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Research And Design Of A Portable Breast Milk Storage Unit Using Solar-Powered Thermoelectric Modules: Engendering Renewable Energy Technologies Amongst Zimbabwean Rural Women

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DECLARATION

I, Samantha Hazvinei Mutirori hereby declare that this submission is my own work and to the best of my knowledge it contains no materials previously published or written by another person. I also declare that all information, material and results from other works presented here, have been fully cited and referenced in accordance with the academic rules and ethics.

Signature:

Date: 30 November 2021

CERTIFICATION

I, Professor Ramchandra Bhandari certify that this final version of the master thesis was submitted with my approval and that all corrections were added as recommended by the examination committee.

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Date: 03.01.2022

ABSTRACT

Thermo-electric cooling that operate by the Peltier effect coupled with solar power energy; can be a strong candidate to replace traditional refrigeration technologies that contribute to harmful atmospheric emissions. This technology can be highly beneficial to rural communities living off the grid without access to technology particularly women in developing countries that are usually left behind in the gender-energy divide. Innovations efforts by designers still have a long way to go as they often omit female users at the center of their thinking, consulting and involving them in building new technologies that can directly impact their economic productivity. The design and development of a solar powered thermo-electric portable cooler to store breastmilk was done after consultation of the rural Zimbabwean women in the Domboshava community. Their feedback was integral to the design and implementation of the prototype. The cooler was tested and it reached 15°C in 50 minutes without load and 80 minutes with heat load, the set temperature important for maintaining the quality of breastmilk for up to 24 hours. A TEC1-12706 Peltier module with 2 heat sinks and fans was selected and designed with a control system programmed in C++ language with Arduino Nano controller, DHT11 temperature sensor and a relay. This fabricated system works on DC voltage generated by photovoltaic cells from a solar panel. The performance of the 12V, 25Ah battery used was evaluated and it took 2 hours 20 minutes to be discharged with load and 1 hour 40 minutes for it to be fully charged by solar.

Résumé

Refroidissement thermoélectrique fonctionnant par effet Peltier couplé à l'énergie solaire ; peut être un bon candidat pour remplacer les technologies de réfrigération traditionnelles qui contribuent aux émissions atmosphériques nocives. Cette technologie peut être très bénéfique pour les communautés rurales vivant hors réseau sans accès à la technologie, en particulier les femmes dans les pays en développement qui sont généralement laissées pour compte dans le fossé entre les sexes et l'énergie. Les efforts d'innovation des concepteurs ont encore un long chemin à parcourir car ils omettent souvent les utilisatrices au centre de leur réflexion, les consultant et les impliquant dans la création de nouvelles technologies qui peuvent avoir un impact direct sur leur productivité économique. La conception et le développement d'une glacière thermoélectrique portable à énergie solaire pour stocker le lait maternel ont été réalisés après consultation des femmes rurales zimbabwéennes de la communauté de Domboshava. Leurs commentaires ont fait partie intégrante de la conception et de la mise en œuvre du prototype. La glacière a été testée et elle a atteint 15°C en 50 minutes sans charge et 80 minutes avec charge thermique, la température de consigne importante pour maintenir la qualité du lait maternel jusqu'à 24 heures. Un module Peltier TEC1-12706 avec 2 dissipateurs thermiques et ventilateurs a été sélectionné et conçu avec un système de contrôle programmé en langage C++ avec contrôleur Arduino Nano, capteur de température DHT11 et un relais. Ce système fabriqué fonctionne sur une tension continue générée par des cellules photovoltaïques à partir d'un panneau solaire. La batterie 12v, 25Ah utilisée a été évaluée et il a fallu 2 heures 20 minutes pour être déchargée avec charge et 1 heure 40 minutes pour qu'elle soit complètement chargée par l'énergie solaire.

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A special note of thanks goes to the Pan African University of Water and Energy Sciences (PAUWES) Administration and the sponsors of the master program and research, for awarding me this once in a life time opportunity to become part of a program that equips young African minds with relevant skills to deal with Africa's energy crisis.

I would be remiss if I did not acknowledge my proverbial village as well. There is simply no substitute for the love, laughter, and generosity of dear friends. For Phillip Kwendesa, I would not like to ponder, even for a moment, what it would have been like without you.

To my son - if you remember nothing else of this time, I hope you have seen what it means to set your sights on a goal, and to work tirelessly to achieve it. I am enduringly grateful that my own mother who stood by me—never a word of doubt uttered, not a single discouragement just full support and showing up to help me juggle my studies and having a newborn baby.

Above all, many thanks to the Lord for his love, mercy, guidance and for making this dream a reality.

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NOMENCLATURE

A	cross-sectional area, mm^2
C_p	specific heat at constant pressure, kJ/kg·K
I	electric current, Amps
J	current density, A/m^2
k	thermal conductivity, W m^{-1} K^{-1}
K	thermal conductance, W K^{-1}
l	length of thermoelement, mm
N	number of thermocouples
$\dot{Q}$	Peltier heat, watts
Q_c	Heat removed from cold side, watts
Q_h	Heat rejected at hot side, watts
R	Resistance, Ω
T_h	Temperature of the hot side, °C
T_c	Temperature of the cold side, °C
u	velocity vector, m/s
V	Potential Difference/ voltage, volts
$\dot{W}$	Input electrical power, watts
Z	figure of merit
α	Seebeck coefficient, V K^{-1}
∇	Del operator
Π	Peltier Coefficient, V
ΔT	temperature difference between hot and cold sides, K

$\boldsymbol{\rho}$	electrical resistivity, Ωm
$\boldsymbol{\tau}$	Thomson coefficient, V K^{-1}
COP	coefficient of performance
TEC	thermoelectrical cooler
$\boldsymbol{\beta}$	Volumetric thermal expansion of air,$1/K$
$\boldsymbol{\epsilon}$	Emissivity
$\boldsymbol{\eta}$	Efficiency
$\boldsymbol{\Pi}$	Peltier coefficient, W/A
$\boldsymbol{\sigma}$	Stefan Boltzmann constant, W/m^2K^2
$\boldsymbol{\upsilon}$	Kinematic viscosity of air, m^2/s
$\boldsymbol{\omega}$	Thermal diffusivity of air, m^2/s
$\boldsymbol{Nu}$	Nusselt number
$\boldsymbol{Ra}$	Rayleigh Number

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CHAPTER 1: INTRODUCTION

1.1 Background

Infrastructure and engineering products that are well-designed, maintained, and operated are critical in addressing Africa's socioeconomic development, population growth, and urbanization levels. Renewable energy technologies such as solar photovoltaic play a critical role in addressing the energy deficit challenges that continue to plague developing countries. The high costs of expanding the main grid impede strides in development of sparsely populated rural areas thus generating a need for the deployment of renewable energy technologies that enable a more efficient use of African resources, accelerating the economic inclusion of women, youth, and disabled people. RE technologies also allow for the creation of energy value chains that have compounding effects through activities such as renewable energy system design, technology manufacture, assembly, installation, repairs, maintenance and sales.

Solar energy not only supports the achievement of SDG 7 of the United Nations Sustainable Development Goals; which is concerned with ensuring that everyone has access to affordable, dependable, sustainable, and modern energy but also facilitates the achievement of many of the other SDGs – from poverty eradication through advances in health, education, water supply, and industrialisation to climate change mitigation, gender equality, women's empowerment, and access to decent work for everyone. SDG 10 is facilitated by solar power in that inequality is addressed in rural communities through the provision of offgrid energy supply. Adoption of electric devices and appliances becomes easier and so does internet penetration, making the world a global village that is accessible to everyone. As stipulated by SDG5, renewable energy opens doors for women to seek empowering entrepreneurial activities thus levelling the playing field on gender equality. Girls can also spend more time on their education in rural areas when they have access to electricity in developing countries instead of being involved in chores such as gathering firewood and preparing meals on fire. It is for this reason that solar energy can be trusted beyond doubt that its adaptation can help the world fulfil the SDGs either directly or indirectly.

1.1.1 The Women-Energy Nexus

Our society is undergoing a fundamental change as a result of the continuing energy transformation, which is being driven by renewables. This opens up significant prospects for increased equality and participation. Still, in order to fully realize this potential, the renewables industry will need to tap a larger pool of people, particularly women, who have been disproportionately underrepresented in the energy revolution, depriving it of vital capabilities. (IRENA, 2019) Women make up half of the world's population, require the same resources, and face the same global difficulties as the other half – frequently at a disadvantage.

In rural areas, the lack of energy services has major socioeconomic and gender consequences. To address them, energy interventions are needed to improve women's quality of life. Such an approach will engender energy by transforming it into a force for bettering life quality and increasing productive capacities thus propagating a virtuous circle of energy for women and energy for women.

With regards to policy formulations; men's issues tend to be vocalized and prioritised whilst on the other hand due to women's lack of influence in decision-making, their issues are disregarded. By improving their economic status, women can improve their influence in the home and community. Women's income-generating activities are mainly in the informal sector varying from vending to other small businesses without huge cash surpluses. Women's businesses are hampered by a lack of information, time constraints, and cultural restrictions, such as movement restrictions, which can prevent them from participating in training that would improve their skills. Furthermore, this invisibility exacerbates their lack of access to platforms and channels in policy making. In short, women lack a formal voice in the community as well as an informal voice through participation in numerous energy-related institutions and organizations. (ENERGIA, 2004)

The gender distribution of tasks in society creates fluid boundaries for women as their responsibilities overlap whether at work, in their businesses and at home. Since the Covid 19 pandemic, over 97% of female micro-entrepreneurs have reported an increase in the number of hours they spend on domestic and caregiving obligations, and approximately 65% have relied on family members to make business choices. (World Bank, 2020)

Women are better positioned to deliver gender-responsive insights because they provide most of the unpaid labor and usually the first contact in the use of renewable energy products. In

Sub Saharan Africa almost half of the buyers of solar lighting systems are women. Despite this, considerably fewer women are involved in the design and development of smart, sustainable technology-based solutions that might improve the plight of humankind.

As energy consumers and beneficiaries, women’s ability to contribute to household energy technologies such as stove programmes and solar cookers has resulted in more effective product design. Breastmilk storage is a ground breaking concept that needs to be further developed and researched in order to find acceptable storage methods that will reduce the loss of nutrients in breast milk and, in the future, become an option for rural mothers without access to conventional refrigeration related to on-grid connection.

There are numerous ways in which women can participate in, benefit from and contribute to a more inclusive energy value chain. Although having access to energy services does not assure gender equality, it does go a long way further easing women and girls of the burden of everyday chores and allowing them to focus on income-generating activities and education. (ENERGIA, 2011)

1.2 Problem statement

Zimbabwe is a poor and developing country with 72.3% of the population living below the poverty datum line. (UN Women) Its labor force constitutes of 50.9% women and one of their most sensitive concerns is postnatal infant care. (World Bank, 2019) The World Health Organization (WHO) recommends that infants should be breastfed for at least 6 months. Some of the factors that hinder the success of exclusive breastfeeding mothers in working mothers are short time offs, lack of workplace support, short time during work (not enough time to milk), and no room to milk. For women who have recently given birth, breastfeeding is considered to be time-consuming (Schindler-Ruwisch et al, 2019). Rural mothers are not exempted from the struggle as being the children’s main caregivers have to withdraw from their usual economically productive activities such as the bulk of farming and the hard work that goes with it in order to breastfeed.

On the other hand, developed countries have access to technologies which allow storage of expressed breastmilk for longer periods of time under cool and optimum temperatures, allowing mothers to delegate breastfeeding and return to work. This brings attention to the gender bias within current economic statistical systems. The statistics of women spending longer periods of time doing non-income generation activities (including breastfeeding) is more invisible in developing countries costing up to 15–70% of gross domestic product (GDP) (van de Ven and Zwijnenburg, 2018).

The heavy workload that women have in child rearing and also working in the fields takes its physical toll and also reduces the time women have to exclusively feed their infants breastmilk. Exclusive breastfeeding (EBF) means solely feeding breast milk, without addition of water, other liquids or solid foods. EBF is crucial in providing substantial protection against diarrheal and pneumonia related morbidity and mortality for all infants (Ashraf et al. 1991; Bhutta & Yusuf 1997;Arifeen et al. 2001; WHO 2001). Additionally the risk of breastfeeding-associated HIV transmission is drastically reduced through expressing, heat treatment and refrigeration supported exclusive breastfeeding. (Bhutta & Yusuf 1997; Coovadia et al. 2007). Inadequate infant-feeding practices bear some responsibility for growth retardation, which mostly occurs in the first year of life. Each year, around 1.06 million avoidable child deaths are attributable to non-exclusive breastfeeding in the first 6 months of life (Jones et al. 2003). Babies are being fed breast milk plus water, or breast milk with some other supplement.

This research will address the gap to develop an energy efficient technology for the storage of expressed human milk, thereby allowing breastfeeding mothers to do more productive activities.

1.3 Objectives of the study

1.3.1 Main objective

The objective of this research is to design and develop a thermoelectric cooling system with a refrigeration compartment made from locally sourced material; for rural Zimbabwean mothers.

1.3.1.1 Specific objectives

- To identify the system variables that affect the cooling efficiency of the thermo-cooler
- To determine the time that the system takes to reach the set threshold temperature
- To determine the factors affecting the cooling rate
- To adequately size the solar energy system required to meet the power demands of the thermo-cooler

- To investigate the adoption of a solar powered portable storage unit for breastmilk by rural Zimbabwean mothers

1.4 Hypotheses

The study tests the following hypotheses:

- A thermoelectric cooler from readily available local material with a green energy source can be designed to produce a refrigeration effect suitable for storing breastmilk for at least 24 hours without compromising its quality
- Engaging women in the development and design renewable energy products can lead to more acceptance and better design which will iterate to an increase in their living standards

1.5 Research questions

The following questions will be considered during the study:

- What are the key variables that can affect the efficiency of the cooler and how do they relate to each other?
- What is the minimum time the prototype will take to cool the milk to the set threshold temperature?
- What are the metrics to measure the economic and social impact for the rural mothers that can be achieved through deployment of the cooler?
- Will the design have client buy in and be readily accepted?

1.6 Significance of the study

There is an increasing number of studies which show that exclusive breastfeeding for mothers in Sub-Saharan Africa is a challenge, and therefore there is a need for technological interventions that promote optimal breastfeeding. (Mundagowa et al, 2019) Breast milk contains all the nutrients needed to build and provide energy for the growth and development of the baby. Expressing breastmilk and storing it can also help in closing the gender gap when it comes to child rearing as men can also be involved in feeding the baby in periods of mother-baby separation. In addition, storage is needed when planning to delay feeding.

This study is significant in addressing storage-related challenges for breastmilk so as to promote optimal breastfeeding amongst rural Zimbabwean women. A solar powered lightweight cooling device can be an inclusive impactful energy intervention that improves the quality of life of women.

1.8 Scope and limitation of the study

The challenge the research might encounter is the procurement of the thermal components. To be prudent, the acquisition of components would be done ahead of time. This research will also take into account the opinions of the research subjects intended for this study, thus validation on the importance of the product will be carried out through administering a survey. This is a difficult task especially during this time of COVID-19 pandemic. The research does not include methods and apparatus for expressing breastmilk, as well as storage containers of the milk. Microbial activity tests on the breastmilk stored in the thermoelectric fridge versus time are also excluded from the work as they would need more resources through lab work.

Variation in solar radiation as well as atmospheric conditions when used in a different area may affect efficiency of the cooler. As with solar powered systems, days of cloud coverage will mean the thermocooler cannot be used as there won’t be stored energy available.

1.9 Thesis structure

This thesis is organized as follows; in Chapter 1, the problem statement is given. Chapter 2 will review previous related work done from literature including documenting the advances made in Peltier technology. After that, a thermal cooler will be designed and modelled in Chapter 3, clearly outlining the methodology for heat transfer and use of microcontrollers. Then Chapter 4, will discuss the development of the proposed model, the materials utilized, and document the results. Chapter 5 discusses the results and gives future recommendations and a conclusion is given.

CHAPTER 2: LITERATURE REVIEW

The intersectionality of women's economic empowerment and technology is discussed in this project's literature evaluation. It also includes an internet assessment of similar study, paper proceedings and research, books, and lectures. The theoretical foundations of the project, as well as recent breakthroughs in related technologies, are also examined.

2.1 Cooling technologies

Cooling technologies such as refrigeration and air conditioning are arguably two of the most important innovations of the twentieth century, reshaping communities around the world by increasing health, sanitation, and overall quality of life.

Air conditioning technologies are defined as those that are used to maintain the ambient temperatures in residential, commercial, and industrial buildings and spaces often between 20°C and 30°C. Refrigeration technologies are those that are used to keep temperatures near or below zero degrees Celsius (0°C) for the safe storage of perishable commodities like food and medicine, as well as the operation of low-temperature laboratory equipment (Kirkpatrick, 2017). Evidently from the use of carved ice blocks by the early human ancestors to the Freon-powered clunkers of the 1960s, refrigeration technology has progressed significantly incorporating innovative designs.

Cooling systems use both the sensible and latent heat of a working fluid to cool it. Specific heat, which measures the energy required to increase or decrease an object's temperature without affecting its thermodynamic phase, determines sensible heat transfer. The heat of vaporization or fusion characteristic determines latent heat transfer since it indicates the energy required to transition from a solid to a fluid phase or from a fluid to a gas phase. The melting of a block of ice will need heat transfer from another body, causing that body to cool. Evaporation of a fluid, on the other hand, necessitates heat transfer from another body, resulting in a cooling effect. Evaporative cooling systems and the evaporator and condenser components of vapor compression systems use latent heat transfer directly (Dossat & Horan, 2002).

Vapor compression cooling, evaporative cooling, absorption cooling, and gas cooling are some of the cooling systems that have been developed. Vapor compression systems are currently the principal technology utilized in most ordinary household, commercial, and industrial cooling applications, as they outperform and cost less than other cooling systems.

However, evaporative cooling, absorption cooling, and gas cooling technologies are preferred in a variety of other applications.

2.1.1 Vapor compression cooling

A mechanical vapor compression cycle produces a net cooling effect by evaporating a refrigerant or working fluid. In vapor compression cycles, the refrigerant can be chosen from a variety of options with the most important criterion being that the fluid thermal characteristics satisfy the application's requirements. The temperature range for vaporization and condensation is limited, and the refrigerant should have a high heat of vaporization (Kirkpatrick, 2017). Global warming potential, flammability, toxicity, stability, cost, lubricant and material compatibility, and environmental effect are all significant factors to consider. Because the halocarbon refrigerants currently employed are greenhouse gases with a large global warming potential, there has been an urge to transition to alternative refrigerants as a result of growing climate change due to such greenhouse gas emissions. However, there is no such thing as a “perfect” refrigerant, and choosing one for a certain application would inevitably entail uncompromising trade-offs (Aste et al, 2017).

2.1.2 Absorption cooling

To provide a cooling effect, an absorption cycle involves external heating of the working fluid. Because the system components in an absorption system are more complex and therefore more expensive than those in a vapor compression system, absorption systems are primarily used in large industrial and commercial buildings, as well as in situations where electricity is unavailable, such as vacation homes, mobile homes, and trailers. In an absorption cycle, there are two operating fluids: an absorbent and a refrigerant. The absorption cycle reduces the pumping energy required to compress the refrigerant by utilizing the solubility of the refrigerant gas in the absorbent liquid (Bansal & Martin, 2000).

2.1.3 Evaporative cooling

In dry or low-humidity conditions, evaporative cooling can be utilized for cooling purposes. The southwestern United States, Mexico, Australia, North Africa and the Middle East are among these climates. This technique makes use of the latent heat of water vaporization. The water absorbs thermal energy from the air as a hot stream of air evaporates a water droplet or film, and the air is cooled. The difference between the dry and wet bulb temperatures of the ambient air, i.e., the initial air temperature and humidity, determines the potential for evaporative cooling.

When low humidity air is available, evaporative cooling is utilized to cool the air through the evaporation of water sprayed into the air stream. It is less expensive to install and maintain than a vapor compression system, and it uses less energy because there is no compressor. Water, not a halocarbon refrigerant, is used as the working fluid. When compared to vapor compression cooling, however, the temperature drop in the air stream is lower (Hasan, 2010).

2.1.4 Gas cooling

Gas is utilized for cooling in the gas refrigeration cycle, as much as vapors are used for cooling in the vapor compression and vapor absorption cycles. When the gas is throttled from high to low pressure in the throttling valve, the temperature drops dramatically but the enthalpy remains constant. Instead of using Freon or ammonia as a refrigerant, this system uses gas as the refrigerant. There are no phase shifts in the gas throughout the cycle, as there are in liquid refrigerants. In gas refrigeration cycles, gaseous air is the most widely used refrigerant.

The reverse Carnot cycle can be utilized to achieve the refrigeration effect when air is employed as the refrigerant in the gas cycle, however, it is an ideal cycle that is not applicable in practice. The Bell Coleman cycle, in which isothermal operations are replaced by constant pressure processes, is a more practical cycle. This is one of the oldest forms of refrigerators, and it was used to convey food on ships (Tassou et al, 2010).

The gas cycles are less efficient than the vapor compression cycle. Because the amount of gas necessary to absorb the same amount of heat or produce the same refrigerating effect is considerably significant in comparison to the amount of liquid refrigerant required, refrigeration systems using gas cycles tend to be very large and bulky.

2.1.5 Alternative refrigeration technologies

Other than the mainstream technologies discussed above; there are also alternative technologies that are still in development and these include: thermoacoustic refrigeration, thermoelectric refrigeration, thermotunneling, magnetic refrigeration, Stirling cycle refrigeration, pulse tube refrigeration, Malone cycle refrigeration, adsorption refrigeration, and compressor driven metal hydride heat pumps (Bansal et al, 2012).

Significant research has been done in the field of magnetic refrigeration, where new materials and system architecture are being developed at a rapid pace. The working principle can be summarised as that solid-state magnetic material warms up in the presence of a magnetic field and cools down when the field is withdrawn thus generating a cooling effect. Magnetic refrigeration equipment is expected to be expensive at first, but the technology's future looks promising with the potential to be used across the whole refrigeration temperature range, according to researchers (Engelbrecht et al, 2007). There have been a number of prototype systems announced. Prototype cooling capacity are limited; the highest recorded to yet is 540W, with a COP of 1.8 at ambient temperature. The first commercial uses are expected to be for low-capacity stationary and mobile refrigeration systems (Dieckmann et al, 2007).

Sound waves and inert gas in a resonator produce cooling in thermoacoustic refrigeration systems. They are currently in development and have a low COP of around 1.0. Even though they are not yet commercially available, they have the potential to cover the entire refrigeration spectrum, from ambient to cryogenic temperatures. The use of heat to drive a thermoacoustic refrigerator is most probable in the small capacity range (Brown et al, 2010).

The Stirling cycle cooler is a regenerative system in which gas is transferred back and forth between the hot and cold ends of the system. A heat exchanger at the hot end rejects heat, whereas a heat exchanger at the cold end absorbs heat from the room to be cooled (Oguz & Ozkadi, 2002). Systems with cooling capacities of up to 300 W are commercially available in niche markets. Cold head temperatures around 0°C have been documented with COP values between 2 and 3, and cold head temperatures near -40°C have been reported with COP values around 1 (Luo et al, 2006). Because it can function at cryogenic temperatures, it can be employed in a variety of food refrigeration applications (Otaka et al, 2002).

Adsorption cooling for air conditioning applications of 35 to 300 kW is now available, capable of being driven by low-grade heat from 50°C to 90°C and producing COPs of roughly 0.7 at temperatures above 0°C (Fan et al, 2007). In the food industry, applications will mostly be in regions where waste heat can be used to power the adsorption system. Food processing plants and transportation refrigeration are examples of such applications.

In comparison to vapor compression refrigeration, these alternate cooling technologies have a lower energy efficiency. When waste heat is available, they have the advantage of flexibility in energy sources and can increase household energy efficiency. Implementing heat pump technologies for water heating can result in significant energy savings. Furthermore, by integrating systems, such as employing an integrated heat pump system to serve both air conditioning and water heating demands, residential energy efficiency can be considerably enhanced.

2.2 Thermo electric cooling

Thermoelectric devices are solid-state devices that are capable of converting electrical energy into a temperature gradient. Peltier discovered this effect in 1834, but the thermoelectric principle's use was limited until the discovery of semiconductor materials (Zheng, Y et al, 2017). Thermoelectric devices were originally employed for refrigeration and air conditioning in the 1950s, and various papers detail their theoretical explanations.

2.2.1 Thermoelectric Governing Effects

The Seebeck effect, the Peltier effect, and the Thomson effect are all combined in the thermoelectric effect. Thermoelectric devices work by utilizing these phenomena.

2.2.1.1 The Seebeck effect

When a temperature difference exists between the junctions of two dissimilar conductors, the Seebeck effect develops, resulting in a potential difference (Seebeck, 1822). This effect is what allows thermocouples to measure temperature. In Figure 1, two conductors are joined electrically in series and thermally in parallel. One material is a p-type and the other is a n-type. The difference in these materials are the impurities which are introduced, which is achieved through doping. The naming convention of the materials comes from the terminology used in doping, where p represent the electron hole concentration, and n represents the free electron concentration.

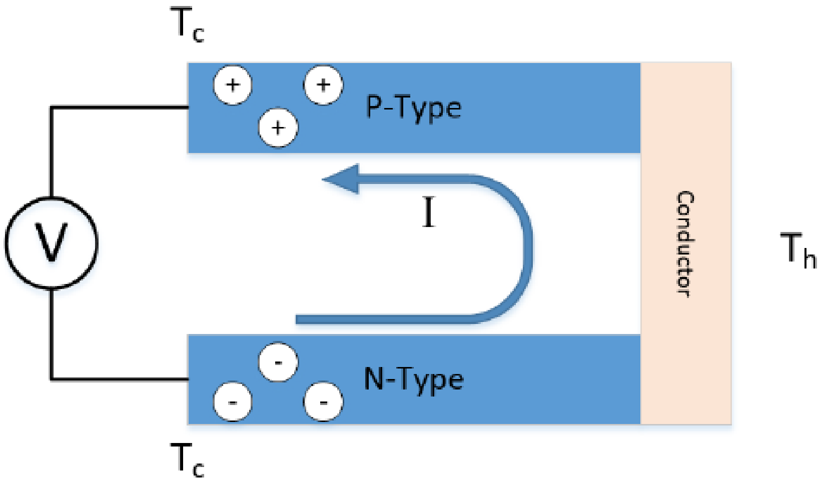


Figure 1: The Seebeck Effect

If a temperature difference is applied across the two legs, given as Th for the hot side temperature and Tc for the cold side temperature, then thermal energy added at the hot end of the conductor frees electrons causing them to diffuse to cold end (Lee, 2016). This diffusion creates a voltage difference in the thermoelectric material. This voltage is calculated by

$$V = \alpha \Delta T \tag{2.1}$$

where α is the Seebeck coefficient and ΔT is the temperature difference across the materials.

2.2.1.2 The Peltier effect

The Peltier effect occurs when a potential difference is introduced across two conductors, resulting in a temperature difference (Peltier, 1834). The applied current causes electrons to flow through the thermoelectric. In doing so the electrons carry thermal energy from one side to the other. The heat flow from the intersection is governed by:

$$Q_{Peltier} = \Pi I = \alpha T I \tag{2.2}$$

where Π is the Peltier coefficient and I is the current. This is seen in Figure 2.

2.2.1.4 The Thomson effect

The Thomson effect states that if a conductor which has a current passing through it also experiences a temperature difference, then heat will be either absorbed or emitted by the conductor, depending on the thermal gradient and the direction of flow of current (Thomson, 1854). The amount of heat absorbed or released is

$$Q_{Thomson} = \tau I \Delta T \qquad (2.3)$$

where τ is the Thomson coefficient and is given as

$$\tau = T\frac{d\alpha}{dT} \qquad (2.4)$$

The Thomson coefficient is unique amongst the three thermoelectric coefficients as it can be measured for individual materials. The Seebeck and Peltier effects require that two conductors are connected at a junction.

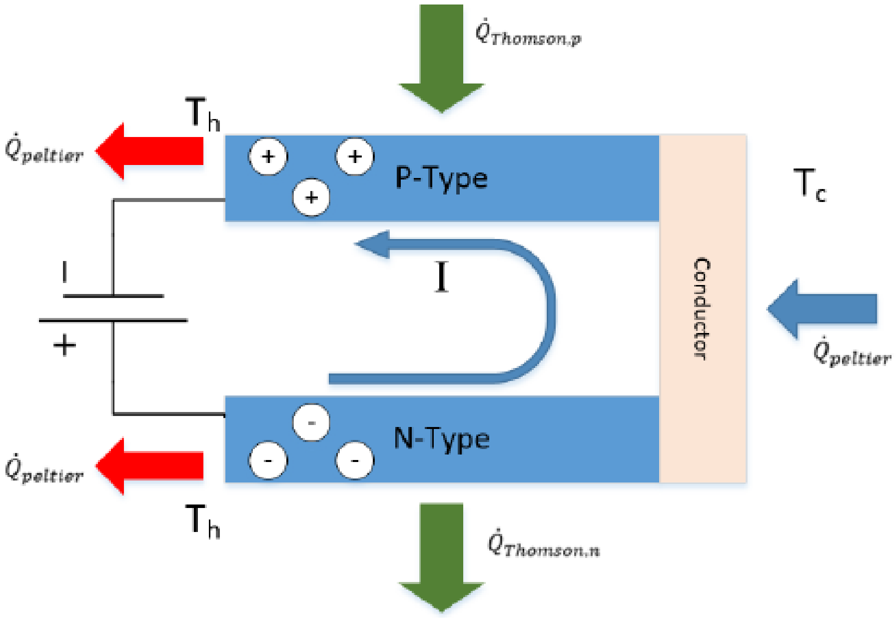


Figure 2: Peltier and Thomson Effect

2.2.2 The figure of merit

This is an important term used to describe thermoelectric materials. It is denoted by

$$Z = \frac{\alpha^2}{\rho k} \qquad (2.5)$$

where ρ is the electrical resistivity of the material and k is the thermal conductivity. The units of Z are $1/K$. The higher the figure of merit, the better suited a material is for thermoelectric applications. This term relates the power production capabilities of the material to its electrical and thermal properties. The ideal thermoelectric material would have a large Seebeck coefficient and low thermal conductivity and electrical resistance. A material such as this would allow current to flow freely through it while maintaining a large thermal gradient. Typically, the figure of merit is multiplied by the absolute temperature to obtain the non-dimensional figure of merit or ZT value. Currently, ZT values are about 1 for most thermoelectric materials (Lee, 2016). Bismuth telluride (Bi_2Te_3) has a figure of merit equal to 2.5×10^{-3} K^{-1} and has been widely used for thermoelectric cooling along with its alloys, whereas lead telluride (PbTe) with Z equal to 1.3×10^{-3} K^{-1} has been used for thermoelectric generation. Instead of Z, the dimensionless figure of merit ZT is often used as a material characteristic, where T is the average of the temperature of the hot and cold junctions (Lee, 2010). Zhao et al. (2014) reviewed that the highest ZT value in the literature is about 3 reported by Harman (2005). Thermoelectric-based domestic and commercial heating, ventilation and air conditioning would become practical if ZT value is reached to 2, whereas the current commercially available materials have a ZT value up to 1 (Zhao et al., 2014).

2.2.3 Thermoelectric generator

Most thermoelectrics used today fall into two main categories: thermoelectric generators (TEGs) and thermoelectric coolers (TECs). A thermoelectric generator is a solid-state power generation device with no moving parts, where thermal energy converts to electrical energy (Fig 3). The simplest thermoelectric generator consists of a thermocouple of the p-type and n-type semiconductor materials, and the working principle is based on the Seebeck effect. In commercial thermoelectric generators, many thermocouples are electrically connected in series and thermally in parallel between two ceramic plates.

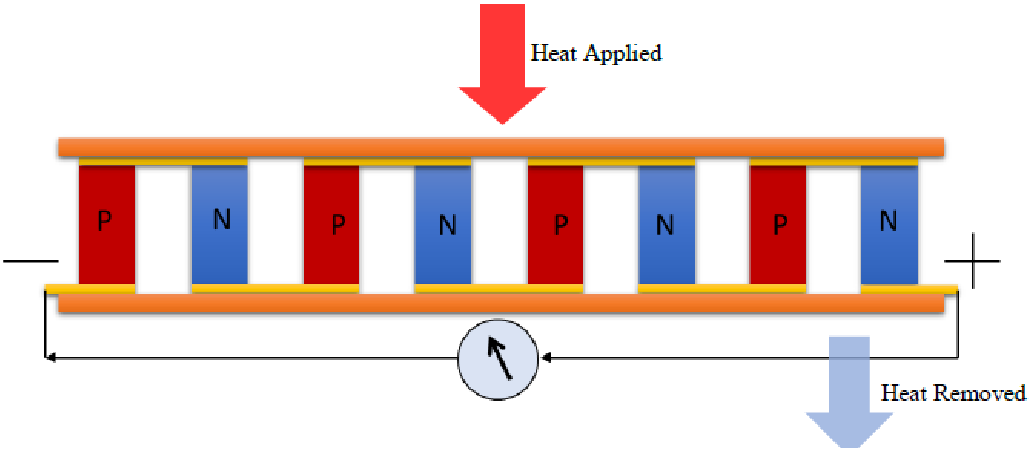


Figure 3: A Thermoelectric Generator

At the hot junction, the total heat flow involves the heat associated with the Seebeck effect, the half of the Joule heating, and the thermal conduction (Lee, 2010).

$$Q_h = \alpha T_h - \frac{1}{2} I^2 R + K(T_h - T_c) \qquad (2.6)$$

Where α is the Seebeck coefficient, R the internal electrical resistance of thermoelements, K the thermal conductance, I the current, and Th and Tc are the hot and cold junction temperatures, where heat is applied and rejected, respectively, as shown in Figure 3.

Notable devices which have utilized this technology include the Lincoln Experimental Satellites and the Voyager space probes (Garvey, 1979). Each of these spacecraft were powered by TEGs which used heat generated by nuclear fission. More recently, TEGs have been used to produce small amounts of energy from waste heat sources. Additionally, many researchers have built and tested solar powered TEGs (Baranowski, 2012). Future applications of thermoelectrics are broad. Current proposals suggest that they could be used to harvest energy from the human body to power health monitoring systems (Bahk et al, 2015).

2.2.4 Thermoelectric cooler

The Seebeck effect in a thermocouple shows that a counter effect can be created, which is the Peltier effect as described earlier. The device based on the Peltier effect is called a Peltier cooler or a thermoelectric cooler and is defined as a solid-state heat pumping device with no moving parts, where electrical energy is converted to thermal energy, the simplest of which consists of a thermocouple of the p-type and n-type semiconductor materials.

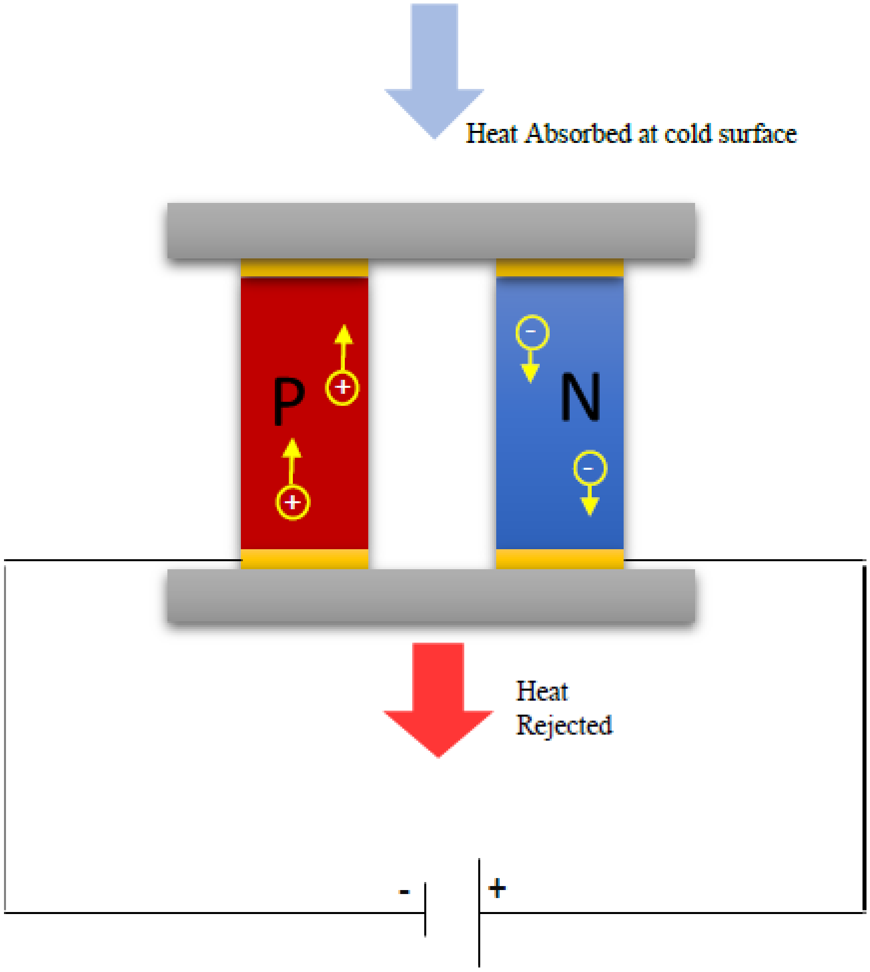


Figure 4: A Thermoelectric cooler

2.2.4.1 Working principle

When the current is applied to a thermocouple, the charge carriers in the p-type material, which are at a lower energy state, are forced to move towards the n-type material, a higher energy state.

The required energy is absorbed from the junction resulting in lower temperature at the junction. When these charge carriers are moved from n-type material to p-type material, energy is released, and the temperature of this junction increases. If the direction of the current is reversed, the direction of the heat flow will also be reversed.

TECs have also found uses in many products. These devices utilize electrical energy to produce thermal gradient, in effect acting as a heat pump. Several manufacturers currently provide portable coolers and climate controlled car seats which utilize TECs (Gentherm, 2017)(II-VI Marlow n.d). They have also been proposed as a means to cool electronic components (Zhu et al, 2013).

2.2.4.2 Heat flow in a thermoelectric cooler

A basic electrical circuit for a thermoelectric cooler (TEC) consisting of one thermocouple is shown in Figure 5. The heat absorbed at the cold junction is the resultant of the Peltier heat, the half of joule heating, and the Fourier conduction. The Joule heat and the Fourier conduction are in the opposing direction of the Peltier heat but are inevitable as they are associated with a current flow and a temperature gradient in a conductor which are present in a thermoelectric cooler. The energy balance gives the net heat absorbed at the cold junction (Lee, 2010).

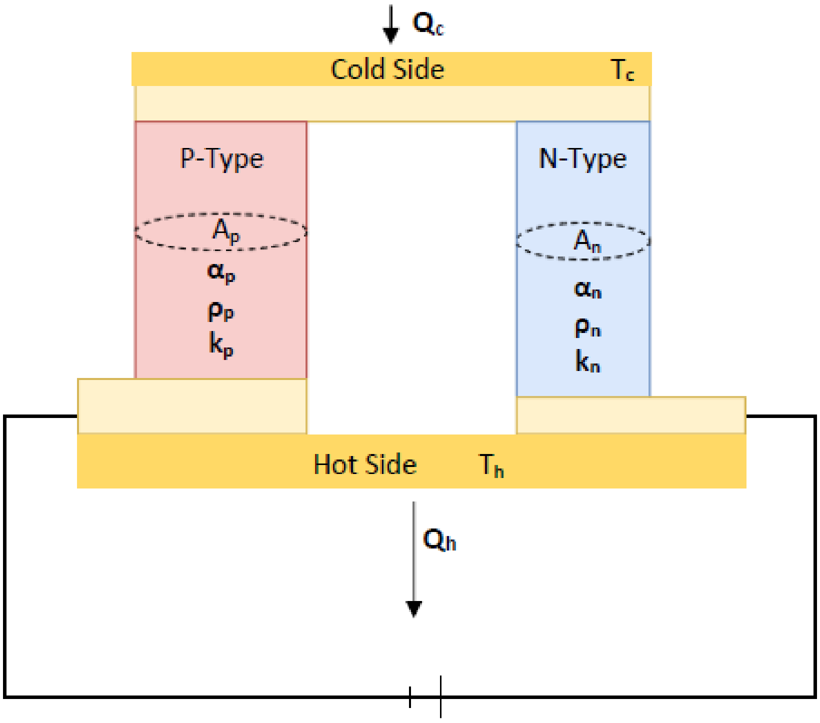


Figure 5: Heat Flow in a thermoelectric cooler

$$Q_c = \alpha T_c I - \frac{1}{2} I^2 R + K(T_h - T_c) \tag{2.7}$$

Here α is the Seebeck coefficient, R the internal electrical resistance of thermoelements, K the thermal conductance, I the current, and Tc and Th are the hot and cold junction temperatures, where heat is removed and rejected, respectively.

2.2.5 Thermoelectric module

For the commercial use, many thermocouples are electrically connected in series and thermally in parallel between two ceramic plates. This arrangement is called a thermoelectric module and is shown in Figure 6.

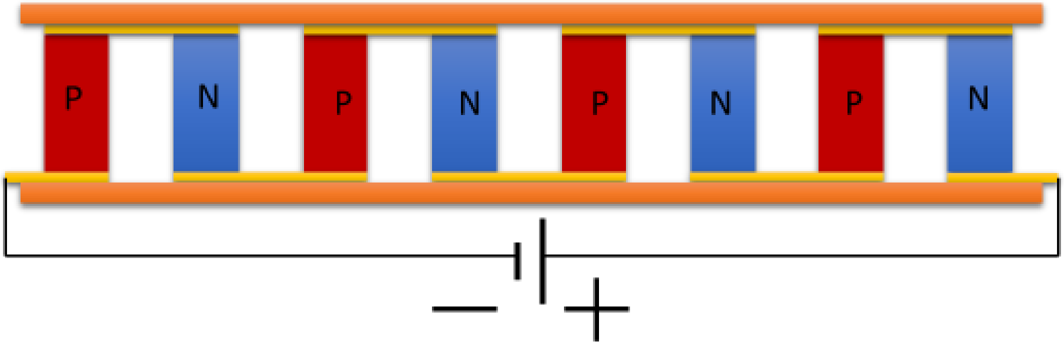


Figure 6: A Thermoelectric module

A thermoelectric module consists of the following components.

(1) A matrix of thermoelectric elements (also called pellets): This matrix is the basic component responsible for the thermoelectric phenomenon in a module. In the commercially available bulk thermoelectric coolers, the p-type and n-type pellets are normally of the same material and the same size. However, for the purpose of performance optimization, different materials and different sizes for a p-type and n-type thermoelement may also be used.

(2) Ceramic plates: These plates are used to insulate the module electrically and to receive or reject the combined heat of thermoelements. These plates also provide the module with mechanical strength. The high thermal conductivity of these plates is essential for module performance. Aluminum oxide (Al2O3) is common due to its optimal cost/performance ratio and developed processing technique. Aluminum nitride (AlN) and beryllium oxide (BeO) have much better thermal conductivity, but due to high cost and carcinogenicity of BeO, they are less common.

(3) Electrical conductors: To carry the current from the DC power source and from one thermocouple to the other, electrical conductors in the form of Cu tabs are used.

(4) Solders: Mounting of thermoelements in a module is achieved by soldering. It is the soldering temperature that would determine the operating temperature of the thermoelectric cooler/module.

2.2.6 Thermoelectric cooler performance parameters

2.2.6.1 Coefficient of performance

The difference between the heat removed from the chamber by the cold side of the peltier and the electrical power input creates a cold environment.

This can be expressed as Coefficient of Performance:

$$COP = \frac{Q_c}{\dot{W}} \tag{2.8}$$

$$COP = \frac{\alpha T_C I - \frac{1}{2} I^2 R + K\Delta T}{I^2 R + \alpha I (T_h - T_c)} \tag{2.9}$$

where Q_c is the net heat absorbed at the cold end and W is the electrical power applied. It is similar to thermal efficiency except that it can be greater than 1 (Lee, 2010).

Low capacity Peltier coolers have become popular and present in the cooling of electrical and electronic devices and for use in small capacity refrigerators. The COP of these units is currently below 0.5 but Bierschank and Johnson showed that the theoretical COP of these devices can be significantly higher than 1.0 for DT less than 30 C.

2.2.6.2 Optimum current of maximum cooling rate

The net heat absorbed at the cold junction is given as (Lee, 2010):

$$Q_c = \alpha T_c I - \frac{1}{2} I^2 R + K(T_h - T_c) \tag{2.9.1}$$

To get the current optimized maximum cooling rate, differentiation of the equation with respect to I and setting it equal to zero. The optimum current after solving for I is:

$$I_o = \frac{\alpha T_c}{R} \tag{2.9.2}$$

2.2.6.3 Maximum performance parameters

Maximum current I_{max} : It is the maximum value of the current or the voltage to achieve the maximum temperature difference. The equation below is the maximum current for a given material and geometry.

$$I_{max} = \frac{\alpha T_c}{R} \quad (2.9.3)$$

Maximum temperature difference ΔT_{max} : It is the maximum temperature difference that can be achieved across the module between the hot side and the cold side. $\Delta T = \Delta T_{max}$ when $Q_C = 0$ and $I=I_{max}$

$$\Delta T_{max} = \frac{\alpha^2 {T_c}^2}{2KR} \quad (2.9.4)$$

Maximum cooling rate $Q_{C\ max}$: It is the maximum heat that can be pumped from the cold side for a given thermoelectric cooler $Q_c = Q_{c\ max}$ at $\Delta T = 0$

$$Q_{c\ max} = K\Delta T_{max} \quad (2.9.5)$$

2.2.7 Multistage thermoelectric cooler

Single stage thermoelectric coolers can achieve up to a certain value of temperature difference. However, in many applications, an even greater temperature difference is required. Multistage thermoelectric coolers are employed to achieve this requirement, where each lower stage acts as a heat sink for the upper stage. This structure is also called cascading and may result in a pyramid shape or for two-stage coolers, where the two stages are with the same length and width but different height.

2.2.8 Heatsink for thermoelectric cooler

The temperature of the hot side of a thermoelectric cooler increases because of the heat that has been rejected from the cold side. For the cooler to continue its operation, the hot side temperature needs to be maintained, and heat must be rejected to ambient through a heatsink. The heatsink plays a great role in the performance of the thermoelectric cooling system. In each of the thermoelectric cooling applications, a unique heatsink and cooling technology would be required. Natural convection is effective for low current carrying small modules. But as the input current and heat load increases, forced convection, phase change cooling and liquid cooling may become necessary.

2.2.9 Previous research

Several studies have been reported on the use of thermoelectric cooling (DiSalvo, 1999, Brown, J. S, 2014). Norhazwani et al (2018) conducted a similar study that utilized the Peltier effect to cool human expressed breast milk within 24 hours at a temperature range of between 4-15 degrees Celcius. From the prototypes developed, Aluminium reached the lowest temperature of 11.2degrees C at 100 minutes and also the fastest to reach 15 degrees at 80 minutes compared to the other prototypes made from polystyrene and polypropylene.

A study by Huang et al. demonstrated an experiment which linked the thermal resistance of a heat sink to 0.2515°C/W. Another experiment was carried out by Bansal et al and Chien et al. to investigate the behavior of thermoelectric coolers driven by solar cells. However, Chien et al. used nitrogen (NH_3- H_2O) on their refrigeration system, which consumed a large amount of power and took a long time to achieve optimum temperature.

Dia et al. (2003) carried out an experimental investigation and analysis on a thermoelectric refrigerator driven by solar cells. They reported that the unit could maintain the inside temperature of a refrigerator within the range of 5–10°C with a COP of about 0.3. Further analysis indicated that the performance of the system is strongly dependent on the intensity of solar insolation and the temperature difference of hot and cold. sides for the thermoelectric module. Atrain et al. (2012) demonstrated the improvement of the performance of a domestic hybrid refrigerator that combines vapor compression technology for the cooler and freezer compartments and thermoelectric technology. The authors reported lower energy consumption in the hybrid system for a new chamber. Abdul-Wahab et al. (2009) conducted an experimental investigation on the portable solar thermoelectric refrigerator. They showed a reduction in the refrigeration temperature from 27°C to 5°C in 44 min and the coefficient of performance of the system was 0.16. Zhao and Tan (2014) presented a thermoelectric system integrated with phase change materials for space cooling. In their experiment, they achieved a temperature difference of 7°C and a maximum COP of 1.22 for a 2-h cooling experiment. They also proposed a steady-state simplified energy model to predict the performance of the system.

Suwit Jugsujinda et al. (2011) analyzed the performance of a thermoelectric refrigerator by applying electric power. They managed to reduce the temperature from 30°C to □ 4.2°C within 1 h and continuously reduced to 7.4°C. However, they did not use a renewable source of energy in their investigation. Gokçek and Shahin (2017) conducted an experimental evaluation of the performance of a mini channel water cooled thermoelectric refrigerator. The COP was found at about 0.41. An experimental study on a hybrid refrigerator combining thermoelectric and vapor compression technologies together with a computational model using finite differences was also carried out by Vian and Astrain (2009). Martinez et al. (2016) worked on a computational model for a thermoelectric refrigerator that simulated the entire system under transient state and illustrated their results with a prototype thermoelectric refrigerator. They obtained an agreement with 10% of the maximum deviation from the experimental values of the main outputs. Similarly, a thermoelectric refrigerator was connected to a microgrid powered by a photovoltaic plant and equipped with an electric storage system was designed and simulated by Enescu et al. (2017). This was an addition to the works of Enescu and Virjoghe (2014) who presented a review of the parameters and performance of the thermoelectric cooling system (using both electricity and solar based cooling system). According to this review of the literature, the COP of the thermoelectric refrigerator operated with electric energy was typically below 0.5 with a temperature difference of 20°C or higher using electric energy for cooling in households.

A complete review of thermoelectric cooling, materials, modeling, and applications was conducted by Zhao and Tan (2014). The review revealed that there are two ways to combine thermoelectric modules and solar PV panels: 1) PV panels provide direct current for thermoelectric cooling; 2) thermoelectric modules are attached to the backside of PV panels to decrease panel temperature, thus increasing PV panel efficiency and gaining extra electric power from thermoelectric modules. Reviews of present and potential applications were also carried out by Riffat&Xiaoli (2004) and Niccolo Aste (2017). Based on the overall review of extant literature, it was found that a solar-powered thermoelectric refrigerator has a lower COP, does not need in-depth design methodology, has a very minimum modelling approach and has almost zero effort on the life cycle analysis. These are the key aspects that may improve the performance of a solar thermoelectric refrigerator.

New technologies for thermoelectric coolers are being investigated and developed. Over the last 6 years, Hi-Z Technology, Inc. (USA) has been developing quantum well technology, with very promising results. A 11μm, Si/SiGe on 25μm Kapton cooling module sized 4.9 cm by 0.25 cm has been built and tested, showing a cooling capacity of 102 W and a COP of 2.85 at a ΔT of 30°C. In their current state of development thermoelectric cooling machines cannot as yet compete with vapour compression systems for refrigeration because of the relatively high ΔTs and corresponding low COPs (0.5 for chilled food transport applications compared to 1.5 for vapour compression systems). This situation, however, may change with the development and commercialisation of the quantum well thermoelectric cooler technology(Bass et al, 2004).

2.3 Breastmilk storage

The World Health Organization and other interest organizations have recently increased their campaign efforts targeted at enlightenment and education about the indispensable benefits of breast milk and nursing, promoting both exclusive and complementary breastfeeding for longer periods of time. In underdeveloped nations, there is conclusive evidence that breastfeeding protects the newborn from a wide range of infections and other ailments. (France et al, 1980; Jason et al, 1984, Jeurink, 2013). Because breast milk is the most ideal source of nutrients and an unrivalled supply of essential antimicrobial and other protective components, the requirement to retain breastmilk for at least limited periods of time in a neonatal unit caring for unwell and preterm newborn children is unavoidable (Slutzah et al, 2010) Even in poor nations, an increasing number of mothers are required to return to work soon after birth (Hamosh et al, 1996), despite their desire to exclusively breastfeed their children.

Although the necessity for storage is no longer arguable, deciding on the best storage technique is not always straightforward. The major concern that has hampered the feasibility of long-term in-vitro preservation of breastmilk is the risk of bacterial contamination and the growth of infectious pathogens in the preserved milk, rendering it unfit for human use (Ogundele, 2000). Refrigeration is the most convenient and cost-effective way to store milk for short periods of time at home or in small clinics. Compared to freezing, this method provides a lot of advantages. It prevents thawing and lengthy rewarming, which can occur when something is frozen (Human Milk Bank Association of North America, 2011).

2.3.1 Storage conditions

For a limited period of time, milk can be safely stored at room temperature. Warmer temperatures are related with greater bacterial counts in expressed milk, while research range in terms of the exact optimum period (Eglash et al, 2017). One important study found that bacterial growth, which is mostly limited to non-pathogens, is negligible at 15 °C and continues low at 25 °C for the first four to eight hours when stored at 38 °C, but increases fast after four hours when held at 15 °C. Milk at 15°C was safe for 24 hours while milk at 25°C was safe for four hours, according to the authors. As a result, expressed milk can be securely stored at temperatures up to 26°C for around four hours. In clean circumstances, storage for up to six hours at lower room temperatures may be possible. (Martinez-Costa et al, 2007)

When human milk is refrigerated at around 4°C, it retains its integrity for longer than when it is left at room temperature (Mustafa et al, 2013). For up to three days, refrigeration has been demonstrated to decrease gram-positive bacterial growth. It has been suggested that freezing breast milk at -20°C for up to three months is the best option. Vitamins A, E, and B, total protein, fat, enzymes, lactose, zinc, immunoglobulins, lysozyme, and lactoferrin, as well as total protein, fat, enzymes, lactose, zinc, immunoglobulins, lysozyme, and lactoferrin, are all preserved after three months, while vitamin C may be lost after one month. Although changes in taste and smell may occur at -80°C as lipase continues to break down fat into fatty acids, up to 9 months in deep freeze at -20°C is deemed acceptable (Yundelfa et al, 2018). After freezing, milk can be thawed in the refrigerator, or by using a container of warm water or by running it under warm water.

Table 1: Guidelines for storing breastmilk (Medela, 2018)

Storage place	Room Temperature (16°C to 25°C)	Refrigerator (4°C or colder)	Freezer (-18°C or colder)	Previously frozen breast milk thawed in the refrigerator
Safe storage time	Up to 4 hours is best. Up to 6 hours for milk expressed under very clean conditions	Up to 3 days is best. Up to five days for expressed under very clean conditions	Up to 6 months is best. Up to 9 months for milk expressed under very clean conditions	Up to two hours at room temperature. Up to 24 hours in the refrigerator. Should not be refrozen

2.3.2 Breast milk storage technologies

While the current era of baby care has seen many innovations, one that hasn't caught up is breast milk preservation. Nursing mothers with newborn babies must frequently pump milk into a bottle, store it in a plastic bag, and then re-transfer the milk into a different bag when their baby is ready to eat (Medela Inc, 2005; Rasmussen, 2011). Due to the fact that plastic bags leak, many parents are obliged to double- or triple-bag their milk, which isn't exactly eco-friendly. The average mother uses 1500 plastic bags per year per baby. As such, a gap exists for breast milk storage and preservation.

The design of refrigerated products must include two scenarios for use: en-route and at home. The requirements are higher during shipment, and the freezing unit must be strong to survive various transit conditions. To avoid total colony deterioration, it is critical to maintain a temperature that is stable and does not fluctuate dramatically; thus, a -20°C environment is advised. As a result, the breastmilk's overall storage time is extended. Milk research is a significant element of the design process because it directly affects the unit's function, therefore key characteristics like the storage environment (temperature, humidity) are crucial (Arnold, 1996).

Breast milk storage units are not as common in household but mainly found in the baby department of hospitals and require cool temperatures. A recent brainchild of two Brown University students is a breast milk storage system that uses reusable silicone bottles that can attach directly to a breast pump and feeding nipple, avoiding the need for milk transfers. A storage unit is included in the design to guarantee that the oldest milk is easily accessible initially.

Phononic, another business, created medical refrigerators that use solid-state technology to replace the compressor found in regular refrigerators. As a result, the refrigerators are tiny and quiet enough to be kept in the patient's room, promoting mother-baby bonding while preventing cross contamination. The Thermo ScientificTM TSG Series Countertop Refrigerator has been designed to meet the rigorous and demanding needs of healthcare, research, and industrial applications where solid performance is required, such as breastmilk and medication storage, analyzer kits and reagents, and even cell culture media (Figure 7).

A Chinese appliance company, Haier, is currently working on the development of a dedicated breast milk storage freezer as a collaboration with a lactation researcher for their philanthropic platform called Hope.

Figure 7: Thermofisher breastmilk storage unit

Developed countries have access to technologies that allow mothers to delegate breastfeeding and return to work by storing expressed breastmilk for longer periods of time at cool and optimum conditions. A different scenario exists for mothers in developing countries with some mothers pumping and disposing the milk during separation with the baby so as to avoid breast engorgement.

2.4 Engendering technology

The ability of technology to help women develop economically may be the most exciting transformational characteristic of it. It is vital to empower women and improve their job efficiency in order to reduce poverty. A growing body of evidence shows that improving women's economic standing leads to a slew of beneficial economic and welfare consequences for children, families, and society (Gill et al, 2010). Improving women's access to technology has the potential to boost their economic advancement as well as the overall economy. Unfortunately, technology has been underutilized in opening up economic prospects for women. In both old and modern technologies, the gender disparity is visible.

Women in poor nations are also denied essential technological benefits like efficient domestic energy for cooking, heating, and lighting, as well as for home-based agricultural and industrial activities. The rural poor, the bulk of whom are women, have little choice but to rely on inefficient energy conversion fuels (Cecleski, 2002). As a result, impoverished rural women have disproportionately limited access to energy services that are clean, efficient, reliable, safe, and inexpensive (Clancy et al, 2003). Despite disparities, the global economy and its associated rapid technical advancements provide a significant potential to bridge the gender and technology divide and utilize the benefits of technology to accelerate lower and medium class women's economic advancement in developing countries.

One consistent method emerges from an examination of successful cases of technology interventions for women's economic advancement: Women were involved in at least one stage of the technological lifecycle in each of the projects. The barriers that have traditionally led to the technology and gender divide must also be addressed. These include the lack of basic education and training required to be ready technology adopters, and being frequently viewed as “users” or “receivers” of technology rather than innovators involved in its design and development. Women’s domestic responsibilities and multiple roles as caregivers and economic actors mean they have little free time to explore and experiment with new technologies. They are also limited by social conventions that give men control over much technology; and they lack the financial and institutional resources to utilize, rent, or buy established and innovative technologies that could help them develop economically. (Grown et al, 1997) However through consistent effort from multiple stakeholders, these obstacles can be overcome. Women's participation in the technology development lifecycle can start a positive chain reaction that allows them to use technology to improve their economic activity, either by increasing productivity in present activities or by allowing them to pursue additional income-generating options (Gurumurthy, 2004).

2.4.1 Women as innovators

Users play a significant role as sources of innovation in this process, in contrast to the long-held assumption that product innovations are generally pushed forward by product makers (Oudshoorn & Pinch, 2008; von Hippel 1988). It would be financially beneficial for technology businesses to pay more attention to women's innovative power and other specific user groups, or in this case nursing mothers in the area of childcare or juvenile products. One of these well-known instances of successful things designed directly by consumers who were mothers physically active in sports is the three-wheeled running stroller known as the "baby jogger" (Von Hippel 2009). Schwartz Cowan, one of the first scholars, noted that technologies utilized in the context of 'female problems,' such as child rearing, women's health, or fundamental household duties, are usually misclassified as technology and overlooked by historians and designers. Tampons, baby bottles, bottle sterilizers, cradles, and the teeth ring are just few of the items that come to mind (Schwartz Cowan 1979). These "commonplace" technologies, as well as the contributions women may make to the design process, represent a large untapped market to explore in order to develop new products and grow market share. Schraudner & Lukoschat (2006) make elaborate arguments for including gender issues into strategic R&D planning and increasing the number of female researchers, developers, and designers. To begin with, including gender in the definition of a study topic increases the number of related research questions and hence the chance for creativity, as well-worn paths are abandoned and new avenues for discovery arise. Second, enterprises and organizations will get new starting points for the creation of technology, goods, and services by recognizing new contexts of usage, upgrading existing offerings with gender-relevant qualities, and generating additional solutions based on the identified new demands. Gender-sensitive design could be a valuable method to establish market share in a specialist industry, especially for smaller enterprises (see also Rommes/Faulkner 2003). Third, including female viewpoints, expectations, and preferences early in the innovation process is likely to increase female customers' interest in the products, lowering the current barrier to many technological improvements.

2.4.2 Gendered design

Design, as a crucial part of engineering and technology, is similarly complicated. “Design is that field of human experience, talent, and knowledge concerned with man's ability to mould his environment to fit his material and spiritual needs,” wrote Archer in 1973.

Design is defined as a structured problem-solving process that begins with the perception of a need or the identification of a problem, continues with the formulation of a specification, the generation of ideas and a final solution, and concludes with the evaluation of the solution in the context of engineering and technology (Bratteteig, 2002).

Engineering and technology have a huge impact on society and people's lives. Using these disciplines, natural resources can be harnessed to meet the fundamental and sophisticated demands of human kind . Both are required for a country's infrastructure to expand and prosper, as well as its economic growth.

As a result of globalization's effects, as well as social and demographic challenges, markets have altered considerably in recent decades. This refers to the shift in gender ratios that has taken place in developed Western countries and a slower shift in developing countries where culture and religion stifle the liberalisation of women. Despite an increasing number of highly educated and economically independent women acting as autonomous customers and design-conscious users of technology, gender has been largely overlooked in the realm of technology products (Van Oost, 2003). Technical research, design, and development are still heavily reliant on the underlying experience of a homogeneous group of scientists and engineers who rarely consider the needs of female consumers (Joost et al. 2010; Schraudner & Lukoschat, 2006).

Engineers frequently reduce projects to solve technological problems by omitting "disturbing aspects" like people. The result is buildings that meet the most recent technical and energy efficiency requirements, but they lack practical features like spaces for washing machines or windows in the right places that allow mothers to watch their children at the playground while cooking (Schultz & Hummel 2002; Wächter, 2002). Designers make "gendered assumptions" about customers, which are subsequently implicitly translated into technologies and products.

The most important current political trend in the liberal tradition is gender mainstreaming. The European Commission (2011) defines gender mainstreaming as “the incorporation of the gender viewpoint into every step of policy processes [...] with the goal of attaining equality between women and men.” This approach is applicable to all public and governmental institutions. It entails assessing how policies affect men and women's lives and positions – and taking responsibility to address them if necessary; allowing everyone in organizations and communities to contribute to the process of articulating and translating a shared vision of sustainable human development into reality. Although material preconditions and resources to remove existing barriers are critical for many women's involvement, the inadvertent repetition of the male norm in society has been challenged, notably through political initiatives. As more liberal governments around the globe have chosen gender mainstreaming as a means of bridging the women-technology gap, a broader conversation about how to address the flaws of this relatively technocratic approach to women's issues is required (Stiegler 2008).

CHAPTER 3: RESEARCH METHODOLOGY

In more details, in this part the author outlines the research strategy, the research method, the research approach, the methods of data collection, the selection of the sample, the research process, the type of data analysis, the ethical considerations and the research limitations of the project. The material and method analytical design of the thermocooler for sizing including the selection of auxiliary components for its control is also discussed.

The methodology used in this study is two-fold. The first part being a qualitative research to investigate the adoption and design needs of the breastmilk cooler from the intended users being the rural Zimbabwean women. The second part consists of the actual design of the cooler and experimental evaluation of its performance.

3.1 Methodology for the Energy-Gender Nexus

The research design for the energy-gender nexus is based on a case study unit of analysis and sampling. The focus area is the rural community of Domboshava which is located around 30 kilometres just outside the capital city of Harare. The use of case study can be understood as a bounded system, entity, or a particular unit of analysis to be studied (Stake 1995, 2006; Creswell 1998).

According to Clancy (2000) bridging the gender gap in energy related project begins with separation of data on energy by specific needs of men and women. The value of this practice can be enhanced by the use of research strategies that rely on participatory approaches and as the methodology of this study conflate; bring women on board as research collaborators. Participatory approaches are centred on the proposition that the people who are the focus of the investigation, implementation, or analysis know more about their lives and environment and what they need to improve their quality of life than do the professionals who are working with them (Ward, 2000). Participatory approaches facilitate the mobilisation and sharing of local knowledge in combination with the expertise of outside specialists, a process that results in knowledge that is more accurate and more useful than knowledge that is produced and deployed by professionals alone (Jackson and Kassam, 1998).

The present study represents a practical attempt to address the shortcomings of depending solely on quantitative methods engaged by engineers to conduct research. The methods used here are based on a combination of qualitative and quantitative research techniques (i.e.semi structured questionnaires with experimental research). This research approach represents an effort to obtain gender-disaggregated information and to avoid overly reductionist data gathering approaches that can obscure local conditions. These local realities, often influenced by gender issues, can be crucial to understand more clearly the life and circumstances of local people.

Another academic consideration in this thesis is the use of a mixed method ‘gender and empowerment’ approach where the data collected can be used to generate specific tangible outcomes from the qualitative data and also the generalisability of quantitative studies (Kabeer 1999; Stake 2006; Tsikata and Darkwah 2014). This is also influenced by post-colonial critiques of development as embedding power inequalities between researchers, engineers, designers and people on the ground (Tambe and Trotz 2010; Rai 2011). This will be an essential contribution to current energy literature studies that have been predominantly focusing on outcomes rather than process (Cecelski 2005; Parikh 2009; Moezzi, Janda, and Rotmann 2017).

A group of breastfeeding mothers visiting the local community clinic for their baby check-ups were asked to participate in the research to investigate their breastfeeding practices together with a market analysis on the possibility of their acceptance to store their breast milk in a solar powered cooler. A questionnaire was administered and the sampling method used is a convenience sample, because the participants are volunteers and they were chosen based on their availability.

3.1.2 Questionnaire design

Questionnaires are specialised and structured tools of human interaction that are meant to make communication more effective and predictable. (Harris D.F, 2014) In this research a written questionnaire in English was used to collect the data.

The following steps were taken in developing the questionnaire:

1. Identification of assessment objectives and information needs- This entailed review of the research question and the hypotheses that the research needed to answer
2. Deciding on the source of information, data technique and modality- The hypotheses from secondary data identified the gaps that need to be addressed by the questionnaire, key informants being the breastfeeding mothers were selected
3. Draft questionnaire

4. Field test- colleagues who were not part of the project were consulted so as to help in identifying errors. 3 respondents were given to test the questionnaire under similar conditions to those of the assessment. This was done to check if the respondents answer the question in the intended way and also confirm the validity of the questionnaire
5. Review and format the questionnaire – After a review and changes the questionnaire was then deployed to the case study area

The questionnaire was designed in such a way that it provided structure to the interview enabling it to flow smoothly and systematically. Only questions with data that had a direct use in addressing the objectives were included.

3.1.3 Data collection

To establish rapport between the enumerator and the respondents, bridge building conversations about children and breastfeeding and general health were started in trying to reorient the respondent’s perspective in preparation for the questionnaire. The researcher was available during distribution of the instrument to answer any questions about the questionnaire from the subjects and also translate into Shona for respondents that were not fluent in English. The mothers were asked to answer the questions after introducing the goals of the study and its objectives.

As per ethical considerations, the consent form was distributed to the participants prior to data collection. Informed consent is important for ethical research practice and respecting the rights of people to self-determination, and which is commonly captured through written statements (Liamputtong 2010). However Liamputtong (2010) notes that in cross-cultural contexts consent can be more complex than simply signing an individual form. Liamputtong (2010) maintains that it is important to verbally gain consent through clearly explaining the purpose, intended outcomes and nature of the study in the language of the participants, through building trusting relationships, and to take note of non-verbal cues and body language which may indicate comfort or discomfort. The consent form enabled the participants to understand the study goals and their responsibilities in the study. The volunteers were also assured of the confidentiality.

3.1.4 Study limitation

Notwithstanding the care and deep thinking that went into the design of this study, there are several methodological shortcomings are nevertheless observable and must be mentioned as such. First, because data for this study were generated from a single data collection method i.e. Semi-structured questionnaires, one cannot discount the additional insights that would have been obtained if other methods of data gathering in qualitative research such as observation and/or focus group discussion were used to complement the questionnaires. Second, since participation in the study was limited to only breastfeeding women, other important interest groups such as family members, husbands and health care workers were not represented; and this will obviously impact the intended understanding and nuances that affect breastfeeding related issues and also product purchases. In addition; there is an inconsideration of the shifts in women's empowerment when viewed relationally with men. The study only takes women as participants which theorists such as Agarwal (2001) have discouraged. On the other hand; the research on this particular demographic is justifiable in that it seeks to address a gap in which women are committed to voicing their own empowerment in renewable energy products which is rarely accounted for energy literature.

3.1.2 Results and discussion

The early stages of the product development process play a key role, as most of a product's social and ecological impacts during its life cycle are determined by decisions taken during early phases (McAloone and Tan, 2005). An important aspect of this research study is the use of knowledge from women as collaborators as a baseline for proposing a novel set of recommendations that can enable integration and accurate design of a product that will satisfy the intended user's needs. User- or human-centered design inverts the traditional human-machine relationship by suggesting that technologies must adapt to match humans instead of humans adapting to technologies (D'Ignazio et al., 2016). More specifically, UCD is a cyclical approach that seeks to identify and understand users and their needs, and meet these needs through design iterations (User-centered design basics, 2019). The UCD process has proven beneficial across multiple domains as it identifies challenges early in the design process allowing for quicker solutions, avoids poorly defined system requirements, improves performance by reducing the number of user errors, and results in products that meet user's needs (Benefits of user-centered design, 2019). In order to initiate the first steps in a UCD and feminist design process of a breast milk cooler, empowering mothers to share their ideas on what characteristics should be incorporated in the product design is vital.

A questionnaire with 20 questions was presented that addressed three themes which were on familiarising with the participant's background, breastfeeding status and their perspective on the breastmilk cooler design. Different types of open and closed questions were combined in order to gather both quantitative and qualitative data and to achieve synergistic effects (Eisenhardt, 1989) and a balance between the weaknesses of each type of questions and scaling techniques (Karlsson et al., 2009). The respondents were strictly breastfeeding mothers and 16 of them were interviewed over a course of three days during visits to the local clinic.

After collecting the data, the data were summarized and analyzed by SPSS software. The results highlighted that the majority (69%) of the participants in this study fed their babies on breastmilk and other substitutes which varied from fermented maize meal porridge (maheu) to mashed seasonal fruits such as bananas. The exclusive breastfeeding rate was low (19%) despite the mothers' high knowledge levels and positive attitudes towards the practice. It was also mostly prevalent for babies below the age of 6 weeks where the mother was still grounded and going through post-partum recovery. The major economic activity in Domboshava is agriculture; mainly horticulture through growing vegetables that can be sold in the capital city. Most families are heavily involved in farming from the women to the children that is why 50% of the respondents are self-employed. All of the mothers agreed to leaving the babies with family members citing different reasons such as for work, personal errands and other economic activities.

Analysis of open ended questions from the questionnaire helped explain and substantiate quantitative findings. Access to electricity is still very low even with the community's proximity to the city and still limited to the local clinic and schools. The rest of the villagers rely on solar power and bioenergy for fuel and power. 81% of the mothers expressed that owning a cooler would satisfy their needs however all of them were not willing to pay more than $30 for a unit. This can be reasoned from the point that it is a new technology they had not used and seen its economic benefits or improvement of lifestyle and they would not spend more money for the product. Based on the findings, Table 4 shows the main key criteria that appeared related to the design of the breastmilk storage unit.

Table 2: Design criteria results

Design criteria	Description and purpose
Efficiency	The cooler should be energy efficient with low power consumption and achieving low temperatures at a fast rate so as to preserve the integrity of the breastmilk
Easy to clean	The inner lining should have material that is easy to clean and can also be easily replaced
Bottle space	The volume of the cooler should be large enough to store at least 1 feed, which can range from 250ml-500 ml depending on the age of the baby
Low weight	Small product size will allow it to be moved to different location thus increasing portability
Ease of use	Respondents emphasized on a product that is easy to operate with minimum moving parts
Durability	It should be robust and can last for a long time. It should also be food safe and corrosion resistant.
Cheap	The cost of the product has to be affordable therefore the material used should be low cost and readily available

3.2 Design of the thermoelectric cooler

The methodology to be used for this part of the research is experimental. The final goal of the experimental system is to determine the effectiveness of an autonomous Peltier-effect-based system to cool breast milk. To design this prototype, the following input data must be known:

- optimum temperature needed to keep breast milk fresh and safe for consumption,
- estimate of the solar energy budget required to power the system and
- the specific Peltier cooler to be used.

Solar energy is used to generate power that will create heat flux between the junctions of two different types of materials in the Peltier plate effecting a temperature difference between its two sides. When DC current flows through the device, it brings heat from one side to the other, so that one side gets cooler while the other gets hotter. The "hot" side is attached to a heat sink so that it remains at ambient temperature, while the cool side goes below room temperature. This chosen method will be effective in the design of an energy efficient breastmilk cooler prototype using solar renewable energy.

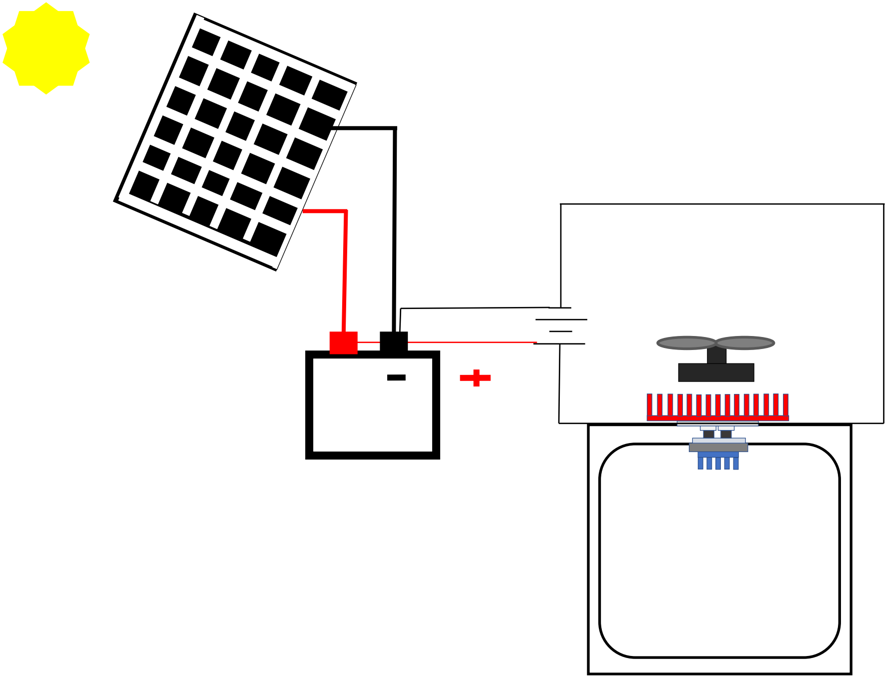
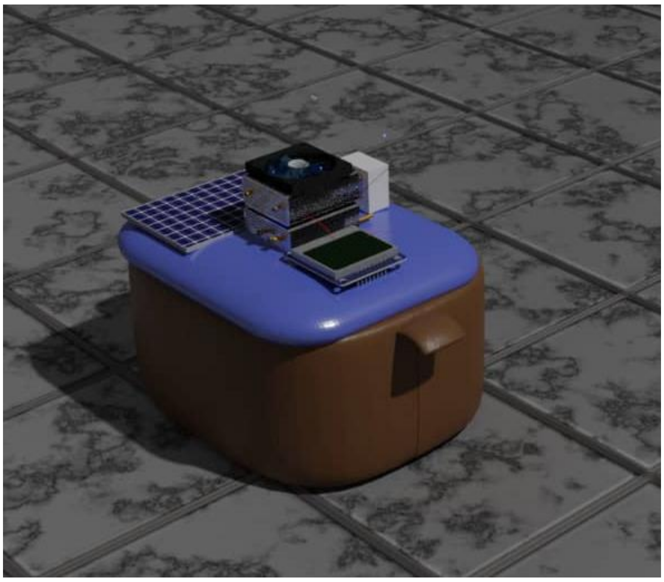
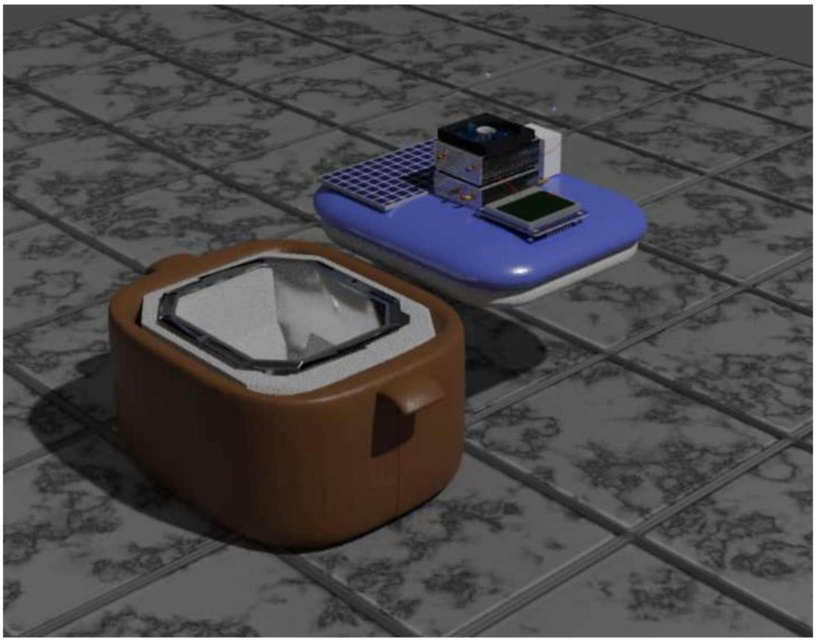


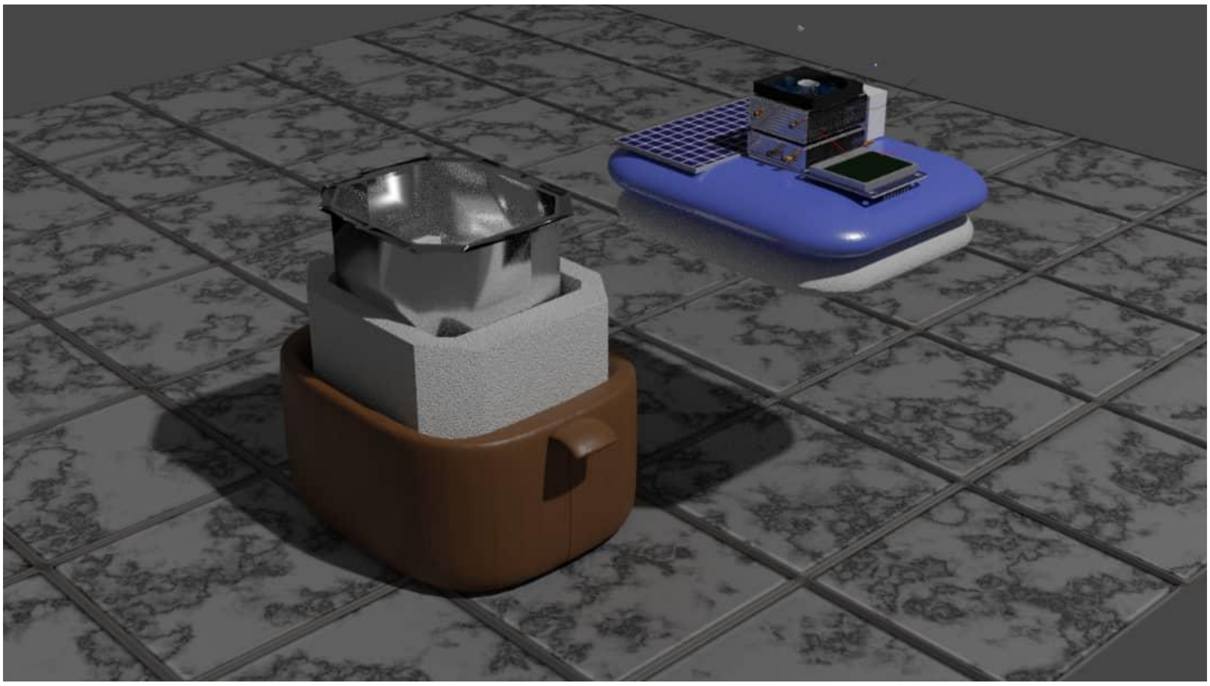
Figure 8: Conceptual design of cooling unit

3.2.1 Geometric design

The proposed solution consists of a compact cooling holder that is well isolated and can house at least 500ml of breastmilk. Isolation of the compartment where the milk is stored from the controlling unit is also a necessary requirement. It is necessary to utilize material that allows portability of the prototype which makes it easy to carry around. Two fans will be installed with one on the cold side and another on the hot side of the thermoelectric module. The cold side fan drives cold air into the cooling chamber where the milk is stored and the one on the hot side will cool the heat sink fins. A model was designed using blender software to show how the concept would look beyond the prototype as shown below:







Because of its abundance in Domboshava and almost zero cost, clay will be moulded as a casing and used to house the cooler. The clay is excavated from a nearby stream and before casting of its structure by mixing it thoroughly with water to increase its plasticity. The clay was also chosen because of its low conductivity of heat and porosity.

A common problem for many Peltier fridge projects is that they don’t end up reaching the desired temperature. This may be mainly attributed to not having proper insulation or the enclosure being too big for size of Peltier module they are using so it is crucial that the container is not oversized. For experimentation purposes the volume of the chambers is kept low. The size was selected based on a variety of factors with portability being the most crucial one. To accomplish a key aspect of the problem statement, portability and adaptability, a smaller area will be easier to cool with less power and be lighter when moving it. In this case the size range was chosen to be 500 ml-1 litre. As the temperature inside the chamber becomes lower the amperage will be reduced to reflect the optimum current for that temperature difference.

The square shape was considered due to the ease of insulation installation. Insulation provided to the chamber is done by expanded polystyrene and aluminium foil casing so as to minimise heat dissipation into the cooler from the environment preventing any effect on performance by external heat. Aluminium foil is chosen for the inner wall because of its low price and lightweight (smallest value of ρ). Hygiene wise, any spillage of the milk from its container can be easily wiped and also the foil can be replaced at a cheap cost.

3.2.2 Working condition design

One of the most important elements in breastmilk storage is its temperature regulation. To ensure that human milk is safe for consumption, immediately expressed milk has to be kept under cool temperatures, therefore, the design requirements of the breast milk cooler is to maintain ambient temperatures (M. K., & van Goudoever, J. B, 2019). In this proposed work, the main aim is to design a system capable of maintaining the temperature of the materials between 0°C to 15°C in a cooling chamber of not more than 1L. A data acquisition logger connected to the system will be used to measure the progression of temperature against time.

System components

User interface

The user interface will consist of an ADC (Analog to Digital Converter) which is a device which converts the readings of a physical quantity into a digital number that represents the quantity's amplitude. In this the result is a sequence of digital values that have converted a continuous time and continuous-amplitude analog signal to a discrete time and discrete-amplitude digital signal. An LCD (Liquid Crystal Display) will be used to display the temperature on the user interface.

Microcontroller

The controller will receive information from the user interface, solar power system and the temperature probe. This information will be used to control the temperature by controlling the status of the cooling unit. The controller will also send information like the temperature to the user interface.

Temperature sensor

The temperature probe will capture the temperature inside the cooling holder and send this information to the controller.

Heat sink

The heat sink is part of the cooling unit responsible for maintaining the required temperature inside the cooling holder. The cooling unit’s status will be determined and controlled by the controller. Selection of a heat sink is crucial to the overall operation of a thermoelectric system. The heat sink consists of fins that are coupled to a fan.

Figure 9: Heat sink with fins

The fins have a high surface area to facilitate the transfer of heat from the surface of the thermoelectric. This could be achieved by free convection and forced convection.

In a natural convection, the air comes in contact with the warm fin, absorbing heat from the TEC and thus increasing the temperature of the air. The warm air being lighter, rises up and the cold air from below rises to take away to take away the heat from the fin. This cycle continues in natural convection air cooled fin, since the rate of heat transfer in natural convection is lower, therefore they require a larger surface as compared to forced convection.

In forced convection there are two methods which can be employed to facilitate the transfer of heat from the surface of the thermoelectric, by air-cooled and water-cooled. In forced convection air cooled, the fan is used to force the air over the TEC fin to increase its heat transfer capacity. But in forced convection water-cooled is used pipe and pump to facilitate the transfer of heat making it difficult to handle, low flexibility and more expensive. For solar TEC, it will be used forced convection air-cooled, as in figure (3.1). Despite its efficiency is low compared with the water-cooled, but the size of the project is small so that it will not be affected by this efficiency.

Figure 10: DC fan

Peltier Plate

A typical thermoelectric module consists of an array of Bismuth Telluride semiconductor pellets that have been "doped" so that one type of charge carrier – either positive or negative – carries the majority of the current. Their ability to actively cool to sub-ambient temperatures, and their ability to enable precise temperature control makes them a popular choice for precise temperature control. While all Peltier devices share the same basic construction and operate using the same principles, discovered by Thomas Seebeck and Jean Peltier, differences in structure can have a significant impact on their performance. It is therefore important to design and size the system to be cooled to as to choose the appropriate module for use.

Solar panel

A solar panel is a photovoltaic module which is built up by a certain combination of solar cells. The material of the solar cell for the solar panel used in this research project is polycrystalline silicon. This because the efficiencies are set off to almost the same as monocrystalline solar panels as the area of case study has average temperatures above 25°C. A solar panel functions by directly converting the solar radiation into direct current electricity.

3.2.3 System power design

The total electrical energy required by the system will be established which will be used to size the solar panel size and battery required to power the system efficiently and for at least 5 hours of autonomy. An iterative design process is used that starts with estimating the heat load and the TEC module is chosen according to the requirements.

3.2.3.1 Cooling Load

The total heat required to be removed from the refrigerated space to bring it at the desired temperature and maintain it by the refrigeration equipment is known as cooling load. The purpose of load estimation is to determine the size of the cooling equipment that is required to maintain inside design conditions during periods of maximum outside temperature. The design load is based on inside and outside design conditions and its cooling equipment capacity to produce and maintain satisfactory inside conditions.

The cooling loads to be computed are:

1. Active Heat Load.

2. Air Changing Load (Infiltration).

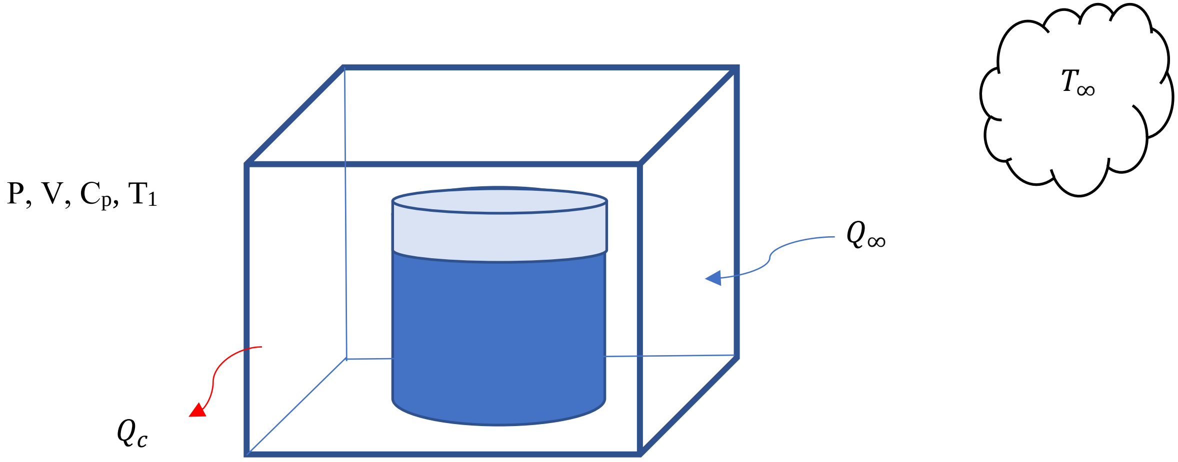
3. Transmission Heat Load

The target temperature in the cooling space is below 15 °C, and the ambient temperature is about 30°C based on the average maximum temperatures that occur in Domboshava. The volume of thermoelectric cooler is to be at most 1litre and the desired cooling time is 1 hour. The density of human milk is 1.03g/ml (Neville et al, 1988; Woolridge et al, 1985).

Active Heat Load

Moreover, the calculation focuses on heat transfer rate from outside to inside cooling room, insulation thickness, and number of TEC to satisfy the requirements and objectives that had been mentioned before. In addition, at transient condition, TEC absorb heat from cans, room, walls, and heat gain from surroundings in difference to time, as shown by Figure 3b.

Heat Transfer in Transient condition



The active heat load is the heat released from a mass which is kept inside the cabinet during the cooling and is calculated by,

$$Q_{active} = \frac{mC_p\Delta T}{\tau} \qquad (3.1)$$

Where:

Q_{Active}: heat load supplied by beverage box [W].

m: mass product of beverage [kg].

C_p: specific heat capacity of human milk [3.930 kJ/ kg. $_{o}$C].

ΔT: the change in product temperature [$_{o}$C].

τ: desired cooling time [sec].

$$\Delta T = T_i - T_f \qquad (3.2)$$

Where

T_i: initial product temperature [25 $_{o}$C].

T_f: outlet product temperature [5 $_{o}$C].

$$m = \rho V \qquad (3.3)$$

Where:

ρ: human milk density [1. 03 kg/L].

V: volume of product [L].

Applying equations (2.1), (2.2), (2.3), the active load for the product (Beverage box) is:

$$Q_{active} = \frac{(1.03\times500\times10^{-3})(3.930\times10^{3})(25-15)}{60\times60} \qquad (3.4)$$

$$= 5.66W$$

Air Changing Load (Infiltration)

In the practical operation of a refrigerated facility, refrigerator must be opened at times in order to move the product in and out. The infiltration load is one of the major loads in the refrigerator. The infiltration air is the air that enters a refrigerated space through cracks and opening of the lid. This is caused by pressure difference between the internal and external surface and it depends upon temperature difference between the inside and outside air.

The heat losses resulting from air change can be determined by applying the following equation:

$$Q_{inf} = m_f \times C_p \times (T_o - T_i) \qquad (3.5)$$

Where:

Q_{inf}: heat losses by air change [W].

m_f: mass product of infiltrated air [kg].

C_p: specific heat capacity of the air [1 kJ/ kg. ◦C].

T_o: outside air temperature [◦C].

T_i: inside air temperature [◦C].

$$m = \rho V_f \qquad (3.6)$$

Where:

ρ: air density [1.25 kg/m_3].

V_f: volumetric flow rate of infiltrating air [m_3/sec].

V_f = number of air change * volume of refrigeration space.

Number of change =0.5 [time/h], .

V_f =0.5 *(1) =0.5 [m^3/h].

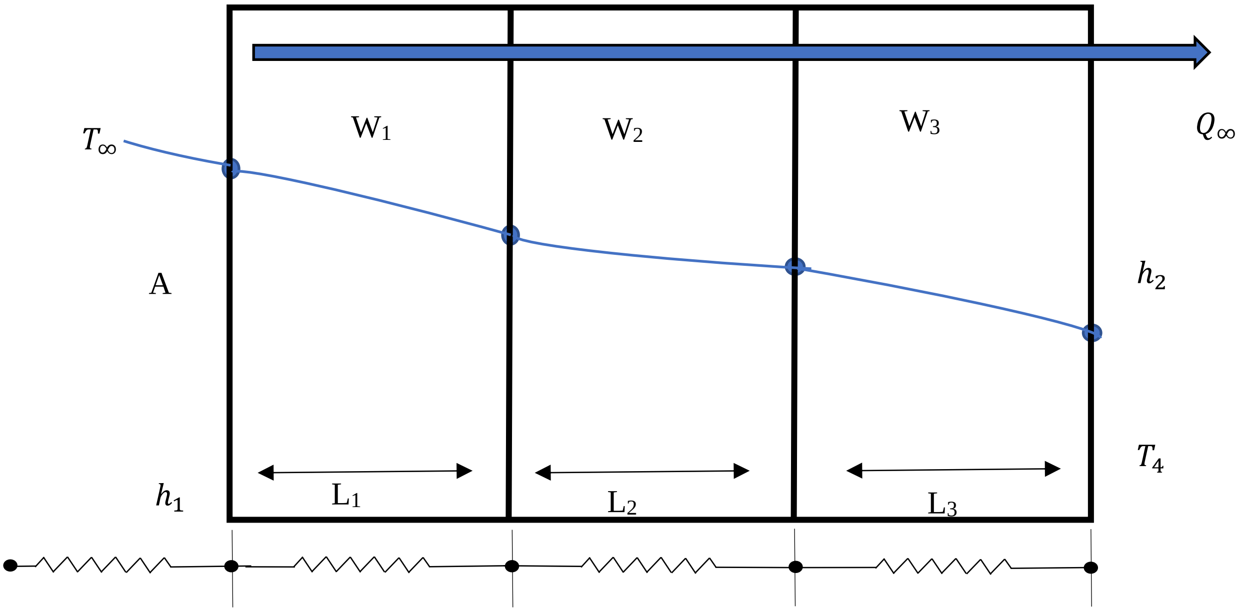
Appling the equation (2.4), (2.5), the Q_{inf} for the beverage box:

$$Q_{inf} = 1.25 \times \frac{0.5}{3600} \times 1000 \times (30 - 15) = 2.60W \qquad (3.7)$$

Transmission Heat Load

This is the heat losses due to convection, radiation and conduction of the enclosed thermoelectric cabinet. The body of the thermo-electric cooler in this project is a clay unit with a dual wall that has expanded polystyrene insulation with an aluminium inner wall as shown below.

Heat load through the walls



$$R_{conv,1} = \frac{1}{h_1 A} \qquad R_1 = \frac{L_1}{k_1 A} \qquad R_2 = \frac{L_2}{k_2 A} \qquad R_3 = \frac{L_3}{k_3 A}$$

The heat loss through the walls is then given by:

$$Q_{trans} = \frac{(\Delta T)overall}{\sum Rth} \tag{3.8}$$

$$\sum Rth = R_{conv,1} + R_1 + R_2 + R_3 \tag{3.9}$$

$$\sum Rth = \frac{1}{h_1 A} + \frac{L_1}{k_1 A} + \frac{L_2}{k_2 A} + \frac{L_3}{k_3 A} \tag{3.9.1}$$

The size of the box is a 20cm*20cm*20cm cube therefore the area is 0.04m^2. Assuming natural convection on an isothermal vertical plate at room temperature. Taking the properties of air at T_∞ =30°C from the Heat and Mass Transfer data book (Appendix B)

Pr = 0.701

k = 0.02675

ν = 16 * 10^{-6}

$$\beta = \frac{1}{30+270} = 3.33 \times 10^{-3} \tag{3.9.2}$$

The Rayleigh number is defined as the product of the Grashof and the Prandtl number as given in equation 2:

$$Ra = GrPr = \frac{g\beta(T_S - T_\infty)\delta^3}{\vartheta^2} Pr \tag{3.9.3}$$

$$Ra = \frac{9.8m/s^2(3.33 \times 10^{-3}K^{-1})(30 - 25°C) \times 0.2m^3 \times 0.7}{(16 \times 10^{-6})^2} = 3.569 \times 10^6$$

For a vertical plate

$Nu = 0.59Ra^{1/4} \qquad 10^4 < Ra < 10^9$

$$\therefore Nu = 0.59(3.569 \times 10^6)^{1/4} = 25.64$$

The heat transfer coefficient then becomes

$$h_1 = \frac{Nuk}{L} = \frac{25.64 \times 0.02675}{0.2} = 3.43W/m^2K \tag{3.9.4}$$

$k_1 = 0.40W/m^2K \;\; , L_1 = 0.12m$

$k_2 = 0.03W/m^2K \;\;\; , L_2 = 0.02m$

$k_3 = 235W/m^2K, \;\; L_3 = 0.005m$

$$\sum Rth = \frac{1}{(3.43 \times 0.2 \times 0.2)} + \frac{0.12}{(0.4 \times 0.2 \times 0.2)} + \frac{0.02}{(0.03 \times 0.2 \times 0.2)} + \frac{0.005}{(235 \times 0.2 \times 0.2)}$$

$$= 31.46$$

$$(\Delta T)overall = T_\infty - T_4 = 30 - 15 = 15$$

$$Q_{trans} = \frac{15}{31.46} = 0.48W$$

Total Cooling Load

The total cooling load is the summation of heat load due to active, passive and Air changing load (Infiltration), as in Table (2.1):

$$Q_c = Q_{active} + Q_{inf} + Q_{trans} \tag{3.9.5}$$

$$= 5.66 + 2.60 + 0.48$$

$$8.74W$$

As it is common practice to add 10%-12% as a factor of safety as general rule 10% is used therefore the total cooling load becomes 9.614W

3.2.3.2 Thermoelectric Module Design

Usually the task is to cool an object to some given temperature. If the object to be cooled is in contact with the cold surface of the thermoelectric module, the temperature of the object can be considered to be equal the temperature of the cold side of the Peltier element after a certain time. The important design parameter ΔT is given by:

$$\Delta T = T_{hs} - T_o = T_{amb} + \Delta T_{hs} - T_0 \tag{3.9.6}$$

Where $T_{hs} = the\ heat\ sink\ temperature\ (hot\ side\ temperature)$

$T_o = object\ temperature\ (cold\ side\ temperature)$

$T_{amb} = ambient\ temperature$

Keeping heat-sink at 15° above ambient temperature,

$$T_{hs} = 15 + 30 = 45°C$$

$$\Delta T = 45 - 15 = 30°C$$

The goal is to find Q_{max} that is large enough to cover the needed Q_c $(8.74W)$ and yields the best COP. In the performance vs current graph, location of the ΔT=30K curve at a current of $I/I_{max} = 0.45$

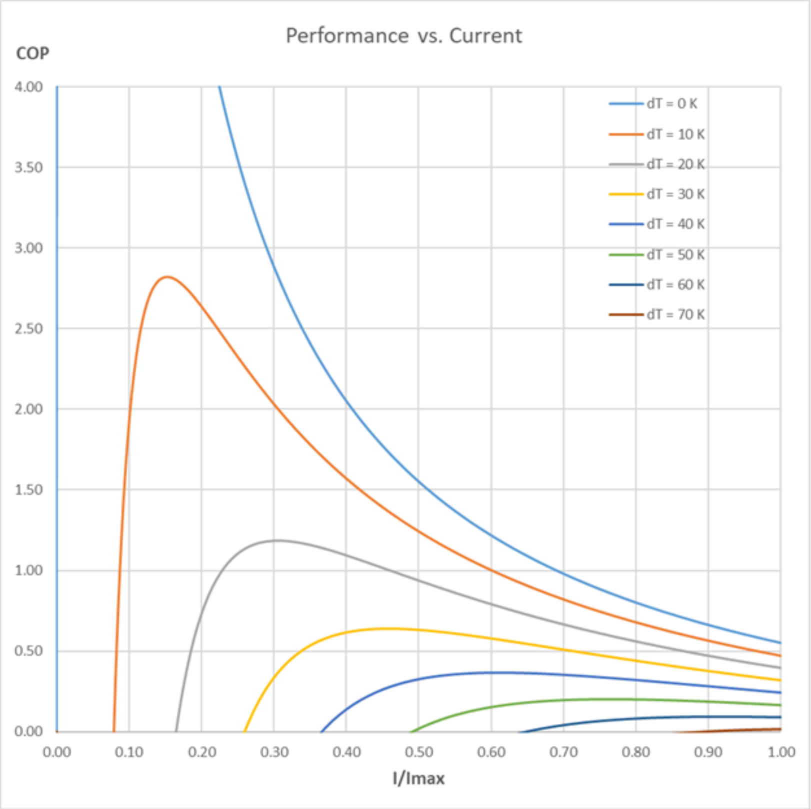


Figure 11: Performance vs Current graph

Using that factor for the current we find in the heat pumped vs current graph the value Q_c/Q_{max}= 0.25 for the given temperature difference of 30K and relative current of 0.45

$$\therefore Q_{max} = \frac{Q_c}{0.25} = \frac{8.74}{0.25} = 34.96W$$

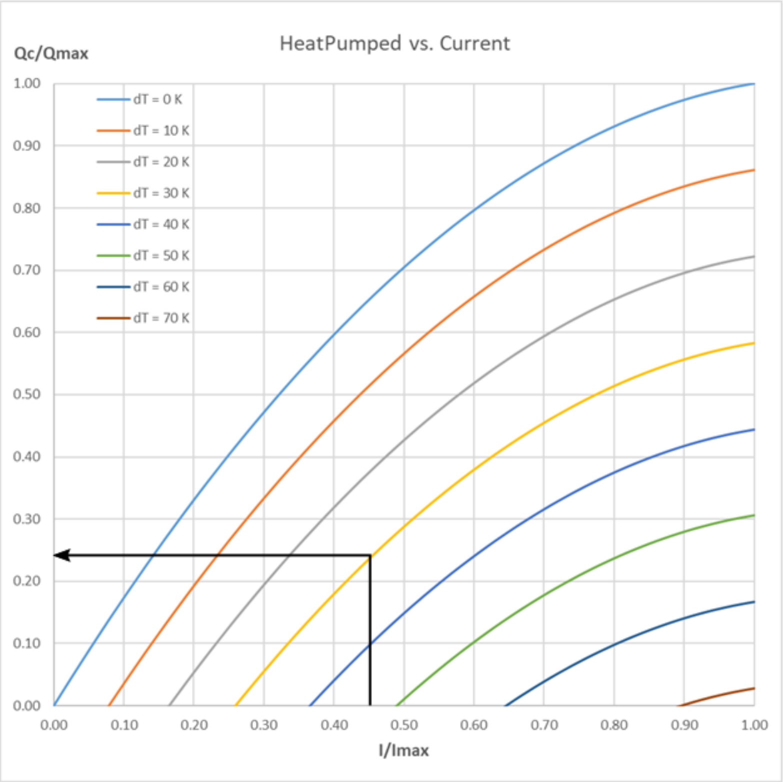


Figure 12: Heat pump vs Current graph

Previously from the performance vs current graph, the COP=0.6, this will calculate

$=P_{el}=\frac{Q_c}{COP}=\frac{8.74}{0.6}=14.57W$

As the temperature difference is 30K a single stage Peltier element is sufficient. From the manufacturer's range of Peltier elements, a choice of one with $Q_{max}=60W$, $dT_{max}=68K$, $I_{max}=6A$ and $V_{max}=14.5V$ will be suitable. The type chosen is a TECI-12706 with dimensions of $40mm\times 40mm\times 3.5mm$.

Figure 13: Thermoelectric module

The operating current and voltage are then calculated as follows:

$$I = I_{max} \times \left(\frac{I}{I_{max}}\right) = 10A \times 0.45 = 4.5A \tag{3.9.7}$$

$$V = \frac{P_{el}}{I} = \frac{14.57}{4.5} = 3.24V$$

Heat sink design

To find a heat sink for the Peltier element, we need to know the required thermal resistance of the heat sink. In the *heat rejected vs. current graph* we find $\frac{Q_h}{Q_{max}} = 0.6$ for the chosen current and ΔT. Thus, $Q_h = Q_{max} \times 0.6 = 34.96 \times 0.6 = 20.98W$

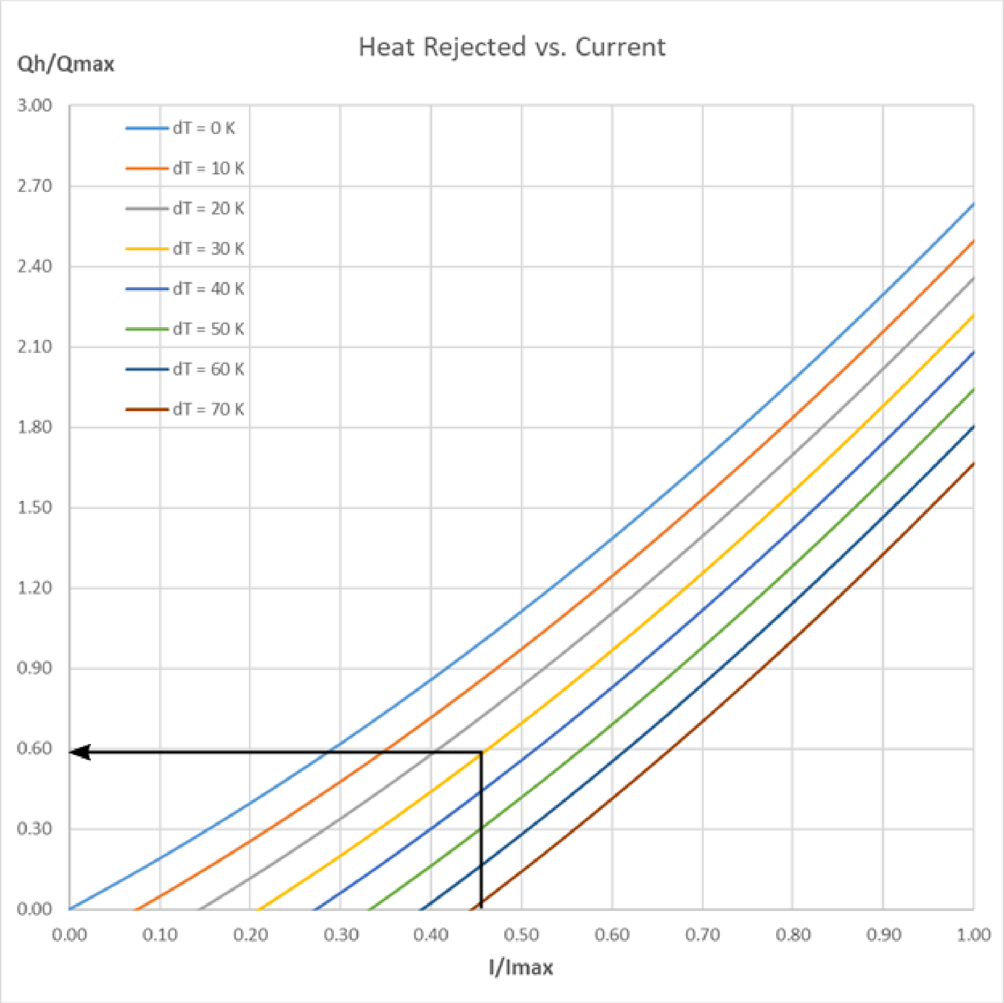


Figure 14: Heat sink vs Current graph

Calculation of the heat sink thermal resistance:

$$R_{thHS} = \frac{\Delta T_{HS}}{Q_h} = \frac{5K}{20.98W} = 0.24K/W$$

We need a heat sink with a thermal resistance smaller than 0.24 K/W.

The above calculations are a first estimation of the parameters for a thermoelectric cooling system. Testing of a real system and iterating through the design steps is necessary to determine optimal system parameters.

3.2.3.3 Solar power system

Solar panels help to harvest electricity from the sun so that it can be converted into usable energy that is utilized in everyday activities. The more solar cells in a solar panel and the higher the quality of the solar cells, the more total electrical output the solar panel can produce.

The Photovoltaic Effect

The Photovoltaic effect is the effect observed when electromagnetic radiation falls on a thin film of one solid deposited on the surface of a dissimilar solid producing a difference in potential between the two materials. The phenomenon in which the incidence of light or other electromagnetic radiation upon the junction of two dissimilar materials, as a metal and a semiconductor, induces the generation of an electromotive force. The conversion of electromagnetic radiation into electric power through absorption by a semiconducting material. Devices based on this effect serve as power sources in remote terrestrial locations and for satellites and other space applications. The sun has constant thermonuclear explosions due to the fact that hydrogen atoms are bonded together with helium atoms. Sun power panels convert radiation into electrical energy which can be stored in batteries for later use.

Many solar panels will not perform and also other solar panels because of atmospheric interference. The quality of power a unit yields is directly influenced by the quality of the solar panel. The types of materials utilized, the types of technology utilized and the quantity of time the solar panel has been functioning all factor into how efficient the solar panel will be. The photovoltaic effect arises from the properties of the p-n junction diode; as such there are no moving parts in a solar panel.

Maximum energy consumption

The energy consumption of each component is computed in order to find the maximum energy required to power the thermoelectric cooler.

Table 3: Maximum energy consumption

Component	**Maximum energy consumption (W)**
Peltier module	34.96
Temperature sensor	2
Axial Fans	20.98
Total	57.94

The maximum energy consumption in watts is 57.94 W and the system would thus consume a maximum of 695.28Wh per 12-hour day cooling the system. The TECM together with the rest of the components require an input voltage of 12V. Solar energy is available everywhere but due to intermittency in its nature, to satisfy energy demand storage system is required. Batteries are needed to supply TEC module and electrical elements with suitable electric current in the absence of direct electricity from solar radiation.

To account for the battery losses; the watt hours are then divided by 0.85 to give 817.98 Wh.. Assuming an 80% Depth of discharge the energy required will be 1022.48Wh and dividing the watt-hours by the nominal battery voltage of 12V gives 85.21Ah. Based on the solar insolation of Domboshava where there is sunshine 360 days per year, the cooler can be powered directly from the solar panels during the day and the battery can be used as back up during the night and on days where there is cloud cover.

To determine the size of PV panels that are needed to supply enough energy to the cooling system and sufficiently charge the batteries the peak watt (Wp) produced is needed. The peak watt (Wp) produced depends on the size of the PV module and climate of site location. We have to consider “panel generation factor” which is different in each site location. For Zimbabwe, the panel generation factor is about 5.9 on average. The watt-hours per day needed from the solar panels:

$$57.94 \times 24 \times 1.2 = 1668.672\mathrm{Wh}$$

The watt peak becomes:

$$\frac{1668.672}{5.9} = 282.82\mathrm{Wp}$$

The solar charge controller is typically rated against Amperage and Voltage capacities. Its selection is based on matching the voltage of PV array and batteries and then identifying the controller right for the intended application. According to standard practice, the sizing of solar charge controller is to take the short circuit current (Isc) of the PV array, and multiply it by 1.3

Solar charge controller rating = Total short circuit current of PV array x 1.3

CHAPTER 4: RESULTS AND DISCUSSION

4.1 Fabrication

This section will discuss the fabrication and installation of the hardware components and parts, the mechanical hardware will discuss the cooling chamber components, while the electrical hardware will discuss the components and the connection circuit.

4.1.1 Cooling chamber

The refrigeration chamber was manufactured as shown in Figure 14 and consisted of several fabricated parts: the clay part, the insulation plates which that combines the internal fin and the TEC module with the external fin and fan. They were fixed together by thermal paste and screws.

Figure 15: Cooling unit assembly

Figure 15 displays the full assembly of the Peltier module to the foam box. The slotted area (the box wall opening area) should be perfectly fit with the shape of internal heat sink without any gap. Some heat loss may occur during the cooling process due to the unfitted condition of the slotted area with the assembly of cooling parts. Therefore, the slotted area has been attached with a heavy-duty masking tape to prevent the cooling parts from moving and for the gap insulation. The installation then continued with the wiring circuit to the power source being the battery.

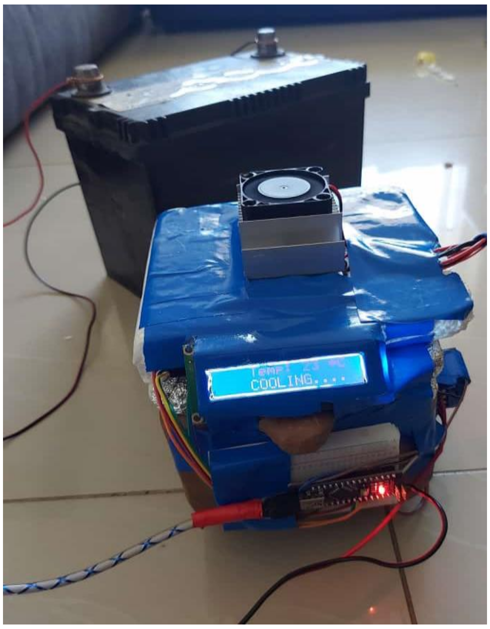


Figure 16: Cooling unit overall assembly

The system was powered by a battery of 12V and 6A that is connected to a 35 Watt solar panel through a charge controller. The components used include an Arduino Nano, 16 by 2 LCD display, DHT11 temperature sensor, breadboard, connector wires, 2 heat sinks connected to 2 fans, 1 Peltier plate.

4.1.2 Software

An Arduino nano was used as microcontroller board with an AT mega 328 as the microcontroller. The AT mega 328 has 12 digital pins starting from D2 to D13 and it also has 8 analog pins starting from A0 to A7. The circuit is shown in Figure 16 below.

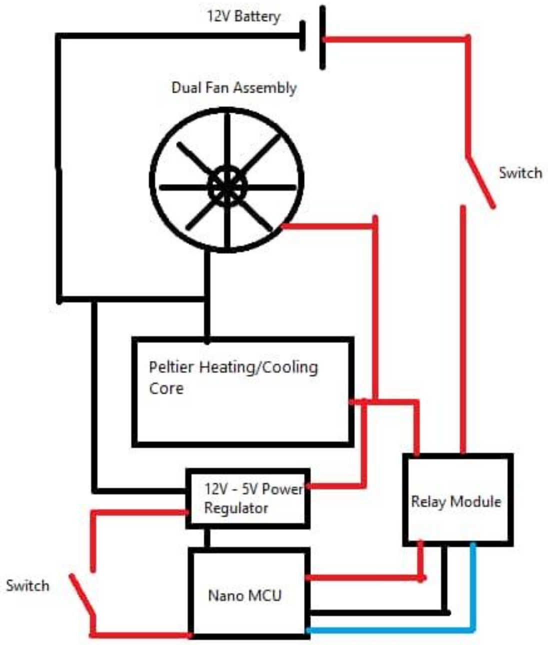
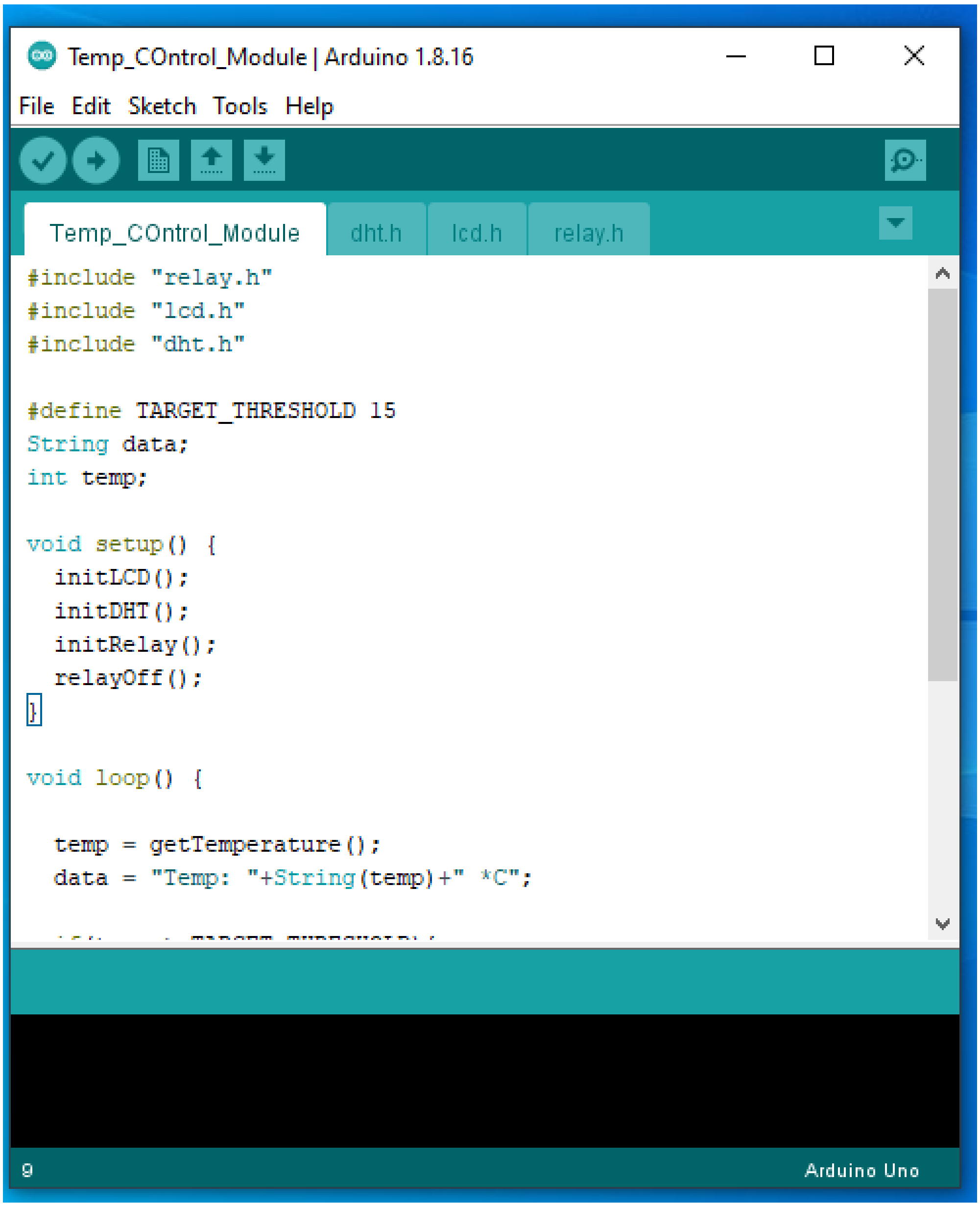


Figure 17: System circuit

The software was coded in C++ language. The program as shown in Figure 17 starts by defining the variables that are used in the code and sets the temperature threshold at 15°C. When the temperature rises above the set limit; the relay will trigger and the Peltier plate will be switched on. The Digital Humidity Temperature sensor (DHT11) receives a signal to read the temperature from the Arduino since it is the central controller. The sensor is set to have a 1 second sampling to read the temperature and take action. This process will run in a loop. The DHT11 relies on reading the temperature drop induced by the cool air being circulated by the fan in the cooler unit. A 16 character, 2 line liquid crystal display (LCD) is used for displaying the temperature and status of the relay. The battery powers the 12V dc operated fan that extracts the heat from the heat sink and also is stepped down to 5V in order to power the Nano MCU by the power regulator. Appendix C contains the complete code for Arduino. The switches are used as physical triggers to interrupt the system.



```
#include "relay.h"
#include "lcd.h"
#include "dht.h"

#define TARGET_THRESHOLD 15
String data;
int temp;

void setup() {
  initLCD();
  initDHT();
  initRelay();
  relayOff();
}

void loop() {

  temp = getTemperature();
  data = "Temp: "+String(temp)+" *C";
```

Figure 18: Temperature control code

4.2 Tests and Results

Considering the primary focus of the cooler is temperature control, thermal testing was conducted to determine the performance of the prototype. Since the experiment was conducted in an open environment, the temperature of the ambient was also recorded with a digital multi-meter temperature sensor. The temperature measurements for both data were logged for every 10 minutes. To get a stable temperature reduction in the internal cooler box, the experiment was conducted for 2 hours long.

Ambient temperature greatly affects the cooling performance of the thermoelectric module. The ambient air temperature during these test ranged from 23.8℃ to 24.1℃. Consistency in ambient temperature reading is required to have a valid comparison between data gathered in each trial. The temperature of the milk was a bit higher than the ambient temperature because the milk was transferred immediately to the container after being expressed. The decrease in temperature was fast at the start giving a change in temperature of close to 2°C in five minutes. But as the temperature decreases, the temperature change also decreases to a value less than 1.5°C in the same period. It can be realized that as the temperature approaches a value below 18°C, the rate of heat transfer begins to slowly stabilize as the temperature comes closer and closer to its lowest point. Once the temperature gets to 15°C the graph fluctuates as the Peltier is switched on and off to maintain the set range.

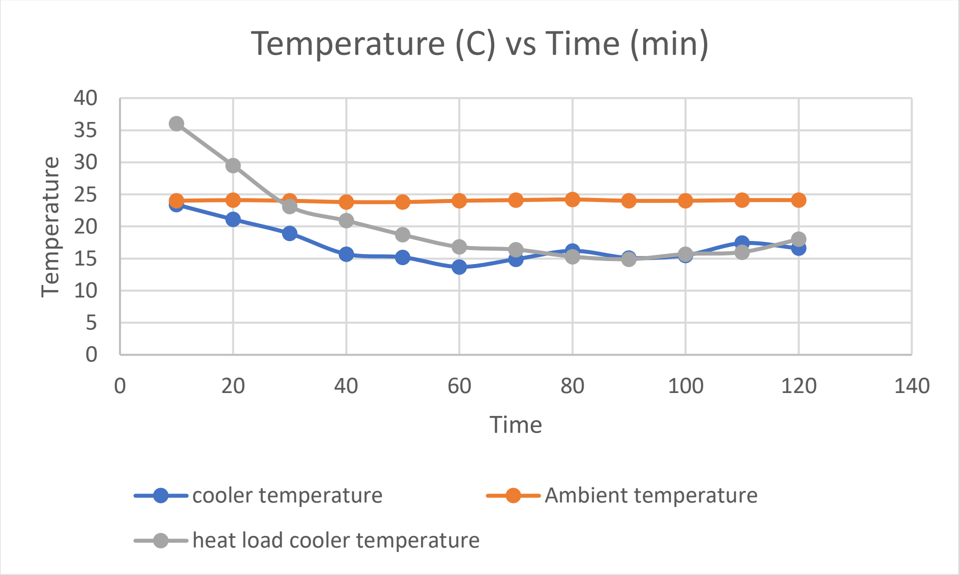


Figure 19: Graph of Temperature vs Time

From 50 minutes the cooler attains steady temperature that is suitable range for storing breastmilk for 24 hours without spoiling. The action to switch off the Peltier is also part of the system energy management. As the graph shows, a steep decrease in temperature can be attributed to the insulation that reduces heat loss into the cooler.

The heat should be rejected from the milk and then is absorbed by the thermoelectric cooler vary depend on cooling time. The faster cooling time is needed to achieve cooling temperature the more heat load should be rejected in such period of time. The experimental results show that the temperature is reduced to 15℃ in 50 minutes without any heat load which is unlike when there is breastmilk where it is reduced to the threshold temperature in 80 minutes. The results of the experiment showed that the heat taken from the air, breastmilk, and from the container decreased with time, and then flattened out. This was because the heat inside the cooler box could not be absorbed anymore after some time.

4.2.1 System energy performance

The battery consists of the brand ICCO gel type 12V, 25AH. A total of 4 batteries would be required to provide back-up power for 12 hours to run the fans and the Peltier module of the cooler. 35 Watt solar panels were considered and these can be connected in parallel whilst a PWM would be a cheaper option to regulate the power being delivered to the battery. For the sake of prototyping, the system was connected to 1 battery and 1 solar panel and the energy performance was tested based on how long the system could run on back-up power and also how long the battery took to charge on solar power. A digital multimeter was used to measure the voltage across the battery using the terminal voltage method which is based on the terminal voltage drops because of the internal impedances when the battery is discharging, so the electromotive force (EMF) of battery is proportional to the terminal voltage. Since the EMF of battery is approximately linear proportional to the state of charge (SOC), the terminal voltage of battery is also approximately linear proportional to the SOC. But at the end of battery discharge, the estimated error of terminal voltage method is large, because the terminal voltage of battery suddenly drops at the end of discharge. A hydrometer could not be used because the battery does not have removable venting caps.

Temperature is a factor that will affect the life of the battery. During the period of measurements; the average temperature was 24°C. The battery was fully charged to get the right run-time and as the load is constant, the current being pulled remains constant. The battery voltage was then used as a proxy measurement; i.e., the run-time was measured at an interval of 10 minutes from 9:00am until the battery voltage reached the lowest voltage threshold when the device stopped working.

The real time data have been analysed. Figure 19, shows the relationship between voltage versus time in charging and discharging process from 0900 to 1310. At 0900 the battery voltage is around 12.67V and during that time the load will be switched on. The terminal voltage starts decreasing as the battery is being discharged. The battery cannot supply energy to the load for a long period time because the capacity of battery is small. According to the design, 4, 25Ah are required to power the system for 12 hours however in this part, only one battery has been used. The fans start slowing down as the battery reaches a low state of charge load and eventually automatically switches off, and immediately after the load is removed whilst the solar panel is connected. At 11:30am the terminal voltage begins to rise and at that time the battery starts to charge. The open circuit voltage after the load was disconnected gives an indication of the charge of the battery.

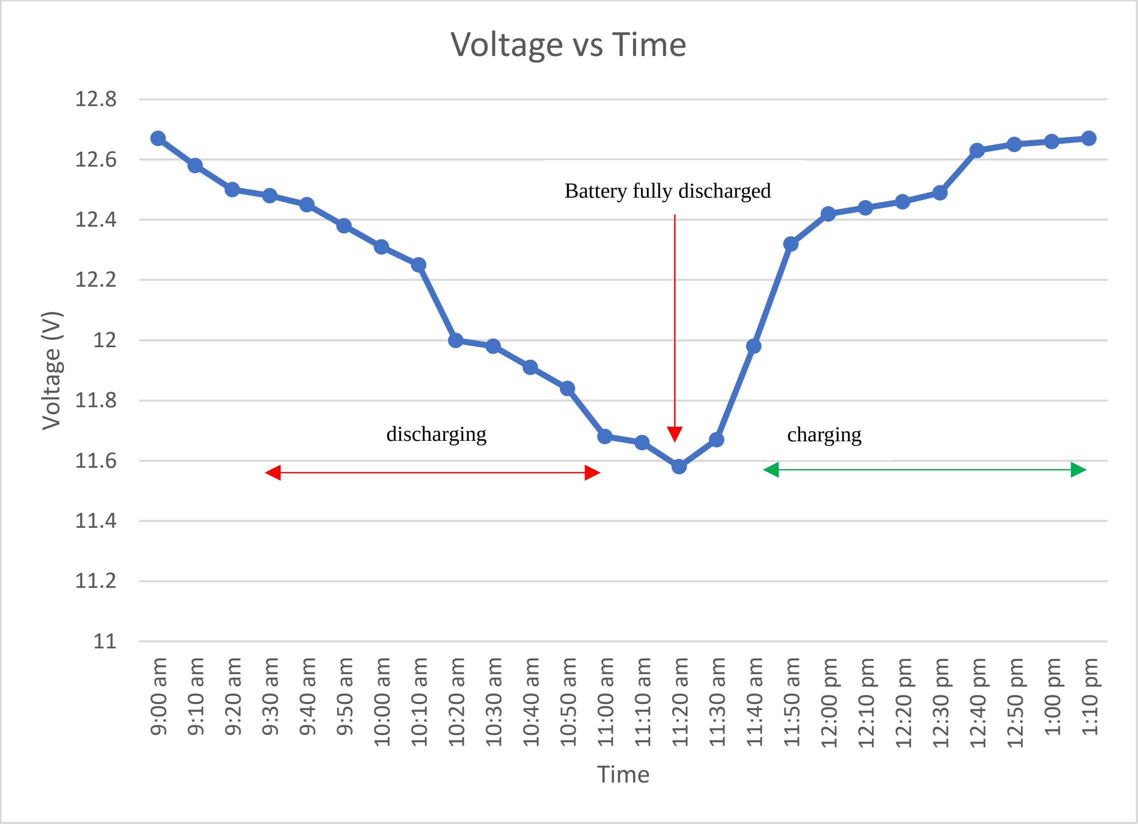


Figure 20: Performance of battery during discharging and charging

It is also clear that the voltage drop is higher during the time of day when the ambient temperature becomes higher as the cooling power requirement increases. The time required to reach a full state of charge is shorter due to the sun’s intensity present during the day and also zero load connected to the battery. The battery run time was 2 hours 20 minutes from an expected 3 hour run time from design calculations. Since the TECM consumes the majority of the power, when it is switched off, only the PLC will consume energy which is only around 2W. If the system is switched on for 40 min of the hour and off for 20 min, the average usage for that hour is, Energy consumption = 57.94(40/60) + 2(20/60) = 39.29W

Ultimately; the energy consumption is expected to be lower and thus making the battery last longer however that is not the case. The discrepancy can be due to the heat and power loss emanating from the leakages present in the prototype.

4.2.2 Considerations

During the experimental runs; it was discovered that the performance was greatly affected by the orientation of the fans; changing it allowed the air to be sucked in and drawn downwards thus effecting a faster temperature drop. The lack of seals also affected the performance as the cool air was being lost to the environment. More duct tape was applied at the inlet with the Peltier-fan assembly so that the air pockets could be plugged. The rate of the temperature drop with time slowed down as the temperature decreased; stalling at 16℃ for an average of 15 minutes. The polystyrene also melts at quite low temperatures and needs heat protection from the Peltier-fan unit.

Thermoelectric refrigeration has very low costs for cooling small appliances and also has a higher reliability with a guarantee of 200000 hours of zero failures. However as the results show, in comparison to conventional refrigeration technologies, cooling efficiency is lower and so is the coefficient of performance. With an increase in refrigeration capacity, the components required become more and bulkier, which reduces its portability. Due to the cooling load variation, the greater the cooling load given in the cooler, then the longer it will take for the temperature stability to be achieved because of the higher energy requirement to decrease the temperature. The prototype can be suitable for use-cases where there is already a solar system installed, however as a stand-alone appliance it would require a significant investment in the power requirements for it to cool the breastmilk for several hours. A small battery can be sufficient for up to 2 hours, this may be convenient for only shorter periods of cooling required.

CHAPTER 5: SUMMARY OF WORK AND CONCLUSION

5.1 Conclusion

Zimbabwean rural women were consulted on the design of a solar powered cooler, with their input integrated within the design. A questionnaire was used and it included several sources of information that would provide insight to key research questions regarding the buy in and adoption of the cooler by breastfeeding mothers A thermo-electric portable unit to cool human breastmilk using a Peltier module has been designed and the prototype fabricated. Its performance was evaluated and it reached the threshold temperature of 15°C within 50 minutes without any load and 80 minutes when cooling breastmilk. A 12V battery connected to a solar panel powered the complete unit. The body material used was the locally available clay with inner walls of expanded polystyrene and aluminium foil insulation. The present design can be used only for maintaining the set temperature of 15°C. However there is a possibility of attaining much lower temperatures especially through cascading the Peltier modules. Such a system will need to be tested for its ability to handle load and also its COP to be determined. Extensive modifications to the prototype need to be incorporated before it can be released for efficient field use. The system developed although being robust is very user-friendly; it does not need high skilled personnel to operate and maintain. Thermoelectric cooling can be suitable for remote areas to inhibit microbial change in the quality of breastmilk.

5.2 Limitations

Resources and mainly time were the major limitations in this study especially in how many participants were interviewed, as well as how the data was analyzed. The Covid19 imposed restrictions in the country also negatively impacted the research as it became more expensive to source the prototype components and timely dispatch them. Ideally, more time would have been needed to ensure the research incorporated adequate checks and balances within the data analysis process together with the prototype testing. The size and type of research prevents generalization of the results to any segment of the population, as well as transferability. As much as the system design was successful in achieving the proposed goals, there is realization that the present design can only be used for a light heat load to lower its temperature to a particular point. The system is yet to be tested on its ability to handle fluctuations in load and extensive modifications will need to be incorporated before it can be a more viable product for the field.

5.3 Recommendations

As technology advances, future researchers are advised to use a lighter batteries when they are available in the market as well as power that has a higher rating; cooling for hours without the need for charging especially for off-grid applications. Reiteration and validation is critical in design thing and product design therefore it is recommended that more time be taken to improve the design of the cooler. This study shows that the thermo-electric module is emerging as a truly viable method that can be advantageous in the handling of certain small-to-medium applications.

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Appendices

Questionnaire

Section A: Background

1. How old is your baby?
   A. Less than 1 month
   B. 2-6 months
   C. More than 6 months
2. Employment status
   A. Self employed
   B. Out of work and looking for work
   C. Out of work but not currently looking for work
   D. A housewife
   E. student
   F. Retired

G. Unable to work

Section B: Breastfeeding status

3. What is your current feeding practice?
    A. Exclusive breastmilk (Only breast milk)
    B. Breast milk and formula
    C. Formula feeding only
    D. Other substitutes
4. If you have ever breastfed how long did you exclusively breastfeed?
    A. Less than 1 week
    B. 2 – 4 weeks
    C. More than 4 weeks
5. When you had your baby, did you have any medical condition that required permanent avoidance of breastfeeding?
    A. Yes
    B. No
6. How difficult is it to find the time you need to give only breast milk to your child for the first 6 months?
    A. Very difficult
    B. Somewhat difficult
    C. Not difficult at all
    D. Don't know
7. Do you have periods of separation from your baby?
    A. Yes
    B. No
8. What is the baby fed during separation?
    A. Formula
    B. Breastmilk
    C. Other
9. What are your breastfeeding habits while working/when you return to work?

10. Have you ever expressed milk for your baby?
    A. Yes
    B. No
11. Would expressing your breastmilk liberate your time to perform other activities
    A. Yes
    B. No
12. Do you have a refrigerator to store your breastmilk when you express?
    A. Yes
    B. No

Section C: Cooler design

13. Would you consider having portable cooler to store your breastmilk for longer periods?
    A. Yes
    B. No
14. What would be the most important feature you would look for in a cooler design?
15. Would a cooler satisfy your needs?
    A. Yes
    B. No
16. How important is cost when deciding to purchase a storage cooler?
    A. Very important
    B. Somewhat important
    C. Not that important
    D. I don’t know
17. How much do you plan to pay for a portable refrigerator for your breastmilk?
    A. $0-$10
    B. $10-$20
    C. $20-30
    D. More than $30
18. Do you currently have access to electricity?
    A. Yes
    B. No
19. What is your current energy source?
    A. Solar
    B. On grid
    C. Bioenergy
    D. Other
20. What electronic/ electric products do you currently own?

Temperature control code

DHT code

```
#include <Adafruit_Sensor.h>
#include <DHT.h>
#include <DHT_U.h>
#define SENSOR_PIN 3
#define SENSOR_TYPE DHT11
DHT_Unified dht(SENSOR_PIN, SENSOR_TYPE);
sensor_t sensor;
sensors_event_t event;
void initDHT(){
 dht.begin();
 dht.temperature().getSensor(&sensor);
}
int getTemperature(){
  dht.temperature().getEvent(&event);
  return event.temperature;
}
```

LCD code

```
#include <LiquidCrystal_I2C.h>
LiquidCrystal_I2C lcd(0x27, 16, 2);
void lcdPrintString(char * buff, int line, int pos){
  lcd.setCursor(pos, line);
  lcd.print(buff);
}
void lcdPrintObject(String * obj, int line, int pos){
  lcd.setCursor(pos, line);
  lcd.print(*obj);
}
void lcdClear(){
  lcd.clear();
}
void initLCD(){
  lcd.init();
  lcd.backlight();
  lcd.clear();
}
```

Relay code

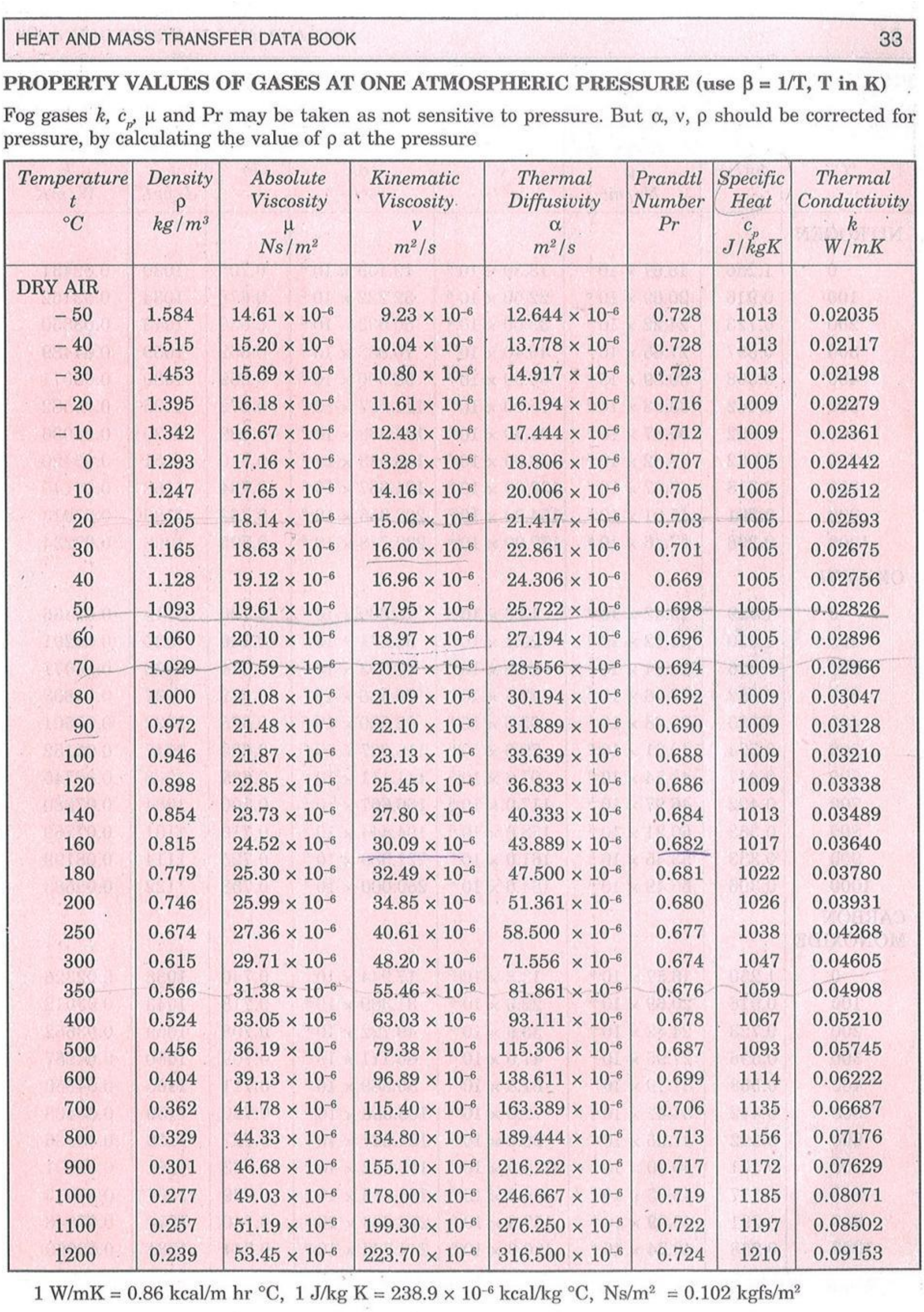
```
#define RELAY_PIN 13

void initRelay(){

  pinMode(RELAY_PIN, OUTPUT);

  digitalWrite(RELAY_PIN, LOW);

}

void relayOn(){

  digitalWrite(RELAY_PIN, HIGH);

}

void relayOff(){

  digitalWrite(RELAY_PIN, LOW);

}
```

Overall Temperature code

```
#include "relay.h"

#include "lcd.h"

#include "dht.h"

#define TARGET_THRESHOLD 15

String data;

int temp;

void setup() {

  initLCD();

  initDHT();

  initRelay();

  relayOff();

}

void loop() {

  temp = getTemperature();

  data = "Temp: "+String(temp)+" *C";

  if(temp > TARGET_THRESHOLD){

    lcdClear();

    relayOn();

    lcdPrintString("COOLING....",1, 4);

  }else{

    relayOff();

    lcdPrintString("SYSTEM CUTOFF",1, 4);

  }
```

```
  lcdPrintObject(&data, 0, 4);

  delay(1000);

}
```

Heat and Mass transfer data



PROPERTY VALUES OF GASES AT ONE ATMOSPHERIC PRESSURE (use $\beta = 1/T$, T in K)

Fog gases k, c_p, μ and Pr may be taken as not sensitive to pressure. But α, ν, ρ should be corrected for pressure, by calculating the value of ρ at the pressure

Temperature t °C	*Density* ρ *kg/m³*	*Absolute Viscosity* μ *Ns/m²*	*Kinematic Viscosity* ν *m²/s*	*Thermal Diffusivity* α *m²/s*	*Prandtl Number* *Pr*	*Specific Heat* c_p *J/kgK*	*Thermal Conductivity* k *W/mK*
DRY AIR							
– 50	1.584	14.61×10^{-6}	9.23×10^{-6}	12.644×10^{-6}	0.728	1013	0.02035
– 40	1.515	15.20×10^{-6}	10.04×10^{-6}	13.778×10^{-6}	0.728	1013	0.02117
– 30	1.453	15.69×10^{-6}	10.80×10^{-6}	14.917×10^{-6}	0.723	1013	0.02198
– 20	1.395	16.18×10^{-6}	11.61×10^{-6}	16.194×10^{-6}	0.716	1009	0.02279
– 10	1.342	16.67×10^{-6}	12.43×10^{-6}	17.444×10^{-6}	0.712	1009	0.02361
0	1.293	17.16×10^{-6}	13.28×10^{-6}	18.806×10^{-6}	0.707	1005	0.02442
10	1.247	17.65×10^{-6}	14.16×10^{-6}	20.006×10^{-6}	0.705	1005	0.02512
20	1.205	18.14×10^{-6}	15.06×10^{-6}	21.417×10^{-6}	0.703	1005	0.02593
30	1.165	18.63×10^{-6}	16.00×10^{-6}	22.861×10^{-6}	0.701	1005	0.02675
40	1.128	19.12×10^{-6}	16.96×10^{-6}	24.306×10^{-6}	0.669	1005	0.02756
50	1.093	19.61×10^{-6}	17.95×10^{-6}	25.722×10^{-6}	0.698	1005	0.02826
60	1.060	20.10×10^{-6}	18.97×10^{-6}	27.194×10^{-6}	0.696	1005	0.02896
70	1.029	20.59×10^{-6}	20.02×10^{-6}	28.556×10^{-6}	0.694	1009	0.02966
80	1.000	21.08×10^{-6}	21.09×10^{-6}	30.194×10^{-6}	0.692	1009	0.03047
90	0.972	21.48×10^{-6}	22.10×10^{-6}	31.889×10^{-6}	0.690	1009	0.03128
100	0.946	21.87×10^{-6}	23.13×10^{-6}	33.639×10^{-6}	0.688	1009	0.03210
120	0.898	22.85×10^{-6}	25.45×10^{-6}	36.833×10^{-6}	0.686	1009	0.03338
140	0.854	23.73×10^{-6}	27.80×10^{-6}	40.333×10^{-6}	0.684	1013	0.03489
160	0.815	24.52×10^{-6}	30.09×10^{-6}	43.889×10^{-6}	0.682	1017	0.03640
180	0.779	25.30×10^{-6}	32.49×10^{-6}	47.500×10^{-6}	0.681	1022	0.03780
200	0.746	25.99×10^{-6}	34.85×10^{-6}	51.361×10^{-6}	0.680	1026	0.03931
250	0.674	27.36×10^{-6}	40.61×10^{-6}	58.500×10^{-6}	0.677	1038	0.04268
300	0.615	29.71×10^{-6}	48.20×10^{-6}	71.556×10^{-6}	0.674	1047	0.04605
350	0.566	31.38×10^{-6}	55.46×10^{-6}	81.861×10^{-6}	0.676	1059	0.04908
400	0.524	33.05×10^{-6}	63.03×10^{-6}	93.111×10^{-6}	0.678	1067	0.05210
500	0.456	36.19×10^{-6}	79.38×10^{-6}	115.306×10^{-6}	0.687	1093	0.05745
600	0.404	39.13×10^{-6}	96.89×10^{-6}	138.611×10^{-6}	0.699	1114	0.06222
700	0.362	41.78×10^{-6}	115.40×10^{-6}	163.389×10^{-6}	0.706	1135	0.06687
800	0.329	44.33×10^{-6}	134.80×10^{-6}	189.444×10^{-6}	0.713	1156	0.07176
900	0.301	46.68×10^{-6}	155.10×10^{-6}	216.222×10^{-6}	0.717	1172	0.07629
1000	0.277	49.03×10^{-6}	178.00×10^{-6}	246.667×10^{-6}	0.719	1185	0.08071
1100	0.257	51.19×10^{-6}	199.30×10^{-6}	276.250×10^{-6}	0.722	1197	0.08502
1200	0.239	53.45×10^{-6}	223.70×10^{-6}	316.500×10^{-6}	0.724	1210	0.09153

1 W/mK = 0.86 kcal/m hr °C, 1 J/kg K = 238.9×10^{-6} kcal/kg °C, Ns/m² = 0.102 kgfs/m²