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PERFORMANCE ANALYSIS OF A THERMOELECTRIC COOLING CHAMBER

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Abstract. *The worldwide need to seek maximum energy efficiency in its products and equipment, coupled with the specification of innovation in conditions of dimensional limitation, are some of the incentives that justify the study of alternative cooling techniques. There is a promising market to be explored in the country, with a strong growth trend, however, investments in research and development related to thermoelectric phenomena, especially those dedicated to refrigeration, are still modest in Brazil when compared to European countries. Thermoelectric cooling offers important benefits for the technology industry, but it still needs to be extensively researched, so that it can evolve at the pace required by the market, since it is still a non-viable solution for large applications, mainly due to: low COP; dimensional; the difficulties of dissipating the conducted heat; limited maximum thermal energy transfer rate. The Peltier effect is a physical phenomenon that generates a temperature gradient between the two junctions of two different materials when subjected to a potential difference in a closed circuit. Studies were carried out on the estimation of thermal loads in refrigeration applications and, based on this information, the prototype of a portable thermoelectric cooling chamber with a capacity of 21 liters with Styrofoam coating was built. This was cooled by two plates with a Peltier effect principle, which is coupled with commercial heat sinks originally used in processors with forced fan ventilation. The prototype and its components were subjected to a series of tests, these with natural and forced convection, in addition to the cooling of 500 ml of water; in order to analyze, understand, and characterize the behavior of the thermoelectric cooling device. Various temperature sensors were used to record the temperature on each side of the Peltier plates in addition to the temperature inside and outside the chamber. In the test with forced convection, the temperature reduction was 15 °C compared to the environment, higher than 12 °C in the case with natural convection in the period of one hour.*

Keywords: *cooling chamber, thermoelectricity, efficiency, cooling techniques*

1. INTRODUCTION

Technological advance tends to the continuous miniaturization of electronic devices. The worldwide need to seek maximum energy efficiency in its products and equipment, together with the complexity that affects innovation in conditions of dimensional limitation, are some of the incentives that justify the study of alternative cooling techniques.

For (Araújo, 2018), the first documented observation of the thermoelectric effect was made by Thomas Seebeck in 1821, who related the difference in electrical potential between joints of different materials. As early as 1834, Jean Charles Athanase Peltier, related the amount of heat that is transported by an electric current that passes through a material, which was called the Peltier coefficient. Thus, when two materials with different Peltier coefficients are placed in contact, there is a net flow of heat between the materials causing a difference in temperature (Flipse et al., 2012). Another advantage is the possibility of using the peltier effect in the production of electrical energy, if the temperature of the two metals is different (Piovani et al., 2014).

Thermoelectric coolers, based on the Peltier effect, operate with reduced sizes; can be integrated into electronic devices and circuits; do not require moving parts and/or refrigerant gases; have high durability and precision; and can be applied in cooling from a microprocessor chip to a portable refrigerator. However, the most powerful modules today can transfer around 250 W, and have dimensional limitations, around 60 mm, in addition to a low COP, between 0.4 and 0.7 (Danvic, 2021).

For (Çengel and Boles, 2013), currently, thermoelectric refrigerators do not compete with vapor compression refrigeration systems, due to the low coefficient of performance (COP). However, they are commercially available and are preferred for some applications because of their smaller size, simplicity, low noise and reliability.

This work aims to analyze, understand, and characterize the behavior of a thermoelectric cooling device in which it works through Peltier, through theoretical and practical approaches. A portable thermoelectric cooling chamber will be built in which theoretical and practical results will be compared.

2. METHODOLOGY

2.1 PELTIER COOLING CYCLE

In accordance with the publication of the Danvic (2021), thermoelectric inserts operate using the Peltier result, in which the voltage applied to the joint of two different materials creates a temperature difference. During the cooling, the thermal energy moves from one face to another through to the power supply. A typical Peltier system may contain a series of p-type components., a material with easy receiving electrons, and type-n, a material with easy electron donation, sorted in pairs, which will act as different conductors. Effectively, the structure of an electricity insert is designed as many thermally interconnected joints in parallel and electrically in series.

2.2 COOLING CHAMBER

Due to the appropriate adjustment in relation to the shrinkage allowed in thermoelectric refrigeration applications, a 21 dm³ box, from the Isofort brand, was selected to compose the fundamental structure of the chamber. It is manufactured in expanded polystyrene, is proven to be a great thermal insulator and analyzing its conductivity (0.033 W/mK), it was concluded that polystyrene would be the most suitable material for our device construction.

2.3 ESTIMATE OF THERMAL LOADS

The step before choosing the chips and/or heatsinks to be introduced into the cooling chamber is equivalent to defining the cooling demand, which starts by defining the amount of thermal energy to be transferred, that is, the "thermal load" of the system. The thermal load can be active, passive, or a mixture of the two. We can define active load, being that in which the heat is dissipated while it is being cooled, usually equivalent to the input power of the system. On the other hand, passive thermal loads are parasitic in nature and consist of radiation, convection, or conduction.

2.4 HEAT SINK

According Danvic (2021), the criterion for the choice or construction of the heat sink, also known as a heat exchanger, is very important in the operation of thermoelectric chips. Since, if the changer is not designed according to the configurations and characteristics of the system, the insert will be permanently damaged. Another notable factor for selection is the temperature distinction between the heat sink and the insert which will vary greatly.

Through equation 1, the exchanger resistance and its ability to dissipate heat will be measured:

$$R = \frac{T_1 - T_2}{q} \quad (1)$$

Generally speaking, it is advisable that for the application of inserts with up to 10W of Q_{max}, a standard aluminum heat sink can be used. For modules between 10W and 70W, a fan is suggested to amplify heat dissipation. If the wafers have a heat transfer greater than this limit, additional advanced heat sinks are required, using copper, or with a liquid cooling system.

2.5 THERMOELECTRIC TABLETS

As the operation of the thermoelectric chips are based on the Peltier Effect, they must be able to drive an extra heat transfer rate out of the chamber in order to stabilize the temperature inside the chamber. Camera at a minimum of 20 °C below room temperature, as well as any retention in the product. In particular, during a minimally accessible part of its time, especially in hot conditions, through the source's calculable thermals. Thus, the heat transfer analysis to select the insert was treated under steady state conditions, in which a safety margin was adopted in order to guarantee the correct

functioning of the device below than most require. When estimating these hundreds, the subsequent boundary conditions for cooling chamber operation:

Table 1. Boundary conditions adopted

Parameters	Reference
Room temperature	25°C + 5°C (tolerance) = 30°C
internal temperature	5°C - 5°C (tolerance) = 0°C
Thermal conductivity of walls	0.033W/mK
Total Surface Area	0.46978 m ²
Thickness of thermal insulation	25mm
Δt to reach Δt of 20°C	3 hours (10800 seconds)
No. of air changes	3.33 per hour (maximum limit)
period of operation	9 hours a day
Average air density	1.225 kg/m ³
chamber volume	0.021 m ³
Use of useful space	70%
Relative air humidity considered	80% (class 2)
Air enthalpy at 0°C	7.58 kJ/kg
Air enthalpy at 30°C	85.29 kJ/kg
Product-specific heat	4186 J/kg.K
Water density at 30°C	995.64 g/m ³

2.6 ACCESSORIES

Due to the convenience of access to the market and prices, the following were acquired:

- Four sets of coolers (Cooler Master, ø 80 mm, 12 V, 0.55 A) for forced air ventilation, with coupled heat sinks made of aluminum. The use of fins aims to maximize heat exchange by increasing the surface exchange area with air. Therefore, the designated geometry was the longitudinal fins, with rectangular section and profile. It will be named as “type A”;
- Two heat sinks also made of aluminum (104x150x25 cm). It will be named as “type B”;
- One changeable voltage supply system, with adjustments (19 V “no load” and 35 A current);
- One Computer power supply, Seasonic complete, with no-load voltage of 12 V and current maximum 18 to.
- Two insulation joints for Peltier boards (40 x 40 mm), composed of high-resistance thermal insulating foams;
- One digital multimeter (Minipa brand, model ET.1110A), with operation of temperature activity through a thermocouple;
- One white thermal paste, Implastec brand, with thermal conduction of 2 W/mk.

2.7 CAMERA ASSEMBLY

After performing the tests, it was found that the accessories were handled in the cooling chamber consecutively and in different mounting configurations, with impacts being monitored within the performance of the device, as follows:

- Perforation of the heat sinks: They were made to improve the contact pressure between the thermoelectric chips and the heatsinks, a fixation was carried out by means of screws, where the heat sink “Type B” was machined to create a perforation compatible with the heatsinks “Type A”, as shown in the figure1;



Figure 1. Drilling of heat sinks

- b) Holes in the polystyrene box: Holes were made at the top of the chamber, with a distance of 4cm between them, in its lid, in order to homogenize and favor thermal exchange by natural convection; and then insert the thermoelectric chips together with the heat sinks, as shown in the figure 2;



Figure 2. Expanded polystyrene box drilling

- c) Insulating term among the chamber accessories: The fragments of the insulation joints were placed at potential points where there could be heat infiltration from the external environment into the chamber, especially in regions where the perforation of expanded polystyrene proved to be imperfect, brittle and/or very thin, as shown in the figure 3;

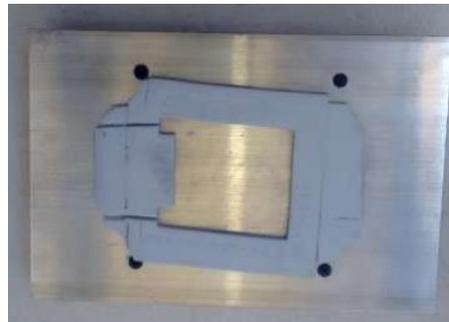


Figure 3. Thermal insulation between camera accessories

- d) Attachment of accessories: with thermal paste support, to reduce the effects of contact resistance, the primary version of the chamber was completed, as shown in Figures 4 to 8;

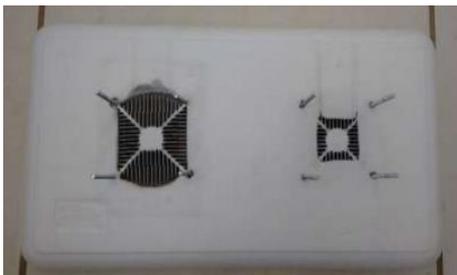


Figure 4. Assembly of "Type A" heatsinks

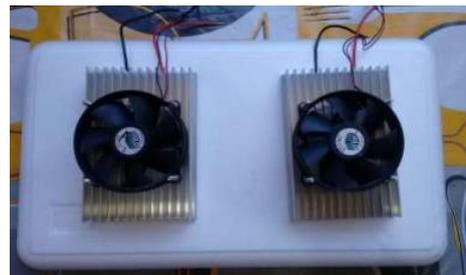


Figure 6. Cooling chamber top view

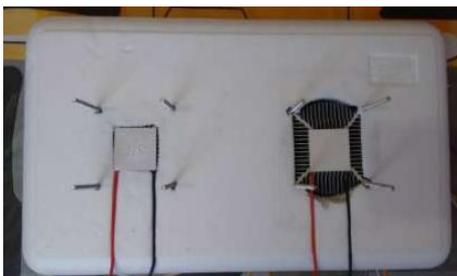


Figure 5. Assembly of thermoelectric chips



Figure 7. Internal view of the cooling chamber

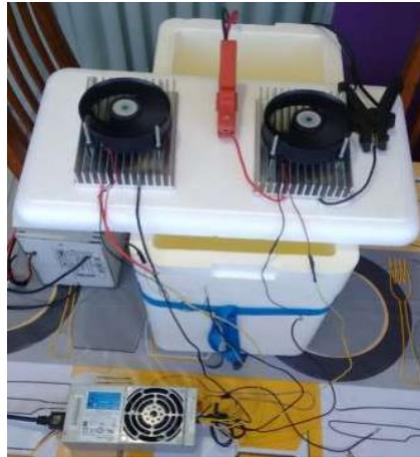


Figure 8. External view of the cooling chamber

e) Installation of internal coolers: Once the device testing was completed, performing the appropriate thermal exchanges by natural convection, a cooler was inserted into each of the internal heat sinks, to determine the impacts on the behavior of the cooling chamber by through the introduction of a forced convection condition in its interior, as shown in the figure 9.



Figure 9. Gears used in the standard test

2.8. TESTS IN THE COOLING CHAMBER IN OPERATION

For the performance study, it was necessary to perform 3 (three) tests individually:

- a) The first test aims to analyze the variation in the internal temperature of the cooling chamber empty, again, using thermal exchanges by natural convection;
- b) The second test aims to observe their variation of the internal temperature of the cooling chamber empty, however made only with thermal exchanges by forced convection;
- c) The third test had the purpose of verifying the temperature variation of a sample of 500 milliliters of water, inserted in the cooling chamber previously cooled to 10 °C, also by means of thermal exchanges by forced convection.

During the performance of these tests, extra measurements of temperature within the elements that structure the device were noted. At this time, the focus was on heat sinks and chips thermoelectric, in order to support the interpretation of the results achieved. The duration of the tests was different for each condition, with the end of the test close to the stabilization of the temperature in the measurand.

3. RESULTS AND DISCUSSIONS

In the 1st battery of tests, the behaviors of the power supplies of "Source A" and "Source B" in the entire power supply of a single insert, model TEC1-12715, with the subsequent results were achieved: a) Source A: 10.85 V and 6.65 A

b) Source B: 11.19 V and 6.85 A

Taking into account that the 2 sources presented similar results, with variation of approximately 3% in the voltage and current supplied to the device, it is possible to use the independent power supply for each chip, so as not to overload the system. Studies were assigned on the cooling potential of the selected thermal chips by completing a series of temperatures recorded on the “cold side” of the two chips, in an assembly using “Type A” heat sinks. During the measurement, a wide range of values, according to the position of the temperature tap, as shown in Figure 10.

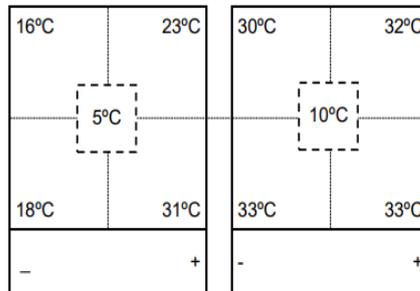


Figure 10. Temperature on the "cold side" with "Type A" heatsinks

The measurements were made at the temperature associated with 25 °C. Considering that the pellets accommodate 127 pairs of bismuth telluride, connected in series, a temperature variation over time at this moment is not surprising, as these pairs can be influenced by variables independent. The temperature was reached in the minimum time of 5 °C, but the typical temperature reached was unsatisfactory compared to the values determined within the projected cooling objective. There is also a marked variation in the results between the two inserts which, as they are identical in design, should behave in the same way.

How well experienced by (Astrain and Martnez, 2012), for every degree centigrade the temperature distinction between Peltier's “hot side” and the environment raises the refrigerator's COP by more than 2.3%. Given the importance of heat dissipation in thermoelectric cooling processes, the main intervention performed was on the heat sink. The “Type A” heatsink has a 25mm solid aluminum contact base, proving to be insufficient for correct heat conductivity at the 40mm base of the used inserts. Keeping the coolers, for forced ventilation, the heat sinks were replaced by “Type B”, with the tests being perennial, currently in a scenario associated with a temperature close to 27 ° C, with the results illustrated in Figure 11:

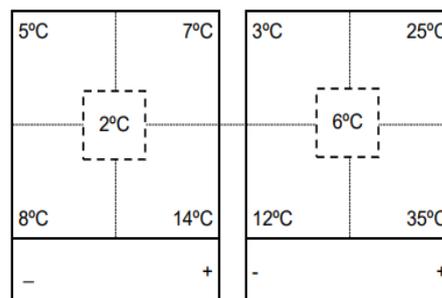


Figure 11. Temperature on the “cold side” with “Type B” heatsinks

There was an evolution in the results, which reinforces the theses that demonstrate the direct association between heat cooling devices on the “hot side” and also the temperature reached on the “cold side” of thermoelectric chips. Even though the minimum temperature recorded in the thermocouple was 2°C, there was ice precipitation over practically the entire length of the first insert, what made the thermal exchange difficult, which allows us to infer that the overall average temperature approached 0°C, a result that allows for instrumentation of the cooling chamber with the tested cooling frame.

	3°C			2°C	
2°C	No access	3°C	2°C	No access	3°C
	3°C			2°C	
-			+		

Figure 12. Temperature on the “cold side” of the inserts - bolted assembly

The screwed assembly did not allow access to the center of the inserts to measure the temperature, however, at the base of the “cold side” heatsinks, the common temperatures of 6 °C and 7 °C were reached in each of the devices, in an environment 22 °C. The results are satisfactory and close to those proposed for the cooling of the cooling chamber (5°C). The temperature reached inside the “Type B” heatsinks applied on the “hot” side is a preponderant factor to achieve success in thermoelectric cooling. A distributed study of these devices allowed measuring their temperature during the operation of the set, as shown in the figure 13.

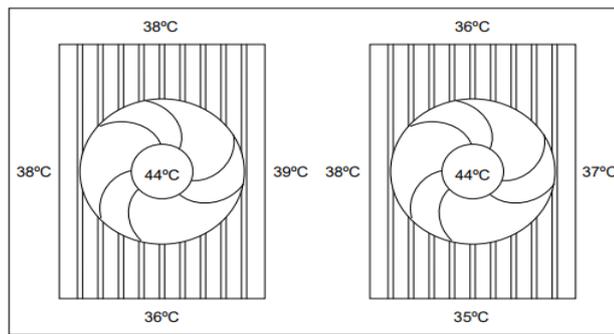


Figure 13. Temperature on the “hot side” of the heatsinks - screwed assembly

The ideal temperature in the device should be no more than 20 °C higher than the ambient temperature (22 °C at the time of the study). Thus, it is inferred that the installed heat dissipation system is incapable of extracting maximum cooling power from the thermoelectric chips. The results obtained from the tests carried out on the final version of the projected model are:

- a) Variation of the internal temperature of the empty cooling chamber, with thermal exchanges carried out by natural convection, figure 14:

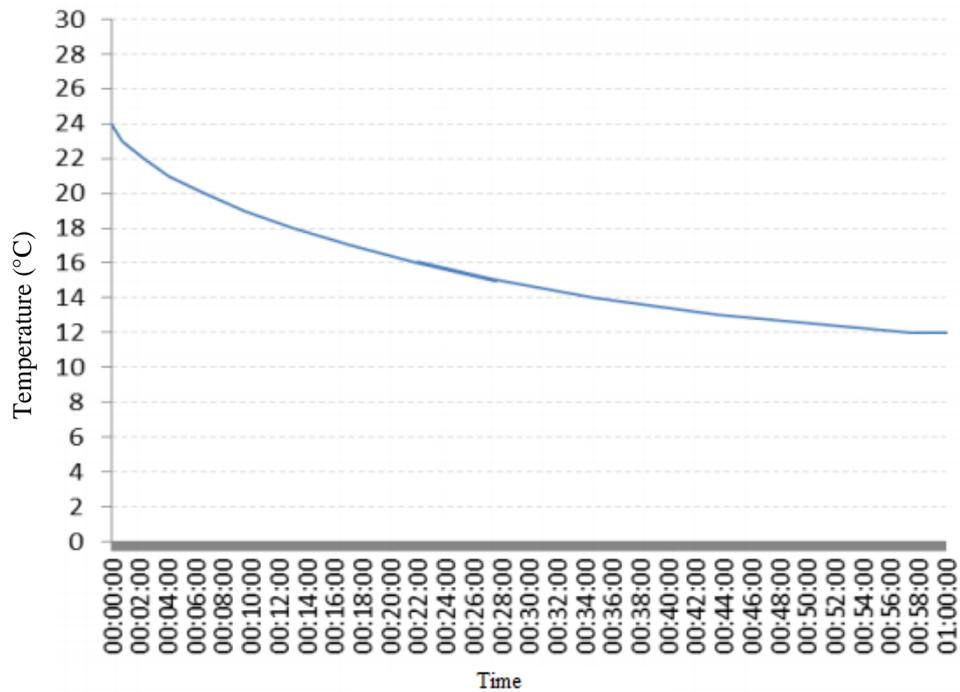


Figure 14. T Temperature Variation - Test 1

After 57 minutes and 38 seconds, the cooling chamber dropped from 24°C to 12°C, when the test had to be interrupted by mechanical failures in one of the forced ventilation coolers of the “hot side” heatsinks, which caused an overheating in the device. The average temperatures at the base of the “cold side” heatsinks, when the test was suspended, were 4 °C and 5 °C. In this way, thermal equilibrium had not yet been reached and the cooling chamber had the potential to further reduce its internal temperature.

b) Variation of the internal temperature of the empty cooling chamber, with thermal exchanges carried out by forced convection, figure 15:

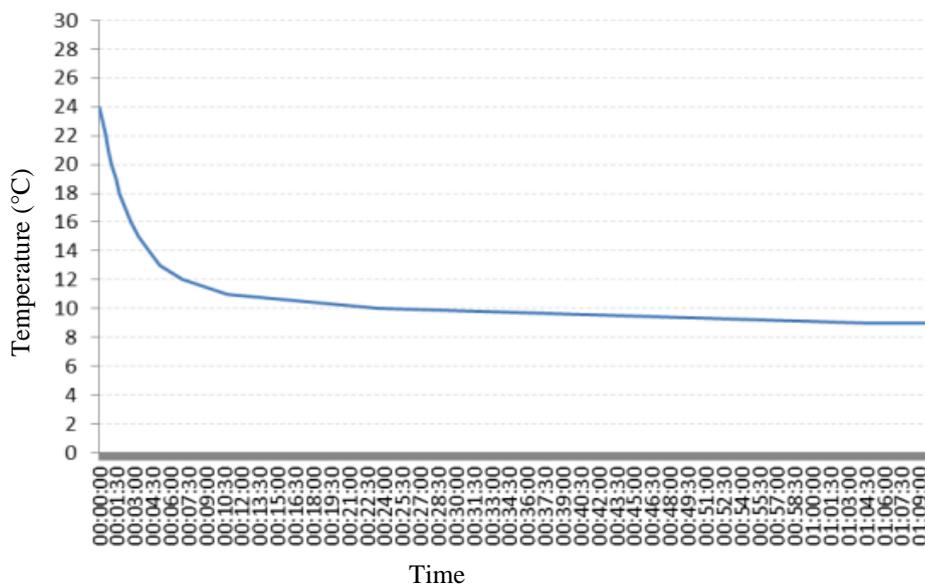


Figure 15. Temperature Variation - Test 2

After 1 hour and 05 minutes, the cooling chamber dropped from 24°C to 9°C, and remained stable. The application of a forced ventilation system proved to be advantageous, due to the sharp drop in the temperature of the device in the initial 10 minutes of operation, far surpassing the results achieved by natural convection. As in Test 1, the cooling system on the “hot side” exhibited a great oscillation in performance, which favored that the objective of 5 °C was not reached

by the built prototype. However, the temperature gradient in the order of 12 °C reached in just 7 minutes of operation of the cooling chamber proves the potential of the technology addressed.

c) Temperature variation of a 500 ml portion of water, inserted in the cooling chamber (previously cooled to 10°C), with thermal exchanges carried out by forced convection, figure 6:

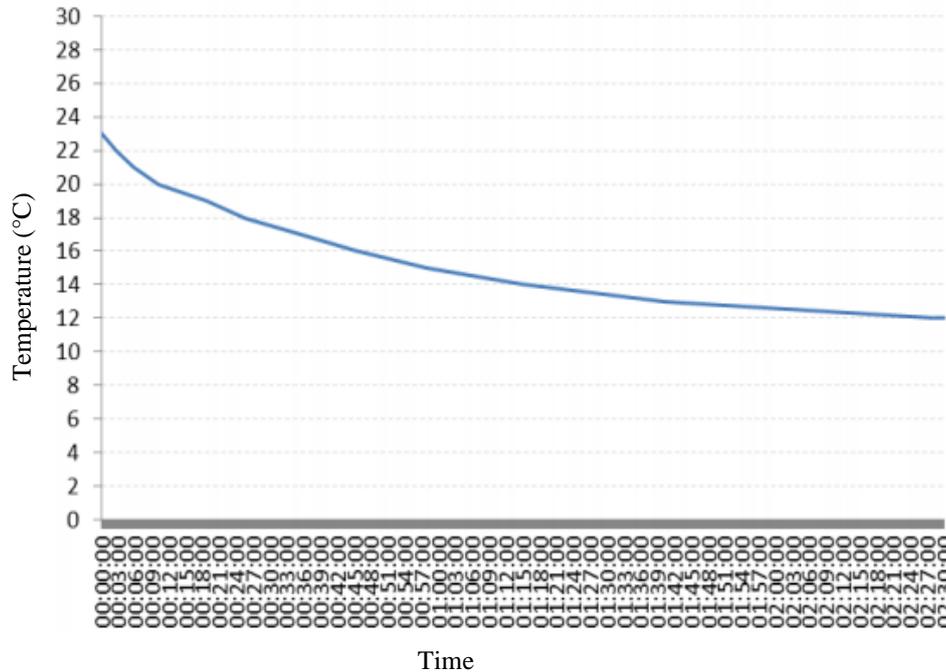


Figure 16. Temperature Variation - Test 3

Some observations were made: the thermoelectric chips used have constructive flaws that make it difficult to make perfect contact with the heat sinks; the coolers for cooling the “hot side” heat sinks they have a low volumetric capacity for air displacement (cubic feet per minute) and have shown repeated mechanical failures; the thermal insulation between the internal and external sides of the cooling chamber was compromised by the geometry of the base of the heat sinks used, as they limit the thickness of the insulating material. Against from the overheating of the external equipment, in direct contact with the built prototype, the heat infiltration by conduction was more significant than initially foreseen; the fastening screws did not guarantee an adequate control in the contract of the thermoelectric chips with the external heat sinks and, as they were metallic, they served as a heat infiltration point in the device; electrical power supplies provided approximately 43% of the maximum electric current capacity of thermoelectric chips, which significantly compromised their performance; the limited availability of tools for building the prototype made room for a low stability of the assemblies, which favored the appearance of oscillations in the behavior of the cooling chamber.

4. CONCLUSIONS

The cooling chamber had a low efficiency for the proposed condition, due to the parameter of 15 °C as the maximum temperature, which makes it slightly inferior to the objective cooling proposal, where the goal was to reach 20 °C. However, a temperature of 2 °C and the precipitation of ice in the thermoelectric chips were measured, even in the case of equipment with homemade characteristics, manufactured with few resources, low-cost components, and improvised tools.

If applied on an industrial scale, with the appropriate components designed and produced in order to meet the technical characteristics of thermoelectric cooling devices, this technology has good potential to contribute to the development of the Brazilian electro-electronic industry and, even, of other industrial segments, such as furniture, through the construction of domestic utensils and functional furniture, which can exploit the micro-cooling capacity offered by the Peltier phenomenon. Consequently, investments in the segment of research and development of new materials, with a focus on improving the figure of merit of thermoelectric materials, welding technologies, and heat dissipation devices, can favor thermoelectric cooling.

5. ACKNOWLEDGMENTS

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