due to the greater demand, more intermediate components are integrated within the four base points of the cycle (WEBARCONDITIONADO, 2016).

REFRIGERATION TEACHING BENCHES

Didactic workbenches are designed to enable practical activities related to a specific topic, where the process of gaining knowledge takes place from a different perspective, as it is done actively. Didactic refrigeration benches make it possible to analyze each stage of the cycle presented above, as well as its components. Among the various configurations, one can target a specific branch of the refrigeration area, and some examples are listed below.

Loesch, Santos and Garcia (2012) presented the development of a teaching bench capable of simulating desired faults manually. The conventional circuit of a refrigerator served as the basis for the work, but a refrigerant gas reservoir, four solenoid valves and two fans were added, making it possible to include the desired faults. The programming *software* used by the authors was called *Codesys*, which makes it possible to carry out, configure, test, condition and visualize the processes to be programmed and automated. The faults presented were: lack of refrigerant gas, capillary tube obstruction and fan failure. The lack of refrigerant gas can lead to the absorption of humidity, which in more serious cases could cause the compressor to burn out. Obstruction of the capillary tube would prevent the refrigerant from passing through the refrigeration circuit. Faulty evaporator and condenser fans can cause damage to stored products and the compressor, as well as making it difficult to expel heat to the outside environment if the condenser fan is affected.

Campos (2015) built a practical module for a mechanical compression refrigeration system. The author details the calculation of the thermal load, the value needed to define the system's refrigeration capacity and, consequently, for sizing the bench. Equations and calculations are presented for each heat source, including losses due to transmission, infiltration, product, packaging, lighting and occupancy, resulting in a total heat load of 717.761 kcal/24h. This bench makes it possible to carry out practical work evaluating the components and measuring pressures and temperatures at various points in the system.

Queiroz (2013) made a teaching bench for a domestic absorption refrigeration system, also with the aim of demonstrating how the refrigeration cycle works. The bench was based on the absorption system of a Consul Junior fridge. During construction, the system was painted in different colors to differentiate the stages of the refrigeration cycle, making it easier to see the transformations that take place, as shown in Fig. 7.

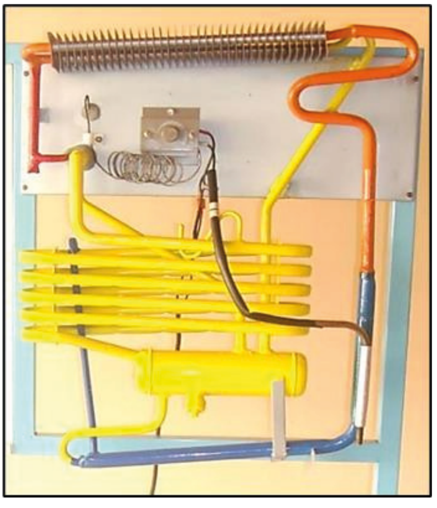

Figure 7 - Teaching bench

Source: Queiroz (2013).

SIGNIFICANT VARIABLES IN INCREASING POWER IN REFRIGERATORS

Some points are considered in relation to the inclusion of heat in the refrigerated environment, which consequently imply an increase in energy consumption. These include transmission heat, which refers to the exchange of heat with the external environment through the structure and materials of the refrigerator; infiltration heat, which is the heat that comes from the external environ-

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ment and invades the refrigerated environment when doors are opened; and heat from people, products and packaging, which refers to the bodies that are included in the cabinet (SILVA, 2018).

Thermal load

The thermal load of a system is determined by the amount of heat that must be removed from the refrigerated environment. The lower the temperature required inside the refrigerator, the greater the energy and, consequently, the greater the thermal load required. In addition to the product to be cooled, other factors such as thermal insulation material, internal equipment (motors, fans, light fittings), access frequency (door openings) also affect the thermal load. Controlling these aspects is essential for reducing energy consumption (NETO *et al.*, 2018).

Toigo (2017) developed a didactic bench featuring a vapor compression refrigeration system. By adjusting the thermal load, the COP of the entire system was obtained. He presented the two ways of modifying the thermal load on the evaporator: by adjusting the power of the heating element or by varying the speed of the water pump in tank 2, using a frequency inverter. There are two more frequency inverters that also made it possible to change the cooling capacity, one located at the refrigerant outlet and the other at the condenser inlet. The results obtained show that the bench is 9% more efficient when working with a low thermal load (1300 W), compared to the test with a high thermal load (1800 W).

Opening doors

The temperature of the room in which the refrigerator is installed is one of the most important variables when it comes to energy consumption, but in addition to this, so is the temperature of the room in which the refrigerator is installed.

Just as important is the number of times, and the length of time, that the refrigerator door is opened (KAO; KELLY, 1996). When the door is opened, natural convection takes place, where air from the outside environment replaces air from the inside (SAIDUR *et al.*, 2007).

When you open the door of a refrigerator, warm, humid air from the outside invades the refrigerated room, increasing the heat load. This increases energy consumption. In addition to affecting the condition of the items that require certain refrigeration, as in the case of food in domestic fridges. Liu, Chang and Lin (2004) start from this concept and show the variation in energy consumption of these systems during door opening and temperature changes in the compartments. The tests they carried out involved collecting data over a 10-hour period, where the freezer compartment door was opened 15 times at 40-minute intervals and the food compartment door was opened 50 times at 12-minute intervals. The data obtained from a refrigerator with a fixed working frequency, where the compressor was controlled by an ON/OFF button, and another with a variable frequency, where the compressor was automatically controlled, were compared. As a result, the variable frequency showed better results, i.e. lower energy consumption, because the system corresponds more efficiently to the fluctuations caused by the air entering through the doors, when the internal standard temperature is gradually re-established.

In an experiment carried out at the Energy Conservation Laboratory, Department of Mechanical Engineering, University of Malaya, the energy consumption of a domestic refrigerator was measured under different conditions. The effects of the number of door openings, duration of each door opening, ambient temperature, thermal load and thermostat position were investigated. The results showed that the actual average energy consumption was 3.3 kWh per day, with the energy consumption of the open door being 40% higher compared to the closed door test, proving that the opening of doors directly affects the consumption of the refrigerator (HASANUZZAMAN; SAIDUR; MASJUKI, 2008).

Grimes, Mulroy and Shomaker (1977) collected data from a refrigerator during 8 hours of operation, during which time the door was opened 24 times. The 8-hour period was used to simulate residential use, dividing the time into three groups representing the three daily meals: breakfast, lunch and dinner. For each of these groups, the door was opened 8 times, each lasting 10 seconds, for a period of 1 hour. Tests were carried out replicating the same conditions, but without the door being opened. This proved that energy consumption was 6-8% higher in the case of door opening.

2.4.3 Relative humidity

Saidur, Masjuki and Jamaluddin (2006) considered that humidity has an impact on energy consumption. Correlating humidity and door opening, we have the transfer of latent heat due to the exchange of air inside the refrigerated environment, where the refrigerator dehumidifies the air after closing the door. Using the study by Grimes, Mulroy and Shomaker (1977) as support, where an increase of 5% was found when the relative humidity was changed from 40% to 60%, a variation from 60% to 90% was tested, corresponding to an increase in consumption of 10%.

METHODOLOGICAL PROCEDURES

Figure 8 illustrates the main stages in the development of the work.

TEACHING BENCH IN THE THERMAL SCIENCES LABORATORY AT UNIFEBE

The general layout of the bench is based on a commercial refrigerator. Its structure is made from aluminum profiles, with the dimensions already following the standard of the other laboratories (1200 x 700 x 1755mm) (Fig. 8). Figure 9A shows the front view of the bench, with the drive panel and other components. The refrigerated internal space has dimensions of 540 x 550 x 730 mm. The condensing unit is fitted with the ELGIN model UCP - 0085-E21 and the evaporator with the ELGIN VCM - 0015 -ER. There are two pressure gauges in the analog monitoring unit, for high and low pressure measurement, shown next to the capillary tube. Figure 9 B shows the refrigerator door, which is the rear view of the bench. The refrigeration space is thermally insulated, and the materials used to make it were galvanized steel sheets and polyurethane (PU) panels. The connections are made of copper pipes. The system works with the refrigerant R134A, following the manufacturer's instructions, where the application range is -30°C to 5°C. It has a time to reach permanent operation of 35 minutes after the equipment is switched on (ROCHA; THIESSEN, 2018).

Figure 9 - Refrigeration teaching bench: A) Front view B) Back view

Source: From the authors (2023).

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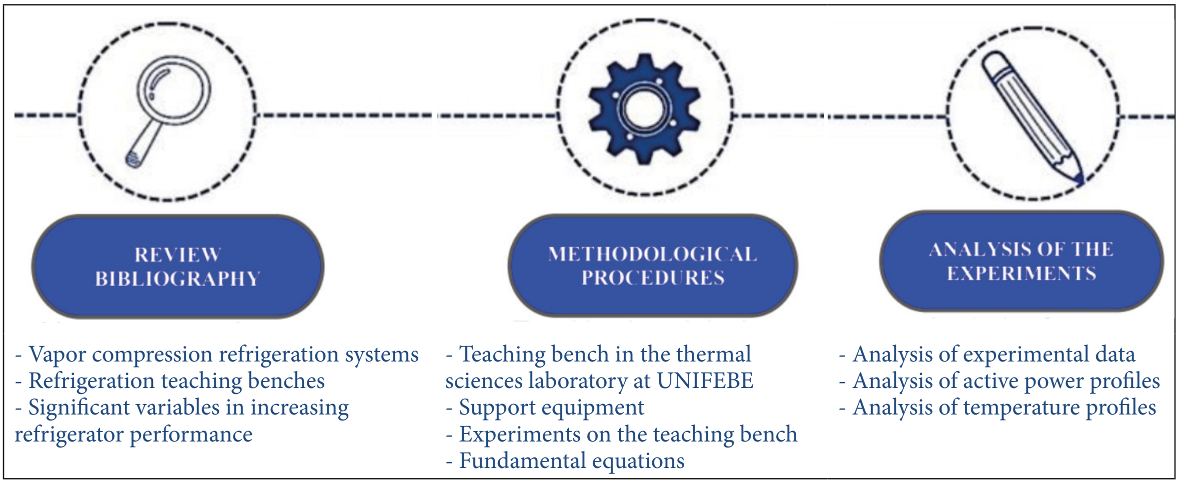

Figure 8 - Flowchart of the work stages

Source: From the authors (2023).

Coolant

The R134a refrigerant has emerged as an option to replace chlorofluorocarbons, especially CFC 12, which is widely used in domestic refrigeration and is highly damaging to the ozone layer. In addition to its socio-environmental advantages, R134a is widely used in medium temperature conditions, as it generates good efficiencies. One aspect to note is that due to its boiling point of -26°C, there are certain limitations depending on the refrigeration need (HEREDIA- ARICAPA *et al.*, 2020).

Sensors

The teaching bench makes it possible to carry out experiments where it is necessary to monitor the stages within the actual refrigeration cycle. Thus, there are monitoring sensors for obtaining and evaluating quantities such as temperature, power, energy consumption, among others. The Energylog Plus 01 sensor (Fig. 10 A), from Full Gauge, monitors the energy consumption, power and working frequency of the compressor. The TC 900E Log/03 sensor (Fig. 10 B) controls the temperature inside the refrigerated room. It is able to self-manage according to a pre-set temperature and can trigger the defrosting of the evaporator. To assess sub-cooling and overheating, there is the TI 44E Plus sensor (Fig. 10 C). In order to make it easier to carry out the cycles, this equipment is connected to a computer using the CONV32 device (Fig. 10 D) and then communicated with Sitrad Pro (FULL GAUGE, 2023).

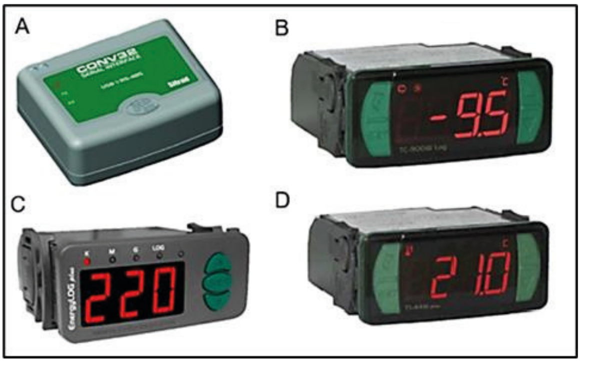

Figure 10 - Equipment used: A) CONV32 B) TC 900E Log/03 C) Energylog Plus 01 D) TI 44E Plus

Source: Full Gauge (2023).

Software

With a view to the practical and accessible management of various processes involving refrigeration, heating, air conditioning and solar heating, Fullgauge supplies the Sitrad Pro *software*. It can handle and store temperature, humidity, time, pressure and voltage data,

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making it possible to change these parameters safely and accurately. This system is applicable to various areas, such as supermarkets, refrigerators, hotels, hospitals, among others, and much of this is the result of its comprehensiveness and mobility, allowing remote access to the control panels installed at the desired workstation (SITRAD®, 2023).

Once the *software* has communicated with the bench, the data from each sensor is read as shown in Figs. 11, 12 and 13.

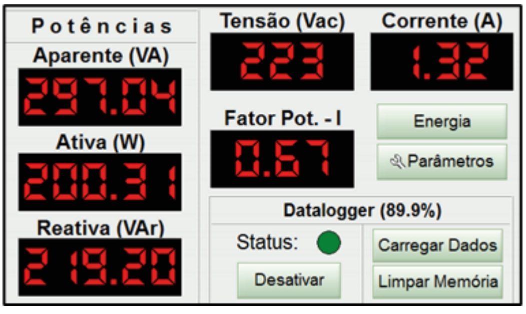


Figure 11 - Energylog Plus 01 sensor

Source: From the authors (2023).

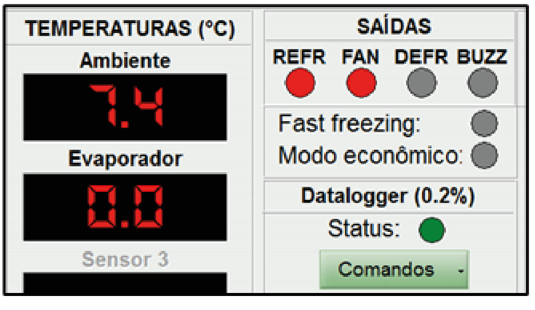


Figure 12 - TC 900E Log/03 sensor

Source: From the authors (2023).

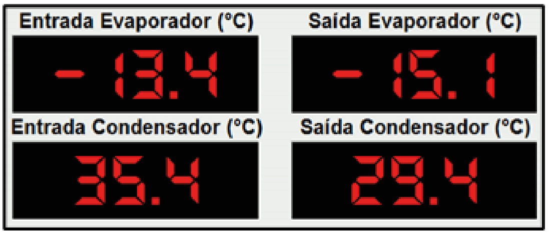


Figure 13 - TI 44E Plus sensor

Source: From the authors (2023).

SUPPORT EQUIPMENT

The following items include the support equipment that enabled the experiments to be carried out, both for preparing the thermal load and for obtaining data and monitoring the significant variables considered.

Container for thermal load

An aluminum container with dimensions of Ø250 x 150 mm, a wall thickness of 1mm and a capacity of 6 liters is used.

Electric stove

Among the other pieces of equipment used during the experiments was the Agratto FM-02 Stainless Steel Electric 2-Burner Stove (Fig. 14). The stove has independent temperature control for each burner and a light to indicate its operation. Its structure is made of stainless steel. The set has dimensions of 505X85x280 mm and power of 2500W (AGRATTO, 2023).

Figure 14 - Agratto FM-02 Stainless Steel 2-burner Electric Table Stove

Source: Agratto (2023).

Thermohygrometer

The thermo-hygrometer from the manufacturer Minipa, model MT-242A, is applied (Fig. 15). The equipment specifications are shown below:

- Sampling frequency (temperature and humidity): 10s;
- Storage environment: -temperature -20°C ~ 60°C; -humidity 20% ~ 80% RH;
- Dimensions: 78(H) x 130(W) x 23(D) mm;
- Accuracy: ± 1.0°C / ± 5% RH (MINIPA DO BRASIL, 2023).

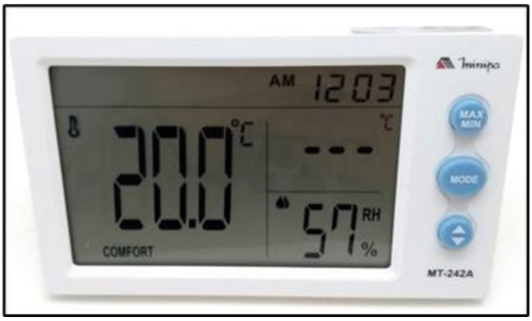


Figure 15 - Thermo-Hygrometer MT-242A
Source: Minipa do Brasil (2023).

Thermometer

The water heating is measured using Fluke's 59 MAX infrared thermometer. It has an operating range of -30 °C to 350 °C and an accuracy of ±2.0 °C (Fig. 16) (FLUKE, 2023).

Figure 16 - Infrared thermometer 59 MAX
Source: Fluke (2023).

EXPERIMENTS ON THE TEACHING BENCH

The experiments were carried out on the refrigeration bench in the thermal sciences laboratory at the Brusque University Center (UNIFEBE). The experiments began 35 minutes after the bench was switched on, at which point the permanent regime was reached (ROCHA; THIESSEN, 2018). During the course of the experiments, the readings of the manometers and sensors on the bench and the thermo-hygrometer, which were in the refrigerated environment, were recorded every 10 minutes. Each experiment lasted 180 minutes and is described in sections 3.3.1 and 3.3.2, 3.3.3 e 3.3.4.

Experiment 1: With thermal load and no door opening

In experiment 1, 5 liters of water were heated to 60 ºC in the aluminum container, which was the thermal load considered. Data was collected on the external environment, temperature and relative humidity. The container with the thermal load was then placed in the refrigerated room. The thermo-hygrometer to collect temperature and humidity data from the refrigerated environment. In this experiment, the refrigerator door was kept closed.

Experiment 2: With thermal load and door opening

In experiment 2, 5 liters of water were heated to 60 ºC in the aluminum container, which was the thermal load considered. Data was collected on the external environment, temperature and relative humidity. The container with the thermal load was then placed in the refrigerated room. The thermo-hygrometer was also inserted to collect temperature and humidity data from the refrigerated environment. The average relative humidity in the laboratory was 84% and the average temperature was 26.5 ºC, while the average relative humidity in the refrigerated environment was 62% and the average temperature was 6.8 ºC.

This experiment included opening the door every 10 minutes. An opening was defined in the pattern called 3-30-3, where the opening movement takes 3 seconds until the door is at 90 degrees to the initial position, it remains open for 30 seconds, and finally closes with a movement lasting 3 seconds. The opening time was defined as presented by Souza (2019), where it was found that in the 30-second period there is a large variation in the internal temperature of the refrigerator, and that this thermal load, due to the exchange of air from the refrigerated environment with the external environment, influences the energy consumption of the compressor.

Experiment 3: No heat load and door opening

The same procedures were carried out as in experiment 2, but in this case without inserting the thermal load inside the refrigerator. However, the defined door opening pattern was maintained as in experiment 2. The external environment, temperature and relative humidity data were recorded and the thermo-hygrometer was inserted into the refrigerated environment. The average relative humidity in the laboratory was 81% and the average temperature was 21 ºC, while the average relative humidity in the refrigerated environment was 74% and the average temperature was -2.1 ºC.

Experiment 4: No heat load and no door opening

In experiment 4, the bench was left undisturbed by the previous variables, i.e. without thermal load and without opening the door. In addition, the same procedures were carried out as in the previous experiments, with data being collected every 10 minutes.

FUNDAMENTAL EQUATIONS

The following are the steps involved in processing the data relating to the opening of the door and, consequently, the entry of humidity into the refrigerated environment. Initially, Eq. 1 is used to quantify the air transfer rate to the refrigerated environment. Once this first equation has been solved, we move on to Eq. 2, which is used to obtain the water vapor transfer rate to the refrigerated environment. For the second equation, we use the psychrometric chart in the Appendix, where we find the absolute humidity values correspondents. Finally, using Eq. 3, we obtain the values for the amount of water that has entered the cabinet.

$$\dot{m}_{ar} = \frac{\rho_{ar} V_{amb}}{\Delta t} \qquad \text{Eq. (1)}$$

where:

ρ_{ar} - air density [kg/m];3

V_{amb} - volume of the refrigerated room [m^3];

Δt - door opening time [s].

$$\dot{m}_{H_2O} = \dot{m}_{ar}(\omega_{lab} - \omega_{amb}) \qquad \text{Eq. (2)}$$

where:

$\dot{m}_{ar}$ - air transfer rate [kg/s];

ω_{lab} - absolute humidity of the laboratory [g of H2O/kg of dry air];

ω_{amb} - absolute humidity of the refrigerated environment [g of H2O/kg of dry air].

$$m_{H_2O} = \dot{m}_{H_2O} N \Delta t \qquad \text{Eq. (3)}$$

where:

$\dot{m}_{H_2O}$ - water vapor transfer rate [g/s];

N - number of door openings per hour;

Δt - door opening time [s].

In order to quantify the additional energy consumption both for the inclusion of thermal load and for the case of door openings, Eq. 4 is presented.

$$E = P_c - P_S \qquad \text{Eq. (4)}$$

where:

P_C - average active power of the experiments with door opening / with thermal load [W];

P_S - average active power of the experiments without opening the door / without thermal load [W].

Eq. 5 is used to convert the calculated consumption to energy consumption in relation to time.

$$E = Pt \quad \text{Eq. (5)}$$

where:

P - active power [W];

t - time [h];

RESULTS

The results obtained from the experiments carried out on the refrigeration teaching bench are shown in the following sections.

Analysis of the experiments

Table 1 below shows the average data for active power and temperature in the refrigerated environment for the experiments carried out.

Analysis of experimental data

By analyzing the data above and using Equations 1, 2, 3, 4 and 5, it was found that:

a) In terms of opening the door and humidity entering the system, for the experiments with a thermal load, experiments 1 and 2, there was an increase in the average energy consumption of the teaching bench of 4.06%. For the experiments carried out without a thermal load, experiments 3 and 4, there was an increase in average energy consumption of 3.55%, due to the door opening process. Comparing these values to the results of Grimes, Mulroy and Shomaker (1977), the bench functioned consistently, with door opening representing a similar increase in energy consumption to the 6-8% shown by the authors. It is worth noting that the additional consumption below the value presented by the aforementioned authors is due to the number of openings and the time of the experiments, where in the experiments carried out at UNIFEBE a smaller number of openings and experiments with a reduced duration were considered.

b) When the thermal load was added to the system, for the experiments carried out with the door open, experiments 2 and 3, there was an increase in average energy consumption of 7.44%. For the experiments carried out without opening the door, experiments 1 and 4, there was an increase in average energy consumption of 6.91%. Comparing these values with the work of Toigo (2017), who found a 9% increase in consumption in the case of a higher thermal load, again confirms the consistent operation of the teaching bench.

c) With regard to the inclusion of humidity, quantifications of the mass of water entering the refrigerated environment were obtained. For the experiment carried out without a thermal load and with the door open, experiment 3, it was calculated that 16.27 g of water entered the refrigerated environment in one hour. This means that 47.51 kg/year of water enters the refrigerated environment. For experiment 2, with a thermal load and door opening, it was calculated that 22.52 g of water entered the system in one hour. This means that 65.76 kg/year of water enters the refrigerated environment. Considering the values obtained in each experiment, the average amount of water entering the refrigerated environment due to the door opening is 56.64 kg/year.

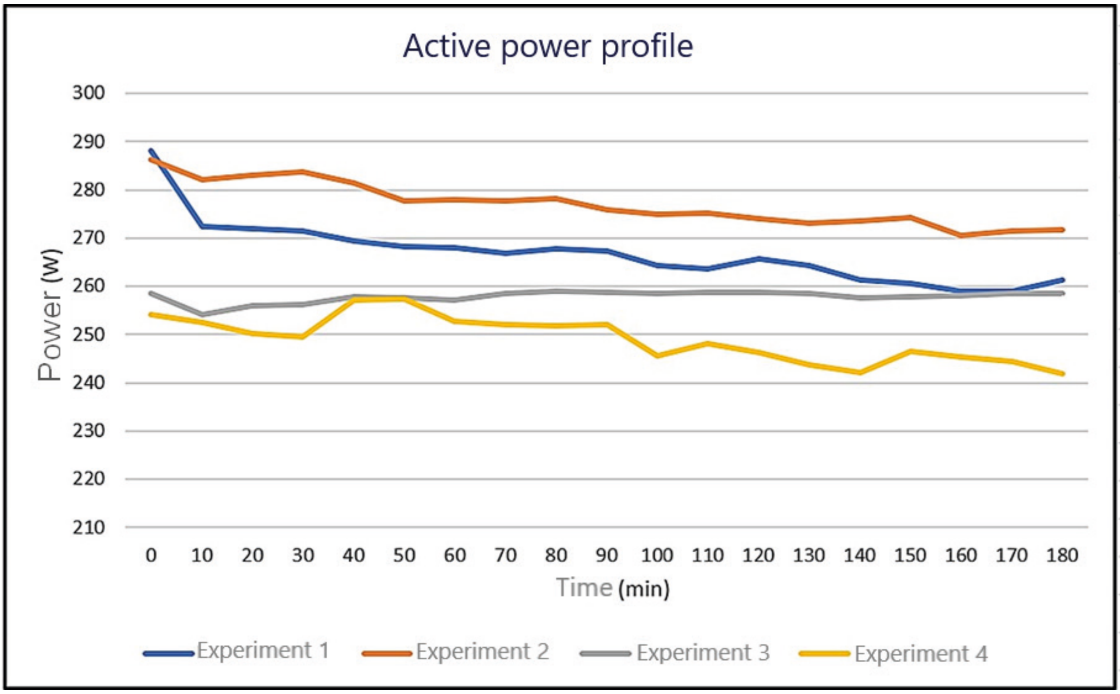
d) Assuming the situation described in the experiments, the energy consumption due to moisture transfer in one year is 28.75 kWh/year.

e) Assuming the situation described in the experiments, the energy consumption due to the thermal load is 53.25 kWh/year.

	Experiment 1	Experiment 2	Experiment 3	Experiment 4
Active power (W)	266,83	277,67	258,44	249,59
Room temperature refrigerated (ºC)	2,88	7,41	-2,39	-6,4

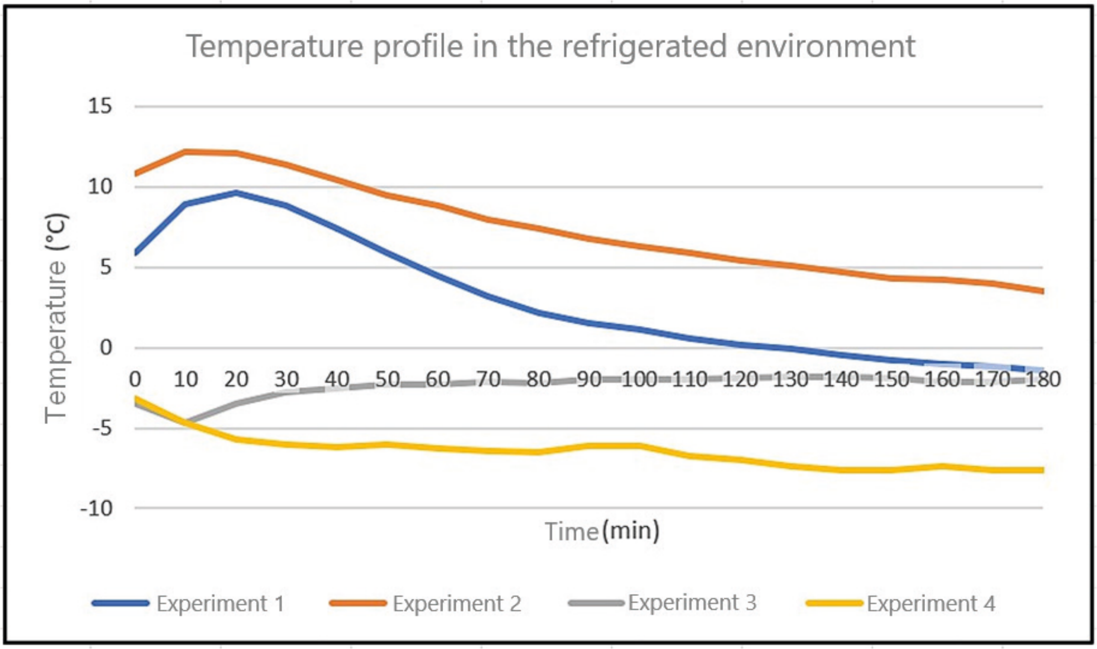
Table 1 - Average data from the experiments

Source: From the authors (2023).



Graph 1 - Active power profile

Source: From the authors (2023).



Graph 2 - Temperature profile of the refrigerated environment

Source: From the authors (2023).

Analysis of active power profiles

The active power profiles for experiments 1, 2, 3 and 4 are shown in Graph 1.

It can be seen that experiment 2 consumed the most energy due to the thermal load and door opening, thus proving the great impact of these variables. Experiment 4, on the other hand, was the one with the lowest active power, because in this case the bench operated without a thermal load and without opening the door.

Analysis of temperature profiles

Looking at the temperature profiles inside the refrigerated environment (Graph 2), we can see the tendency for the temperature to decrease and remain constant in search of a working range close to 0 ºC. Even in experiment 2, where there was a thermal load and the door was opened, the bench showed a significant difference in terms of the highest and lowest temperatures found during the 3-hour period, with a maximum temperature of 12.2 ºC and a minimum of 3.5 ºC. In experiment 4, the refrigerated environment reached the lowest temperature recorded of all the experiments, at -7.6 ºC.

Over time, even in experiments with a greater influence on the variables, the temperatures get lower and lower. This is because the control environment (walls and other components of the structure of the refrigerated environment) remains refrigerated. In other words, even with the insertion of the thermal load (5 liters of water at 60 ºC), and with the door openings, the bench requires less work than it did initially, when it was necessary to cool the cabinet.

FINAL CONSIDERATIONS

Based on all the results presented, it can be concluded that:

- Average energy consumption increased by 53.25 kWh/year, representing an increase of 6.7% due to the insertion of a thermal load in the system;
- Average energy consumption increased by 28.75 kWh/year, representing a 3.67% increase in consumption due to moisture entering the system during door openings;
- Based on the humidity introduced into the experiments from the openings, the average annual water intake is 56.64 kg;
- The lower the frequency of door openings and the lower the amount of thermal load on the system, the lower the internal temperature of the system will remain;
- With regard to the temperature profiles, the bench was able to maintain a trend of temperature reduction and stability, even in the experiment with a thermal load and with the door open;
- The average temperature values showed that 13.81 °C was the difference between the highest and lowest temperatures found in the system;
- The values found in the study showed that door openings and the increase in thermal load in refrigeration systems have an impact on the energy consumption of the process.

Suggestions for future work:

- Automate door openings on the refrigeration teaching bench to increase experimentation time;
- Vary the experiments with more different humidity and thermal load data in the system;
- Perform advanced statistical analysis of experimental data collected in experiments.

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APPENDIX

MEMORIAL OF CALCULATIONS

AIR TRANSFER RATE TO THE REFRIGERATED ENVIRONMENT

$$\dot{m}_{ar} = \frac{\rho_{ar} V_{amb}}{\Delta t} \quad \text{Eq. (1)}$$

where:

ρ_{ar} - air density = 1.201 [kg/m];3

V_{amb} - volume of the refrigerated room = 0.217 [m];3

Δt - door opening time = 30 [s].

WATER VAPOR TRANSFER RATE TO THE REFRIGERATED ENVIRONMENT

$$\dot{m}_{H_2O} = \dot{m}_{ar}(\omega_{lab} - \omega_{amb}) \quad \text{Eq. (2)}$$

where:

$\dot{m}_{ar}$ - air transfer rate = 0.00869 [kg/s];

ω_{lab} - absolute humidity of the laboratory for experiment 2 = 18.6 [g of H2O/kg of dry air];

ω_{lab} - absolute humidity of the laboratory for experiment 3 = 13 [g of H2O/kg of dry air];

ω_{amb} - absolute humidity of the refrigerated environment for experiment 2 = 4.2 [g of H2O/kg of dry air].

ω_{amb} - absolute humidity of the refrigerated environment for experiment 3 = 2.6 [g of H2O/kg of dry air].

Experiment 2:

$$\dot{m}_{H_2O} = 0{,}00869\ (18{,}6 - 4{,}2) = 0{,}1251\ g/s$$

Experiment 3:

$$\dot{m}_{H_2O} = 0{,}00869\ (13 - 2{,}6) = 0{,}0904\ g/s$$

TOTAL MASS OF WATER TRANSFERRED TO THE REFRIGERATED ENVIRONMENT

$$m_{H_2O} = \dot{m}_{H_2O} N \Delta t \quad \text{Eq. (3)}$$

where:

$\dot{m}_{H_2O}$ - water vapor transfer rate for experiment 2 = 0.1390 [g/s];

$\dot{m}_{H_2O}$ - water vapor transfer rate for experiment 3 = 0.0912 [g/s];

N - number of door openings per hour = 6;

Δt - door opening time = 30 [s].

Experiment 2:

$$m_{H_2O} = 0{,}1251\ .\ 6\ .\ 30 = 22{,}52\ g\ ou\ 0{,}02252\ kg$$

$$0{,}02252kg\ .\frac{8h}{\text{day}}.\frac{365day}{\text{year}} = 65{,}76\ kg/\text{year}$$

Experiment 3:

$$m_{H_2O} = 0{,}0904\ .\ 6\ .\ 30 = 16{,}27\ g\ ou\ 0{,}01627\ kg$$

$$0{,}01627kg\ .\frac{8h}{\text{day}}.\frac{365day}{\text{year}} = 47{,}51\ kg/\text{year}$$

Average:

$$\bar{m} = \frac{65{,}76 + 47{,}51}{2} = 56{,}64\ kg/\text{year}$$

ADDITIONAL ENERGY CONSUMPTION DUE TO MOISTURE TRANSFER AND THERMAL LOAD

$$E = P_c - P_S \qquad \text{Eq. (4)}$$

where:

P_C - average active power of the experiments with door opening - experiments 2 and 3 = 268.055 [W];

P_S - average active power of experiments without door opening - experiments 1 and 4 = 258.21 [W].

P_C - average active power of experiments with thermal load - experiments 1 and 2 = 272.25 [W];

P_S - average active power of the experiments without thermal load - experiments 3 and 4 = 254.015 [W].

Door opening:

$$E = 268{,}055 - 258{,}21 = 9{,}845\ W$$

$$9{,}845W.\frac{8h}{\text{day}}.\frac{365day}{\text{year}} = 28747\frac{Wh}{\text{year}}\ ou\ \frac{28{,}75kWh}{\text{year}}$$

Thermal load:

$$E = 272{,}25 - 254{,}015 = 18{,}235\ W$$

$$18{,}235W.\frac{8h}{\text{day}}.\frac{365day}{\text{year}} = 53246\frac{Wh}{\text{year}}\ ou\ \frac{53{,}25kWh}{\text{year}}$$

PSYCHROMETRIC CHART

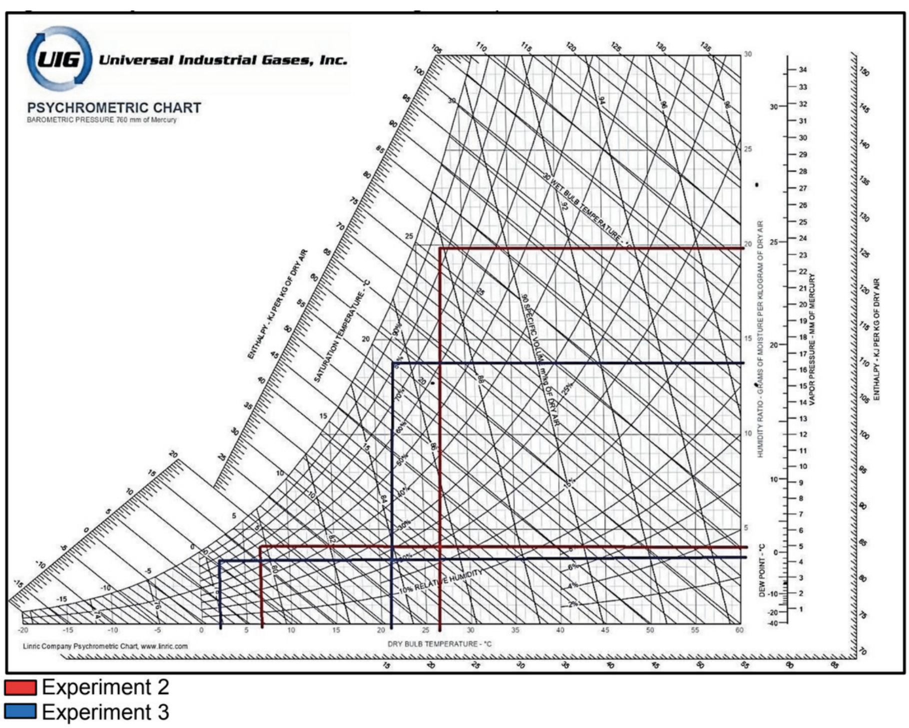


Figure 1 - Psychrometric chart with markings for experiments 2 and 3

Source: Adapted from Universal Industrial Gases, Inc. (2023).

EXPERIMENT DATA

EXPERIMENT 1 - WITH THERMAL LOAD AND NO DOOR OPENING

Experiment 1										
Time (min)	0	10	20	30	40	50	60	70	80	90
Apparent power (VA)	391,48	377,64	376,26	375,19	373,21	373,03	373,67	372,86	378,1	379,42
Active power (W)	288,18	272,45	271,95	271,49	269,43	268,34	268,01	266,83	267,8	267,25
Reactive power (VAr)	264,9	261,4	259,9	258,9	258,2	259,1	260,2	260,3	266,9	269,3
Voltage (Vac)	222	221	221	221	221	221	221	222	224	225
Power Factor -1	0,73	0,72	0,72	0,72	0,72	0,72	0,71	0,71	0,71	0,7
Current (A)	1,75	1,69	1,69	1,69	1,68	1,68	1,68	1,67	1,68	1,67
Refrigerated room temperature (ºC)	5,9	8,9	9,6	8,8	7,4	5,9	4,5	3,2	2,2	1,5
Evaporator temperature (ºC)	5,2	8,4	8,8	7,7	6,2	4,6	3,1	1,8	0,8	0,2
4 -Evaporator input (ºC)	-9	-6,7	-6,6	-6,9	-7,3	-7,8	-8,4	-8,7	-9,2	-9,6
1 -Evaporator output (ºC)	-3,6	6,5	6,5	5,6	3,6	1,7	0	-1,8	-3,3	-4,8
2 -Condenser input (ºC)	45,6	47,1	47,7	48	47,8	47,6	47,6	47,5	47,2	47
3- Condenser output (ºC)	27,7	27,7	27,8	27,9	28,1	28,2	28,3	28,4	28,5	25,5
High pressure (kPa)	950	900	900	900	900	900	900	900	900	900
Low pressure (kPa)	110	100	100	100	100	100	100	100	100	100
Temperature by Thermohygrometer (ºC)	22,6	9,8	9,4	8,8	7,8	5,8	4,2	2,8	1,7	0,5
Relative humidity (%)	38	78	75	68	66	62	60	59	60	60

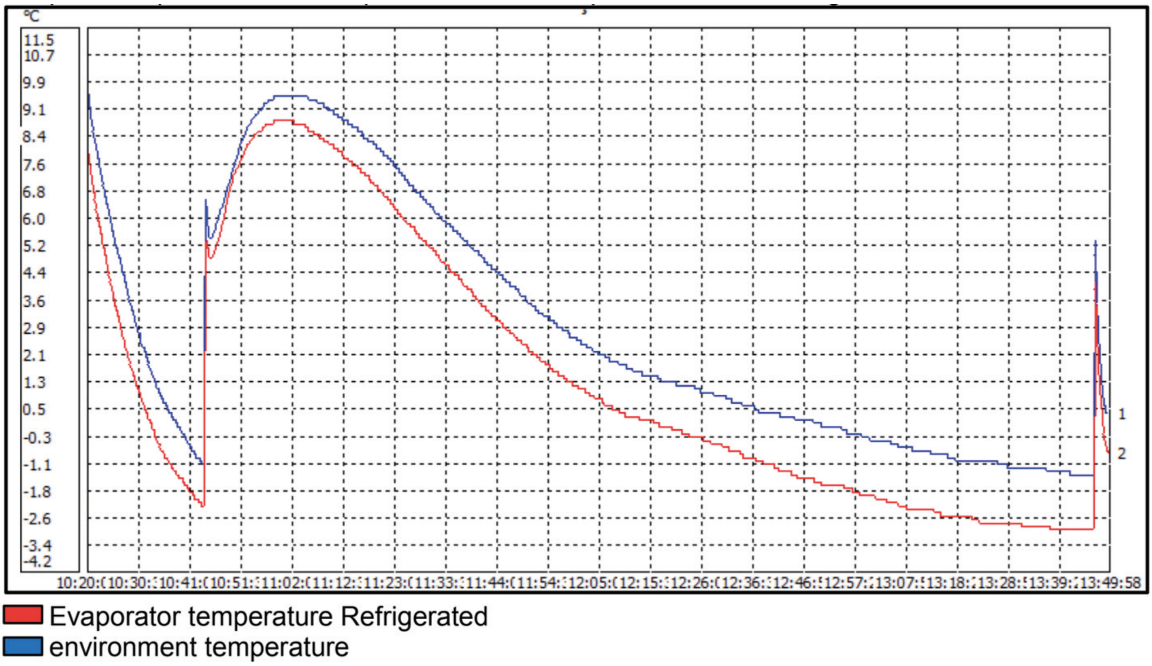
Table 1 - Data from experiment 1 - 0 to 90 minutes

Source: From the authors (2023).

Experiment 1									
Time (min)	100	110	120	130	140	150	160	170	180
Apparent power (VA)	372,19	370,06	376,93	374,38	371,38	369,95	366,64	366,34	374,33
Active power (W)	264,36	263,52	265,7	264,4	261,29	260,58	258,95	258,91	261,42
Reactive power (VAr)	261,9	259,7	267,3	264,9	263,8	262,6	259,5	259,1	267,9
Voltage (Vac)	222	221	224	223	223	222	221	221	225
Power Factor -1	0,71	0,71	0,7	0,7	0,7	0,7	0,7	0,71	0,7
Current (A)	1,66	1,66	1,67	1,66	1,65	1,65	1,65	1,65	1,65
Refrigerated room temperature (ºC)	1,1	0,6	0,2	-0,1	-0,5	-0,8	-1	-1,2	-1,4
Evaporator temperature (ºC)	-0,3	-0,9	-1,4	-1,8	-2,2	-2,6	-2,8	-2,9	-3
4 -Evaporator input (ºC)	-9,8	-10	-10,2	-10,4	-10,9	-11,3	-11,5	-11,5	-11,5
1 -Evaporator output (ºC)	-6,9	-8,7	-10,9	-11,3	-11,8	-12	-12,2	-12,2	-12,2
2 -Condenser input (ºC)	46,9	46,7	46,7	46,4	46	46,1	46	46	45,9
3- Condenser output (ºC)	28,7	28,7	28,9	28,9	28,8	28,9	28,8	28,9	29,2
High pressure (kPa)	900	900	900	900	850	850	850	850	850
Low pressure (kPa)	100	100	100	100	90	90	90	90	90
Temperature by Thermohygrometer (ºC)	0,2	-0,4	-0,8	-1,2	-1,6	-1,9	-2,2	-2,5	-2,6
Relative humidity (%)	60	59	59	58	58	57	57	57	57

Table 2 - Data from experiment 1 - 100 to 180 minutes

Source: From the authors (2023).



Graph 1 - Experiment 1 - Temperature of the evaporator and the refrigerated environment

Source: From the authors (2023).

EXPERIMENT 2 - WITH THERMAL LOAD AND DOOR OPENING

Experiment 2										
Time (min)	0	10	20	30	40	50	60	70	80	90
Apparent power (VA)	390,87	387,05	386,9	388,12	386,49	383,8	384,55	384,05	383,24	380,38
Active power (W)	286,34	282,14	283,07	283,72	281,39	277,67	277,88	277,7	278,16	275,96
Reactive power (VAr)	266	264,9	263,8	264,8	264,9	265	265,8	265,2	263,6	261,7
Voltage (Vac)	223	222	222	223	223	224	224	223	222	222
Power Factor -1	0,73	0,73	0,73	0,73	0,73	0,72	0,72	0,72	0,72	0,72
Current (A)	1,75	1,73	1,73	1,73	1,72	1,71	1,71	1,71	1,71	1,7
Refrigerated room temperature (ºC)	10,8	12,2	12,1	11,4	10,4	9,5	8,8	8	7,4	6,8
Evaporator temperature (ºC)	9,5	11,2	11	10	9	8,1	7,3	6,4	5,9	5,3
4 -Evaporator input (ºC)	-6,8	-5,3	-4,4	-4,7	-5,1	-5,8	-6	-6,3	-6,3	-6,6
1 -Evaporator output (ºC)	5,5	9,6	9,6	8,5	7,6	6,8	5,9	5,2	4,6	3,9
2 -Condenser input (ºC)	47,5	49	50,1	50,1	50,2	49,9	49,8	49,8	50	49,8
3- Condenser output (ºC)	28,5	28,8	29,1	29,1	29,1	28,9	28,9	29	29,1	29,1
High pressure (kPa)	1000	1000	1000	1000	1000	1000	1000	1000	1000	1000
Low pressure (kPa)	110	110	110	120	120	120	110	110	100	110
Temperature (ºC) - before opening		12,8	13,8	13,1	12,2	11,2	10,4	9,6	8,9	8,2
Relative humidity (%) - before opening		72	67	63	63	62	61	61	61	60
Temperature (ºC) - after opening	24,4	13,5	14,2	13,6	12,7	11,8	11,2	10,2	9,5	9,1
Relative humidity (%) - after opening	53	91	90	90	89	92	92	92	91	91

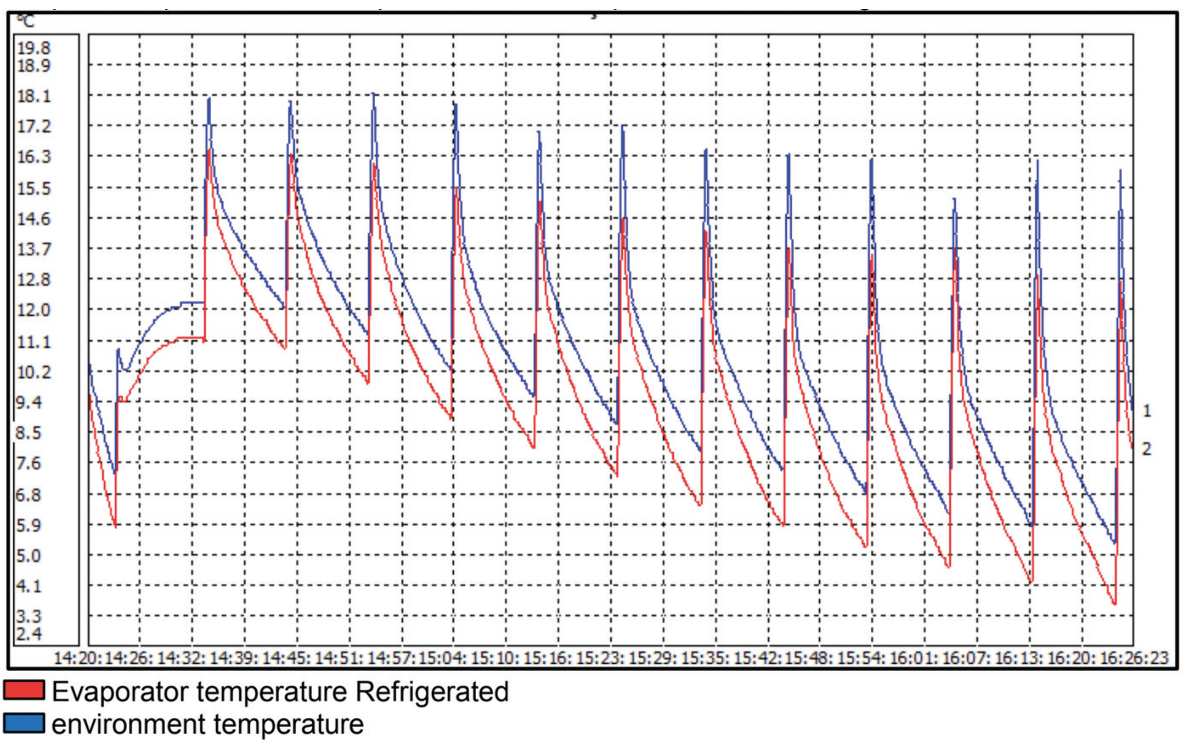
Table 3 - Data from experiment 2 - 0 to 90 minutes

Source: From the authors (2023).

Experiment 2									
Time (min)	100	110	120	130	140	150	160	170	180
Apparent power (VA)	380,13	379,93	378,94	378,5	381,58	383,34	373,77	376,37	376,26
Active power (W)	274,99	375,18	274,09	273,12	273,63	274,26	270,48	271,49	271,66
Reactive power (VAr)	262,4	262	261,7	262	265,8	267,8	257,9	260,6	260,3
Voltage (Vac)	222	222	222	222	224	224	221	221	221
Power Factor -1	0,72	0,72	0,72	0,72	0,71	0,71	0,72	0,72	0,72
Current (A)	1,7	1,7	1,69	1,69	1,7	1,7	1,68	1,69	1,69
Refrigerated room temperature (ºC)	6,3	5,9	5,4	5,1	4,7	4,3	4,2	4	3,5
Evaporator temperature (ºC)	4,7	4,2	3,7	3,3	3	2,5	2,5	2,2	1,9
4 -Evaporator input (ºC)	-6,8	-6,9	-7,1	-7,3	-7,5	-7,6	-7,7	-7,7	-7,9
1 -Evaporator output (ºC)	3,3	2,7	2,1	1,7	1,4	0,9	0,8	0,6	0,2
2 -Condenser input (ºC)	49,3	49,6	49,6	49,3	49,1	49	48,7	48,6	48,5
3- Condenser output (ºC)	29,1	29,2	29,2	29,2	29	29,1	29	29	28,9
High pressure (kPa)	1000	1000	950	950	950	1000	950	950	950
Low pressure (kPa)	110	110	110	100	110	120	100	100	100
Temperature (ºC) - before opening	7,5	7,1	6,5	6,1	5,8	5,4	5,2	5	4,8
Relative humidity (%) - before opening	62	62	62	62	62	62	64	64	64
Temperature (ºC) - after opening	8,2	8,1	7,6	7,2	6,6	6,6	6,3	6,1	5,5
Relative humidity (%) - after opening	91	91	91	94	93	94	94	94	94

Table 4 - Data from experiment 2 - 100 to 180 minutes

Source: From the authors (2023).



Graph 2 - Experiment 2 - Temperature of the evaporator and the refrigerated environment

Source: From the authors (2023).

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EXPERIMENT 3 - NO HEAT LOAD AND DOOR OPENING

Experiment 3										
Time (min)	0	10	20	30	40	50	60	70	80	90
Apparent power (VA)	372,07	367,31	370,36	368,73	370,11	369,75	369,55	370,97	372,04	372,5
Active power (W)	258,57	254,04	256,05	256,13	257,75	257,52	257,1	258,44	258,99	258,86
Reactive power (VAr)	267,5	265,3	267,5	265,2	265,6	265,2	265,3	266	267,1	267,9
Voltage (Vac)	224	223	224	224	224	224	223	224	224	224
Power Factor -1	0,69	0,69	0,69	0,69	0,69	0,7	0,7	0,7	0,7	0,69
Current (A)	1,65	1,63	1,64	1,64	1,64	1,64	1,64	1,64	1,65	1,65
Refrigerated room temperature (ºC)	-3,5	-4,7	-3,5	-2,8	-2,5	-2,3	-2,3	-2,1	-2,2	-2
Evaporator temperature (ºC)	-5,4	-6,3	-5,9	-4,1	-4,1	-3,8	-3,7	-3,7	-3,7	-3,8
4 -Evaporator input (ºC)	-12,4	-12,9	-12,2	-11,7	-11,6	-11,5	-11,4	-11,5	-11,4	-11,5
1 -Evaporator output (ºC)	-12,7	-13,6	-9,3	-7,9	-7,6	-7,3	-7,2	-6,7	-6,7	-6,3
2 -Condenser input (ºC)	41,7	41,3	42,1	42,9	42,8	43,4	43	43,3	43,1	43,2
3- Condenser output (ºC)	25,3	25,7	25,1	25,1	25,1	25,3	25,1	25,3	25,3	25,1
High pressure (kPa)	750	800	800	800	800	800	800	800	800	800
Low pressure (kPa)	80	80	80	90	90	90	90	90	90	90
Temperature (ºC) - before opening		-5,1	-4,1	-3,3	-3,1	-3	-2,9	-2,6	-2,7	-2,6
Relative humidity (%) - before opening		46	72	77	75	76	74	75	74	75
Temperature (ºC) - after opening	13,5	0,1	0,8	0,8	0,9	1,2	1,4	1,2	1,2	1,3
Relative humidity (%) - after opening	46	62	79	82	80	81	80	81	80	81

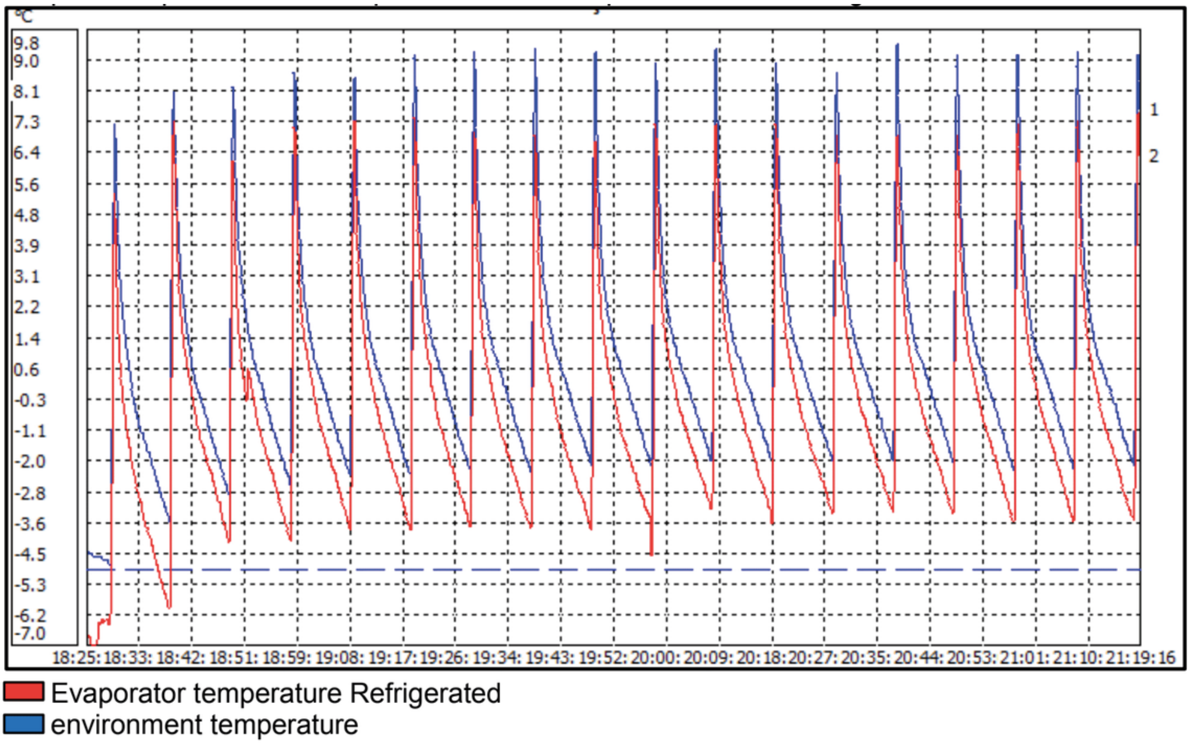
Table 5 - Data from experiment 3 - 0 to 90 minutes

Source: From the authors (2023).

Experiment 3									
Time (min)	100	110	120	130	140	150	160	170	180
Apparent power (VA)	372,04	372,85	372,65	372,55	369,8	370,51	371,89	371,84	372,24
Active power (W)	258,49	258,72	258,74	258,47	257,65	257,86	258,03	258,45	258,61
Reactive power (VAr)	267,6	268,4	268,1	268,3	265,3	266,1	267,7	267,3	267,6
Voltage (Vac)	224	224	225	225	223	224	225	224	224
Power Factor -1	0,69	0,69	0,69	0,69	0,7	0,69	0,69	0,69	0,69
Current (A)	1,64	1,65	1,64	1,65	1,64	1,65	1,64	1,64	1,65
Refrigerated room temperature (ºC)	-2	-2	-1,9	-1,8	-1,8	-1,9	-2,1	-2,1	-2
Evaporator temperature (ºC)	-3,6	-3,3	-3,4	-3,3	-3,2	-3,3	-3,5	-3,6	-3,5
4 -Evaporator input (ºC)	-11,3	-11,5	-11,5	-11,4	-11,4	-11,4	-11,5	-11,5	-11,6
1 -Evaporator output (ºC)	-6,4	-6,2	-6,2	-6,2	-6,2	-6,2	-6,7	-6,6	-6,6
2 -Condenser input (ºC)	43,2	43,1	43,1	43,3	43,2	43,3	43,3	43,1	43,2
3- Condenser output (ºC)	25,2	25,2	25,1	25,2	25,2	25,1	25	25,1	25,1
High pressure (kPa)	800	800	800	800	800	800	800	800	800
Low pressure (kPa)	90	90	90	90	90	90	90	90	90
Temperature (ºC) - before opening	-2,6	-2,5	-2,5	-2,3	-2,5	-2,5	-2,5	-2,5	-2,7
Relative humidity (%) - before opening	74	74	74	75	74	75	74	74	74
Temperature (ºC) - after opening	1,5	1,4	1,5	1,7	1,4	1,5	1,3	1,2	1,3
Relative humidity (%) - after opening	81	81	81	81	80	82	80	81	80

Table 6 - Data from experiment 3 - 100 to 180 minutes

Source: From the authors (2023).



Graph 3 - Experiment 3 - Temperature of the evaporator and the refrigerated environment

Source: From the authors (2023).

EXPERIMENT 4 - NO HEAT LOAD AND NO DOOR OPENING

Experiment 4										
Time (min)	0	10	20	30	40	50	60	70	80	90
Apparent power (VA)	368,78	367,41	363,39	364,81	369,85	371,63	367,77	368,43	368,42	369,85
Active power (W)	254,21	252,47	250,31	249,59	257,15	257,44	252,66	252,1	251,86	252,13
Reactive power (VAr)	267	266,9	263,3	266,1	265,8	268	267,2	268,1	268,9	270,5
Voltage (Vac)	224	224	223	224	223	224	224	224	225	225
Power Factor -1	0,69	0,69	0,68	0,68	0,7	0,69	0,68	1,64	0,68	0,68
Current (A)	1,63	1,63	1,62	1,62	1,65	1,65	1,63	0,68	1,63	1,64
Refrigerated room temperature (ºC)	-3,2	-4,7	-5,7	-6	-6,2	-6	-6,3	-6,4	-6,5	-6,1
Evaporator temperature (ºC)	-4,2	-5,7	-7	-7,3	-7,5	-7,1	-7,4	-7,5	-7,7	-4,4
4 -Evaporator input (ºC)	-12,5	-13,1	-13,7	-13,9	-13,5	-13,2	-13,6	-13,8	-14,2	-11,3
1 -Evaporator output (ºC)	-8	-13,6	-14,3	-14,6	-14,1	-13,7	-14,2	-14,5	-14,7	-12,4
2 -Condenser input (ºC)	39,9	40,1	39,7	38,1	37,8	37,9	37,6	37,3	37,6	35
3- Condenser output (ºC)	23,7	23,8	24,2	24	24,2	24,7	24,4	24,4	24,2	24,2
High pressure (kPa)	750	750	750	750	750	750	750	750	750	750
Low pressure (kPa)	70	70	70	70	70	80	80	70	70	70
Temperature (ºC)	-3,5	-5,2	-6,3	-6,9	-6,5	-6,9	-7,1	-7,1	-7,2	-4,4
Relative humidity (%)	50	52	53	55	55	56	56	56	56	69

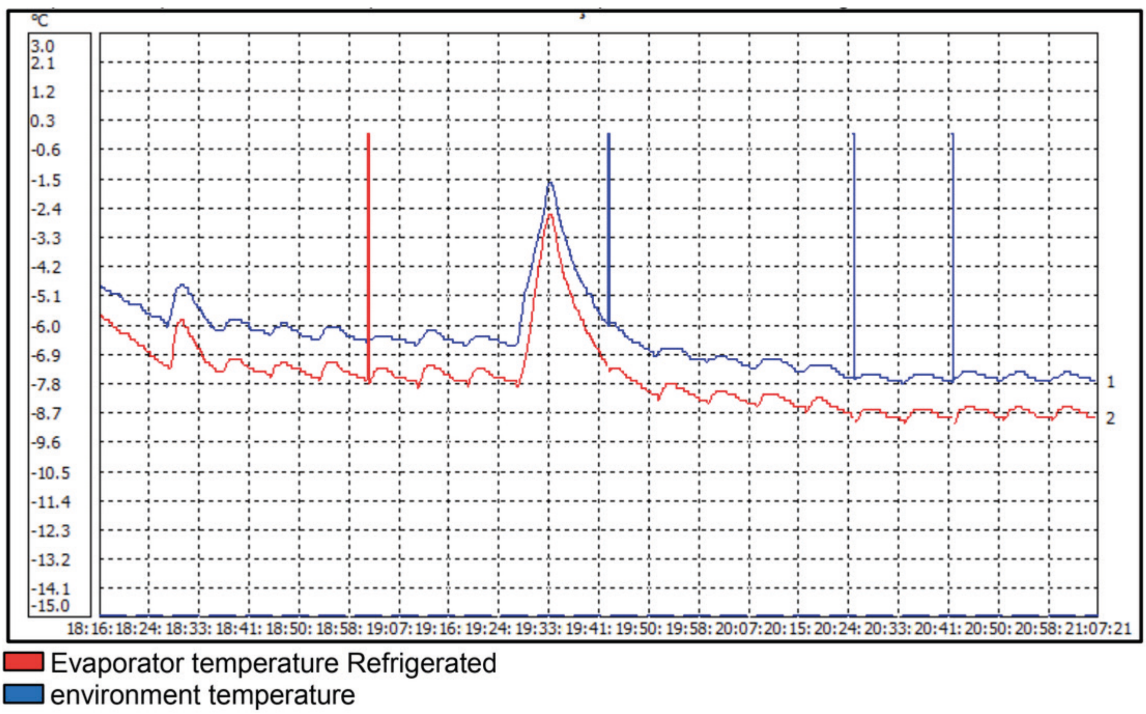
Table 7 - Data from experiment 4 - 0 to 90 minutes

Source: From the authors (2023).

Experiment 4									
Time (min)	100	110	120	130	140	150	160	170	180
Apparent power (VA)	364,76	366,49	365,88	363,39	361,97	367,31	365,68	365,42	359,88
Active power (W)	245,69	247,2	246,22	243,68	242,09	246,56	245,36	244,52	241,92
Reactive power (VAr)	269,6	270,4	270,5	269,5	269	272,2	271	271,5	266,3
Voltage (Vac)	225	226	225	226	225	226	226	226	224
Power Factor -1	0,67	0,67	0,67	0,67	0,67	0,67	0,67	0,67	0,67
Current (A)	1,61	1,61	1,61	1,6	1,6	1,61	1,61	1,6	1,59
Refrigerated room temperature (ºC)	-6,1	-6,7	-7	-7,4	-7,6	-7,6	-7,4	-7,6	-7,6
Evaporator temperature (ºC)	-7,4	-7,9	-8,2	-8,5	8,8	-8,7	-8,5	-8,6	-8,7
4 -Evaporator input (ºC)	-14,7	-14,7	-15,1	-15,6	-16	-15,5	-15,3	-15,6	-15,8
1 -Evaporator output (ºC)	-14,2	-15,4	-15,9	-16,1	-16,7	-16,2	-15,9	-16,4	-16,5
2 -Condenser input (ºC)	37,9	38,7	38,6	38,4	38,5	38,6	38,9	38,9	38,8
3- Condenser output (ºC)	23,4	23,8	23,7	23,6	23,4	23,6	23,8	23,6	23,6
High pressure (kPa)	700	700	700	700	700	700	700	700	700
Low pressure (kPa)	70	70	70	60	60	60	60	60	60
Temperature (ºC)	-6,5	-7,5	-7,8	-7,9	-8,2	-8,4	-8,2	-8,2	-8,3
Relative humidity (%)	55	55	55	55	54	54	55	55	55

Table 8 - Data from experiment 4 - 100 to 180 minutes

Source: From the authors (2023).



Graph 4 - Experiment 4 - Temperature of the evaporator and the refrigerated environment

Source: From the authors (2023).

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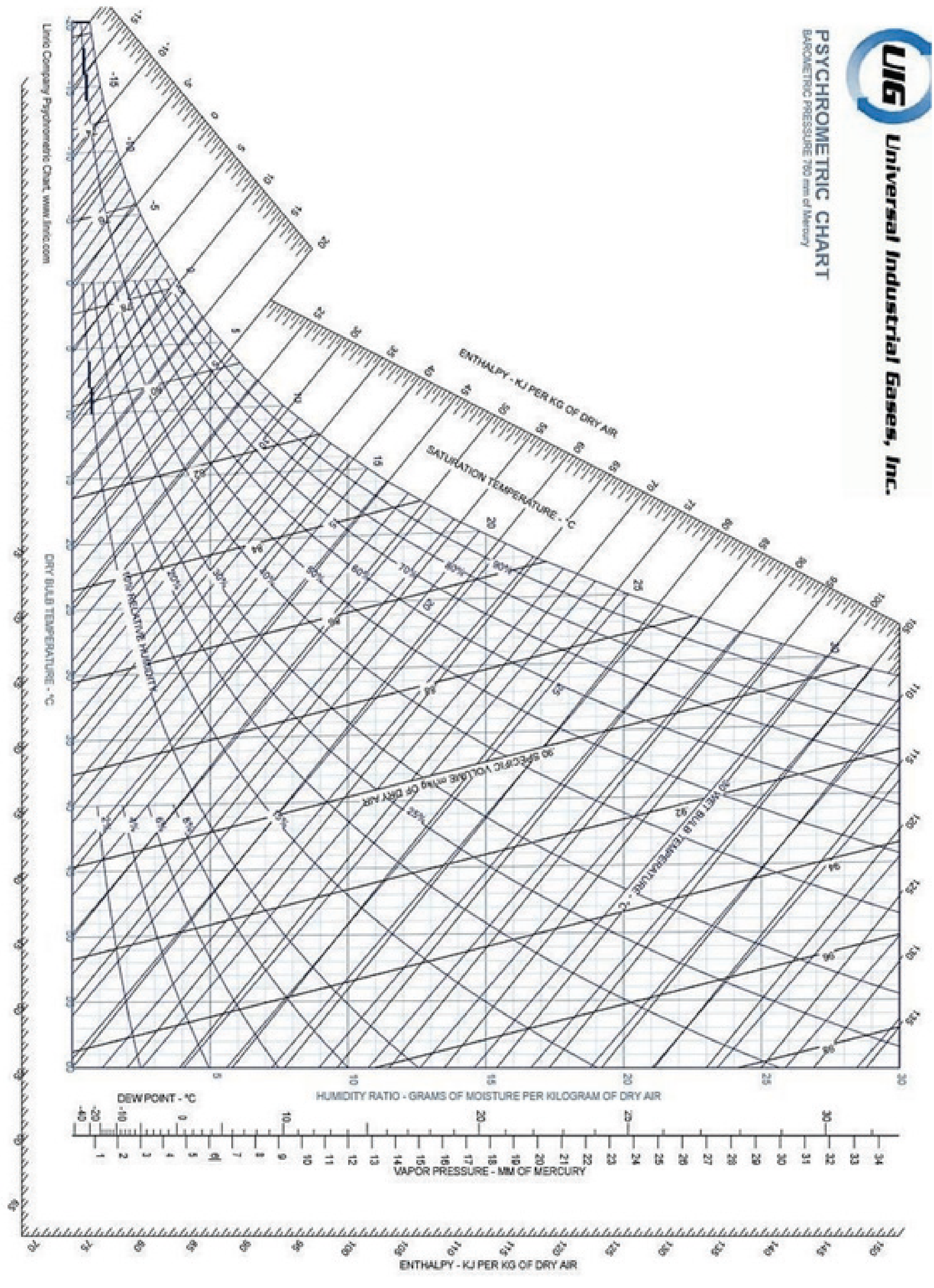
ANNEX 1 - PSYCHROMETRIC CHART



Source: Universal Industrial Gases, Inc. (2023).

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