Development of Portable Chiller for Carabao Milk with Independent Cooling System using Thermoelectric Effect

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Abstract

Carabao milk is particularly known for having short shelf life if not refrigerated immediately after collection. The farmers in the vicinity of the Philippine Carabao Center address this problem by using ice and water to keep the freshly harvested milk refrigerated. This project was devised to find another way to travel the freshly harvested milk. To be able to refrigerate the container, thermoelectric coolers were used. These devices are compact and small in size but are capable of cooling reaching temperatures of up to below freezing temperatures. It develops a temperature difference as electricity passes through it, one side is cold, and the other is hot. The heat given off on the hot side needs to be rejected to be able to further decrease the temperature on the cold side. In this study, the researchers fabricated a container that was used as a cooling container for carabao milk. The main material used in the container was stainless-steel 304, and for the thermoelectric cooler, the researchers used a thermoelectric cooler that was available in the market with a power rating of 12V and 6A. For the heatsink and fan assembly, a thermal paste was used to integrate the thermoelectric cooler to the assembly to increase the heat transfer between the cold side and the container as well as the hot side and the heatsink. The cooling system was powered by two lead-acid battery and the battery was charged using a solar panel. The study was successful in preserving the quality of the carabao milk-based on Physico-chemical analysis done by Philippine Carabao Center (PCCP), however, it did not reach the desired temperature which was 4°C due to several factors namely; fabrication of the flat side, battery power rating, insufficient number of the thermoelectric module used, and heat loss in the system.

Keywords
Carabao milk, portable chiller, thermoelectric effect, independent cooling system

1. Introduction
Nutritionally, milk can be considered as a complete food. It has better nutritional benefits over cow's milk because it is higher in calcium and energy but lower in cholesterol. Currently, the Philippines heavily imports almost 98% of milk and other dairy products available from other countries. The Philippines spend millions annually in buying milk from other countries, placing milk as the 4th highest agricultural import of the country. Out of 5 million kilograms of milk produced in the Philippines, 63% came from cows, 36% came from carabaos, and 1% of it came from goats (Marci & Tingcungco, 2016).

Compared to cow's milk, carabao's milk is recorded to have 58% more calcium, 40% more protein, and 43% less cholesterol. There are now provinces and towns in the country which are into carabao (buffalo) raising. Some farmers are into this industry to maximize their profit from each carabao they own by producing a regular supply of carabao milk to milk stations in their region. One of the well-known provinces to have ample numbers of carabao is the province of Nueva Ecija. In 2010, the dairy cooperatives in the province are set to produce 1,200 to 1,400 liters of carabao milk daily. The farmers deliver the harvested milk from the farm to the Philippine Carabao Center (PCC) in an ice chest with dimensions of 29” x 29” x 18” and an approximate total weight of 250kg including the milk containers. Dairy farming is hard labor as cows were milked by hand. But these days, technology streamlines the process of milking to make it more efficient. Even with the benefits, technological supply, and support for the production of carabao milk remains limited.

The Philippine Carabao Center (PCC) is an attached agency of the Department of Agriculture (DA). PCC is mandated under Republic Act No. 7307 or the Philippine Carabao Act of 1992 to conserve, propagate and promote the carabao as a source of draft animal power, meat, milk, and hide to benefit the rural farmers. Based on the annual report of PCC (2015), the dairy buffalo sector, as stewarded by the PCC, contributed a total of 2,204,105.60 kg of raw milk to the country’s dairy industry. The total value of raw milk traded was Php141,609,802.64 which provides a significant amount to the market.

Refrigeration is probably the most popular form of food preservation in use today. In refrigeration, the idea is to slow bacterial action to a crawl so that it takes food much longer (perhaps a week or two, rather than half a day) to spoil. It is the process of extracting heat from a confined space or substance to lower its temperature. In 1834, a French watchmaker and amateur scientist named Jean Peltier discovered that when an electric current passes through a junction of two dissimilar conductors in a certain direction it produces a cooling effect. A thermoelectric cell can be a heat pump or an electric generator. Most applications of thermoelectric cells are for cooling but it is not that energetically efficient. The ones that make it a very effective device in small-scale refrigeration are its simplicity, compactness in terms of size, lightweight, and high reliability (Zou, et al., 2001).

Since farmers in Nueva Ecija region lack technological advancement, the number one problem of farmers working in PCC is milk spoilage. Scientific research found that a naturally existing enzyme on raw milk called lactoperoxidase reacts to thiocyanate which also naturally exists in milk to produce a compound that has bacteriostatic and even bacterial effects on some bacteria. This gives a natural temporary preservative for the milk that lasts only for 2 hours starting from the initial milk extraction from the udder (Anmar, 2017).

Bacteria spread most rapidly in-between temperature range of 4°C to 60 °C, commonly known as the "Danger Zone". Refrigeration slows bacterial growth. Most of the foods are protected when refrigeration temperature is set at 4°C or below. There are two completely different families of bacteria: pathogenic bacteria, the kind that causes foodborne illness, and spoilage bacteria, the kind of bacteria that cause foods to deteriorate and develop unpleasant odors, tastes, and textures.

Carabao milk should be kept refrigerated as soon as possible to a temperature ranging from 2°C to 4°C. Increasing the milk temperature above 4°C will speed up bacterial contamination while maintaining it at 2°C will make it attain better bacteriological quality for longer shelf life (Griffiths et al, 1987). A raw milk product when exposed to extended sunlight can suffer from light oxidation which could change the taste of the milk and destroy some of its nutrients. The more it is exposed to heat, the lesser its quality becomes which is why immediate cooling will provide a better quality of milk being produced.

1.1. Container Fabrication

This study focuses on the design and fabrication of a container for carabao’s milk that is food-safe, durable, and corrosion-resistant. According to the Philippine Carabao Center (PCC), a milk container should be free of corners, so the shape of the container was designed to be cylindrical with a spherical top and bottom. This is done to avoid right-angle corners where milk fat could seep into and reduce the quality of milk when not thoroughly cleaned. The use of SS304 or a food-grade stainless steel is also required by the PCC to ensure that milk will be free from any contamination when it comes in contact with the container.

1.2. Thermoelectric Effect

Peltier thermoelectric cells, or simply TEC, are formed by a set of thermocouple pairs, which are basically semi-conductors that produces electricity if there is a temperature difference between the two surfaces or elements, or the other way around. Thermoelectric cells when used in refrigeration are considered energetically not efficient but several advantages such as reliability, simplicity, and compactness come very handy in small-scale applications. When used as a cooling device, the current is being passed through it, and in turn, it produces a temperature difference, one side decreases in temperature, and the other side increases. During its operation, the cold side temperature will decrease up to a certain point before the heat from the hot side starts to travel or transfer to the cold side using conduction, convection, and radiation. To be able to minimize thermal bridge and increase the heat transfer rate when TEC was used as a cooling module, it should be tightly clamped between the heat sink and the surface of the container. All of the contact surfaces involving the module are filled with high thermal-conductivity grease which will reduce any contact resistance. In doing this, heat from the hot side will transfer to the heatsink, and the heatsink in turn will dissipate the heat with either natural ventilation or forced ventilation by the use of a fan.

2. Methodology

The whole container development process was subdivided into two major phases, the design phase and the assembling of the prototype phase. The design and gathering of materials were done to ensure that quality materials were used before proceeding to the prototyping phase. A sequence of activities is shown in Figure 1.

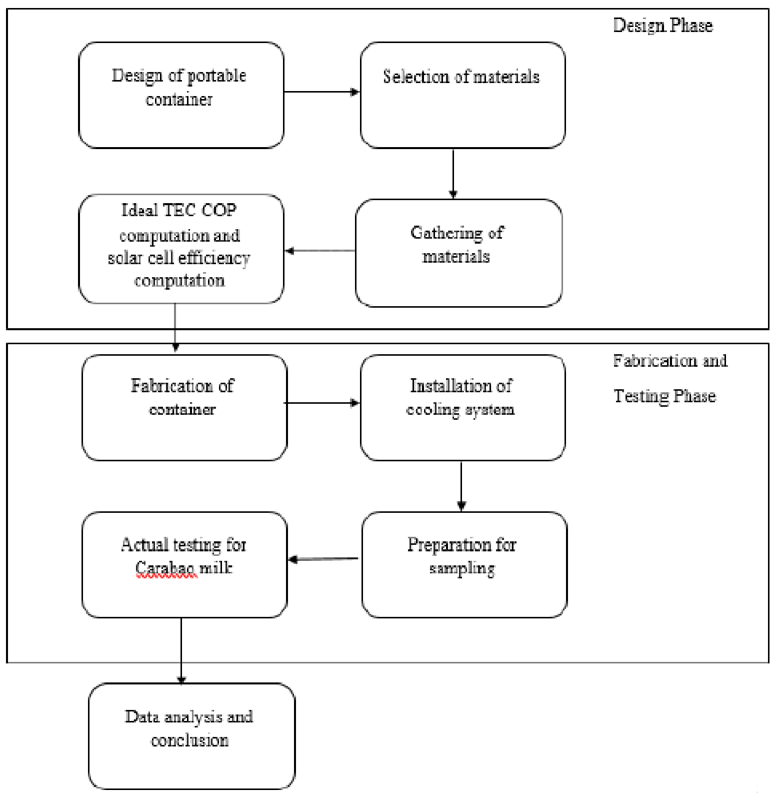

Figure 1. Flow Chart of Activities to Complete the Study

2.1. Design of Portable Container

The researchers had several things to consider when it comes to the design of the container. The container should be made of food-grade material, has no right-angle corners, durable, and malleable since flat sides are required to accommodate the TEC modules to be installed. The food-grade stainless steel (SS304) sheet of 0.8mm thickness was rolled to create a cylindrical body. The top and bottom parts were also stainless steel sheets of a circular shape that were pounded to form a spherical zone figure. These components were welded together to create the inside container. The outside container was just pieces of SS304, which were 3mm thick, that were welded together in the shape of a box to accommodate the brackets that will hold the thermoelectric module- heatsink assembly. The gap between the inside and the outside container was filled with polyurethane foam, and the outside container itself was wrapped with polyethylene foam to effectively insulate the system. The 3D design model of the portable container is shown in Figure 2.

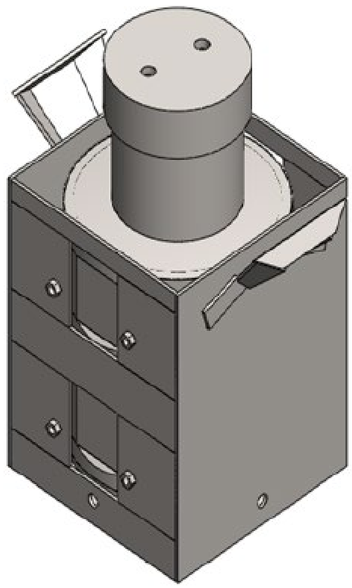

Figure 2. Isometric View of the Container Assembly

2.2. Selection of Materials

A variety of components was selected for the entire assembly namely: heatsink and fan, battery, solar panel, material for container, agitator and temperature sensor, and thermal paste. The proper selection of these components is vital to the overall performance of the thermoelectric assembly. For the heatsink, it is better to select the one with heat pipes and the one with a higher number of fins both of which assist in dispersing heat quickly and efficiently. Since there was no heatsink thermal resistance given by the manufacturer, the total thermal resistance of the heatsink was computed using the principle that all heat transfer systems can be represented as an electrical circuit where parts are all connected in parallel connection from one another. For the battery, the selection only was based on the power consumption of the module. The battery needed to support the module for at least three hours. For the solar panel, the consideration is that it can fully charge the batteries after each of its use. For the material of the container, stainless steel was used over aluminum mainly because of its durability. For the agitator and sensor, we used the blade of an old blender and a thermocouple respectively. For the thermal paste, high thermal conductivity and texture are the basis of selection to ensure a greater heat transfer rate.

2.3. Gathering of Materials

The steel components for the container as well as the batteries and solar panel were bought around Recto and Quiapo, Manila. The thermoelectric modules together with heatsink fan assembly were bought from an online seller. The temperature sensor and agitator were bought at e-gizmo.

2.4. Ideal TEC COP and Solar Cell Efficiency Computation

The researchers needed to compute for the ideal value of the coefficient of performance (COP) of a thermoelectric module selected as well as its cooling capacity to know the actual number of modules needed to reach the desired temperature. The same goes for solar cell efficiency. Solar panels have low efficiency, so it is vital to compute and select a proper power rating that will be able to fully charge each battery after use.

2.5. Fabrication of Container

The final design layout of the container served as the guide for the whole fabrication process. The container is divided into two major parts, the inside container, and the outside container. The design is made to prevent heat transfer from outside to inside containers but at the same time supports a direct contact of TEC to the inside container is able to maximize the cooling capacity. Polyurethane foam was used to insulate the space between the outside and inside containers while polyethylene foam was used to insulate the outside container from the environment.

The main material for the inside container was a stainless sheet that was cut using a plasma cutter in the ME fabrication shop and then rolled using the roller in the machine shop. For the top and bottom part of the container, the stainless sheet was molded into a curved surface to avoid corners in the container. For the neck part of the container, a 4 in x 4 in stainless steel nipple was used. To accommodate the thermoelectric cooler, the researchers put an approximately 2” x 2” four (4) flat parts on opposite sides of the container by heating and molding it using a hammer. The parts were assembled by TIG welding to ensure a leak-proof inside container.

For the outside container, the material used was also a stainless-steel sheet that was cut based on the rectangular 262 design. Each part of the container was assembled by arc welding to form the outside container. The design of the outside container is a rectangular prism with four square openings on opposite sides to accommodate the installation of thermoelectric cooler and heatsink fan assembly.

For the container cover, a stainless-steel cap was used. To increase the heat transfer rate and ensure even distribution of cooling inside the container, an agitator was introduced in the system. The agitator provides motion for the fluid inside the container to have forced convection instead of natural convection. Forced convection was desired to have a better heat transfer between the walls of the container and the fluid inside. To monitor the temperature inside the container, a thermocouple temperature sensor was placed inside the container. The temperature sensor was directly connected to an LCD screen that was placed on top of the cover to display the temperature reading. The temperature sensor was calibrated, and the temperature sensor reading was found 1.6°C above the actual value of the temperature. All data gathered was adjusted accordingly to achieve the correct temperature reading of the system.

For the insulation, polyurethane foam was used to minimize the heat transfer from the environment to the inside container. In addition, it was used to ensure that all spaces between the inside and outside containers were filled with insulating material to preserve the system efficiency. For the outside container, additional polyethylene foam was used to isolate it from the environment, thus creating another layer of insulating material that will prevent heat from entering the system. The process of fabricating the portable container is shown in Figure 3.

Figure 3. Assembly of Inside and Outside Container

2.6. Installation of Cooling System

The thermoelectric modules which were the main cooling components of the prototype were installed on opposite sides of the container. Both the inside and outside containers have specific flat parts for the installation of thermoelectric modules, heatsink, and fan assembly. Since the thermoelectric module is a square prism, it should be installed having direct contact with the inside container for a more efficient heat transfer rate. The reason for directly joining the module's surface and inside the container is to reduce additional thermal resistance that will just decrease the rate of heat transfer of the cooling system. This will prevent a further decrease in the coefficient of performance (COP) of the system knowing that the thermoelectric cells (TEC) alone already has a very low COP. The thermoelectric cooler is combined with the fan and heat sink assembly to efficiently reject the heat that radiates from the hot side of the thermoelectric module. Applying this will further increase the cooling capacity of the cold side of the thermoelectric module. A high thermal conductivity thermal paste was used between the thermoelectric cooler and the heat sink as well as between the thermoelectric cooler and the inside container to aid in heat transfer enhancement. The thermal paste helps improve heat transfer between the thermoelectric cooler and the inside container for better cooling capacity and improved thermal conductivity between the module and the heat sink. If the heat from the hot side is not rejected efficiently, by Fourier's Law the heat from the hot side of the module will travel towards the cold side to attain equilibrium. When the cold side of the module becomes too hot it can cause the module to burn out that's why it should be prevented as much as possible. The thermoelectric cooler together with the fan and heat sink assembly was fixed on the container using a clamp connected by bolts and nuts. The bracket is combined with spacers on each side since the spacers will push the heatsink/TEC towards the inside container and thus introducing a small pressure just enough to ensure good contact between the module, heatsink, and inside container surfaces.

2.7. Preparation for Sampling

The tests are conducted in the Philippine Carabao Center (PCC), more specifically at the gene pool area near the milking facility of the center. The whole assembly of the container and the batteries were placed in a shaded area just outside the milking room to achieve an ideal environment simulating actual conditions done by the farmers. The digital multimeter was used for measuring the ambient temperature. This digital multimeter is placed beside the container assembly. After the trial, the solar panel was placed in an open field and it was directly exposed to sunlight for charging of the batteries. Since there were two (2) batteries used, the other battery was charged through an electrical outlet using a charger controller to reduce the charging time.

2.8. Actual Testing for Carabao Milk

Actual testing for carabao milk was done during their morning and afternoon milking processes. During testing, fresh carabao milk will undergo a cooling process for 3 hours which was the maximum battery lifespan of each lead-acid battery before being drained. The temperature reading was displayed on the LCD screen which is directly connected to the temperature sensor. The temperature reading was recorded every 5 minutes. In addition, the ambient temperature was determined by a digital multi-meter temperature sensor. Lastly, the temperature of the 263 outside container was also recorded every 5 minutes to monitor if there were any losses on the outside container. After cooling, test samples were collected and delivered to the manufacturing facility. Upon arrival, the condition of milk was determined first by several tests including Organoleptic Test, Alcohol precipitation test, acidity test, and clot on boiling test before it undergoes the cooling process.

2.9. Data Analysis and Interpretation

For the cooling capacity of the thermoelectric cooler, the temperature difference in the actual testing was used in the calculations to determine the actual cooling capacity. For the carabao milk, Organoleptic Test, Alcohol precipitation test, acidity test, and clot on the boiling test was used to determine if the carabao milk was already spoiled after the cooling process or if characteristics of carabao milk changed after cooling. For the solar panel, the time before the battery was fully charge was measured to determine its efficiency.

3. Results and Discussion

3.1. Thermoelectric Cooler Performance

Figure 4 shows that within five-minute time, the thermoelectric module with the cold side in contact with air can reach below 0°C temperature. Every trial in this case was run for one hour and recording the data every five minutes. This test shows an average temperature of -9°C from all trial temperatures recorded. This data shows the capacity of the thermoelectric cooler when in contact with air as it will be compared to the data where it is already attached to the container to quantify the difference in output cooling capacity.

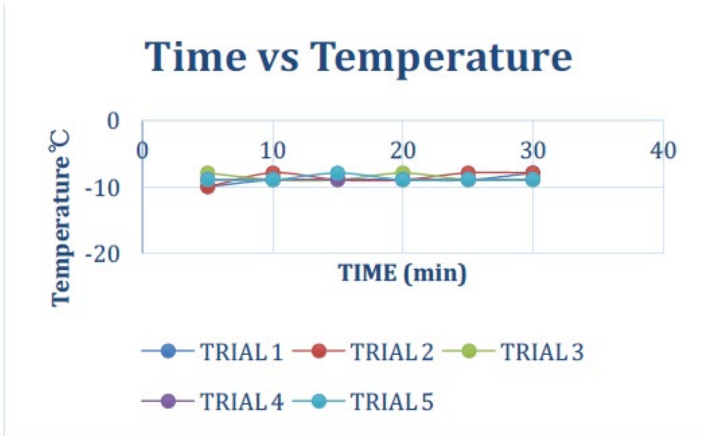

Figure 4. Time vs Temperature of TEC Module in Contact in Air

Each line shows that at a given constant ambient temperature the cold side temperature reading would just fluctuate from – 9 °C at each five-minute interval time.

Ambient temperature greatly affects the cooling performance of the thermoelectric module. The ambient air temperature during these tests is 27℃ at the first trial and 28℃ for the rest. Consistency in ambient temperature reading is required to have a valid comparison between data gathered in each trial.

3.2. Actual Cooling Container Performance

The entire assembly is composed of four thermoelectric modules attached to the container wherein 4L of milk will be placed. The test was done at the Philippine Carabao Center (PCC) at Nueva Ecija in actual conditions. There are two milking schedules every day, one in the morning and one in the afternoon, the first trial was done 8:55 in the morning after the first milking schedule at an ambient temperature of 29 °C. The temperature of the milk was a bit higher than the ambient temperature because the milk was transferred immediately to the container after being extracted from the udder. Figure 5 shows the following data from the 1st trial, where temperature readings continue to drop concerning time. However, because each battery can only last for three hours, the data gathered includes a restriction based on the lifespan of the batteries. Within this time, the temperature of milk dropped by 21°C from a starting temperature of 34°C as shown in Figure 6.

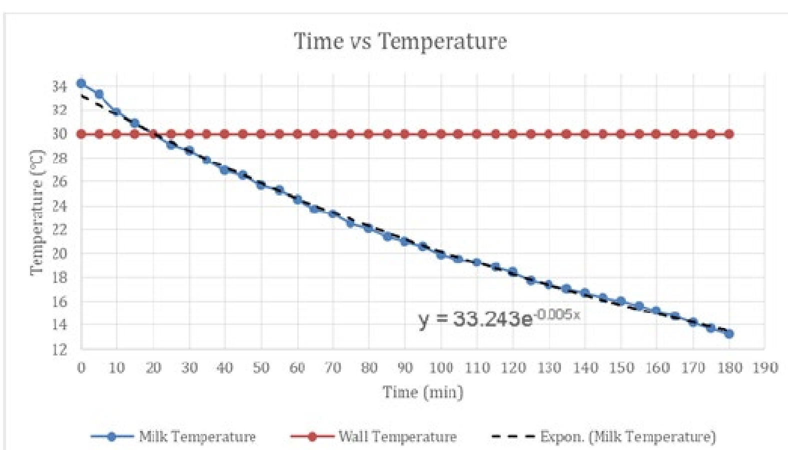

Figure 5. Time vs Temperature Graph of 1st Trial

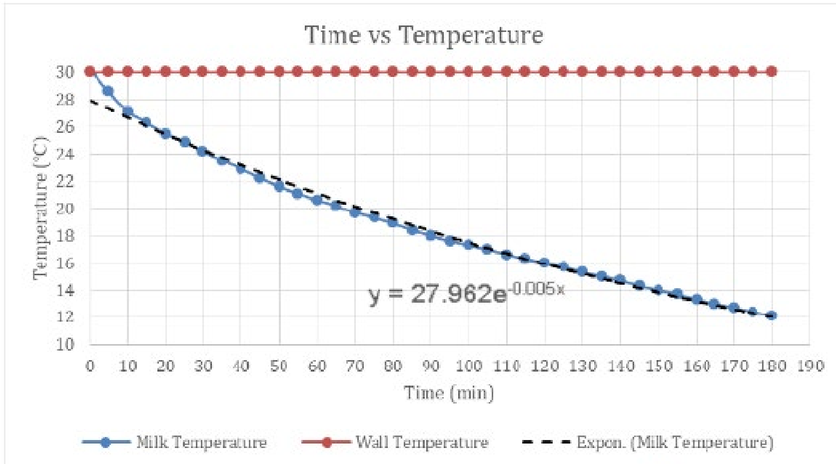

Figure 6. Time vs Temperature Graph of 2nd Trial

The graphical representation of values obtained in the third trial in Figure 7 showed almost the same values as of the second trial. The decrease in temperature was fast at the start giving a change in temperature of close to 1°C in five minutes. But as the temperature decreases, the temperature change also decreases to a value less than 0.5°C in the same period. At this time, the researchers realized that as the temperature approaches a value below 15°C, the rate of heat transfer begins to slowly stabilize as the temperature comes closer and closer to its lowest point.

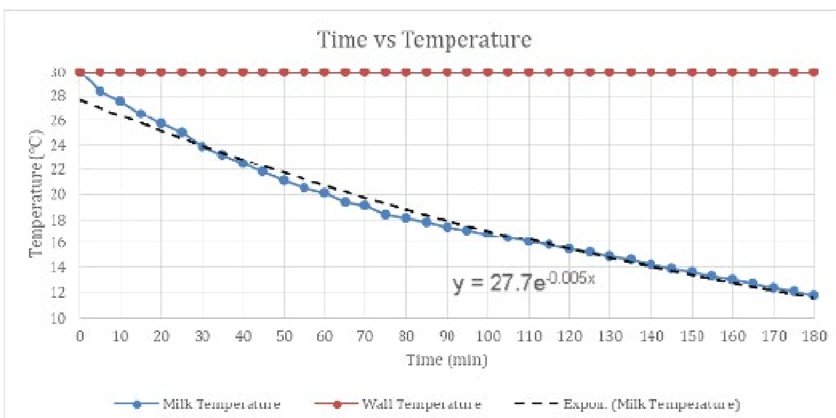

Figure 7. Time vs Temperature Graph of 3rd Trial

3.3. Heat Removed from the Cold Side

The capacity to remove the heat from the cold side is the parameters that determined the performance of the thermoelectric cooler. The heat rejected from the cold side when the thermoelectric cooler is not attached to the container as compared to when the thermoelectric cooler was used in actual testing. Table 1 shows the comparison of heat rejected between the thermoelectric cooler when in contact with air and when it was used in actual testing. The heat removed from the thermoelectric cooler when in contact with air was significantly higher.

Table 1. Heat Rejected by Thermoelectric Module in Contact with Air and Container

		Heat Rejected on each Thermoelectric Module (W)
Thermoelectric module in contact with air		10.0307
Thermoelectric module in contact with the container	1st trial	7.9091
	2nd trial	6.8169
	3rd trial	6.8545

4. Conclusion

This study was done to explore the range of thermoelectric technology applications. It was utilized as a cooling device for milk containers which deviates from conventional vapor-compression systems that require refrigerant in heat transfer. This study on thermoelectric cooler will help future researchers to assess its capacity and ability to reject heat. The main purpose of this study was to provide an alternative way of preserving the quality of carabao milk harvested by farmers. At present, they usually use large ice chests filled with a mixture of water and ice to lower its temperature until it arrives at the receiving facility. The receiving facility utilizes communal freezers to drastically reduce the milk temperature up to its safe storage limit. This prototype was a viable option for the farmers since it offers higher cooling capacity and lightweight characteristics compared to the ice chests they use in the transportation of milk from one place to another.

This study has three objectives. The researchers were not able to meet the first objective which was to maintain the temperature of the milk for 2°C-4°C. This was mainly due to the existence of a thermal bridge in the system, time constraints of each test, and thermal contact of the thermoelectric module. The produced graph of cooling was a representation of an exponential function that estimates a total time of 7 hours before 4C can be attained. The second objective was met based on the physicochemical analysis from PCC which confirms that milk cooled using the portable container did not spoil after 2 hours of testing under actual environmental conditions. The last objective was to charge the battery using a solar panel. The researchers decided to use a 50W solar panel which could fully charge each battery for six hours. Based on the data given by PCC, it would take no more than one-hour travel time to reach the manufacturing plant even from the farthest cooperative. This enables farmers to charge the battery early right after its use to compensate for its long charging time.

The fabrication process of the container is still not ideal for milk storage since cornered surfaces although not at 90-degree angles still exist. The fabricated container contains corners with two surfaces having more than 90-degree intersection angles. This is due to part by part fabrication and lack of equipment utilized in fabricating the design. The flat side part of the container was also fabricated manually which leads to an unsmooth surface finish. A recommendation for improving the fabrication process of the container is to have it machined to have a smooth surface finish. The consequence however is the additional cost of fabrication.

Lead-acid batteries used in the container are heavier than other types of batteries present in the market. It is used most of its flexibility in having huge power capacity that is not currently present in lighter batteries like lithium-ion. Future researchers are advised to consider using lighter batteries if improved power source that is available in the market. In addition, a higher battery rating is also highly recommended if the future researchers decided to increase the number of thermoelectric coolers to improve the cooling capacity.

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