ISSN No:-2456-2165

Arduino Microcontroller Equipped Thermoelectric Cooler Vaccine Carrier Design

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Abstract:- Vaccines have become effective in protecting the health of a population. Vaccine development is a challenge, ensuring safety of the vaccine from its source until it is administered is another. One crucial part in the cold chain system is the transportation of the vaccine carriers from the health centers to poorly accessible communities. The Philippines' Department of Health (DOH) Vaccine, Cold Chain and Logistics Management Manual of Operations recommends actions in order to safely deliver the vaccines with the use of WHO prequalified passive containers such as vaccine transport box and vaccine carrier. This research provides an option to vaccine carrier for use when delivering vaccines from health centers to poorly accessible communities where government health personnel are deployed to administer vaccines to newborn, bedridden, disabled and elderly with mobility issues. The use of the current vaccine carrier requires the use of at least six pieces of ice packs, trained and highly skilled health care personnel capable of manually taking, monitoring and recording vaccine temperature in the course of delivery to the vaccination site. This research output provides not only an alternative design to the vaccine carrier but also a prototype. The prototype is capable of maintaining vaccine temperature within the target range, minimizing risk of temperature damage; taking and recording of the temperature of the built-in dummy vaccine; and eliminating the opening and re-opening of the vaccine carrier's lid in the process. The capability of the prototype in taking, monitoring and recording of the temperature was tested to last for at least a continuous 12-hour duration at a 3-second interval. The prototype can support the cold chain system requirement of temperature monitoring every 30 minutes during the delivery of vaccines from the health centers to poorly accessible communities.

Keywords:- *cold chain system; vaccine carrier; vaccine dummy; temperature damage.*

I. INTRODUCTION

Vaccines have come a long way in improving the health of a country's population. Vaccine development, safekeeping and handling have remained challenges. In developing countries, challenges include vaccine handling and delivery to remote, hardly accessible, mountainous or wet/waterlogged, oppressively hot or bone-chilling cold, poverty or war-stricken communities which require health professionals to travel by foot; manually powered small boats; reindeer, donkey or other local animals; or by use of other available air/land/water motor vehicle [1]. Procurement, storage and maintaining its safety for use and delivery, form part of the cold chain system. Vaccine storage sites and health centers can be made to be equipped with facilities to ensure vaccines are properly stored and maintained.

But there are instances where government health care personnel are deployed to poorly accessible locations to administer vaccines to newborn, bedridden, disabled and those elderly with mobility issues. In this case, proper handling of vaccines includes their delivery inside passive containers like the vaccine carrier which require the use of supplies like ice packs to help maintain safe vaccine temperatures; trained and skilled handling health care personnel; and accurate taking, monitoring and recording of temperature every 30-minute interval in the course of vaccine delivery. The cold chain or the vaccine supply chain is a system for vaccine storage and transportation to ensure their condition is protected from damage as it comes from manufacturing companies to their respective recipients [2].

A. Problem

Recommended vaccine storage temperature may vary from one type of vaccine to another. Storing below or above recommended temperature can result to costly temperature damage to the vaccines. This means that maintaining the recommended vaccine storage temperature all throughout the cold chain system is paramount. During storage and the delivery of vaccines, it is important to ensure that the recommended vaccine storage temperature is being maintained to eliminate the risk of temperature damage to the vaccines.

Current vaccine carrier requires tedious manual taking of temperature and recording and involve opening and reopening of the lid which can potentially lead to vaccine temperature damage. Vaccine carriers by design are smaller in comparison to cold storage boxes, but both are used during transportation and delivery vaccines from bigger health centers with electric refrigeration facility to other areas where immunization takes place which are usually unequipped with refrigerators [3].

The existing manual temperature procedure which is done every 30-minute interval uses a thermometer in taking the temperature inside the carrier. This does not guarantee that the internal temperature of the carrier is the same as the temperature of the vaccine inside each vial. As for the Department of Health in the Philippines, to ensure that all equipment in the cold chain system functions, temperature reading either with the use of thermometer, though not considered as reliable since it requires manual use and only provides instantaneous temperature reading, or with continuous temperature monitoring is required to be recorded at a minimum of two times daily, including weekends [2]. Exposure to heat or freezing temperatures is one of the causes of vaccine wastage in unopened vials [4].

B. Objectives

In general, this research was conducted to come up with an alternative carrier design that better support the cold chain system in the safe delivery of vaccines from health centers to poorly accessible communities for the benefit of newborn, bedridden, disabled and elderly with mobility issues. To be specific, the proposed carrier is designed to protect the vaccines from temperature damage in the course of delivery through use of a temperature sensor module inside the vaccine dummy. The vaccine dummy is a vial with sterile water, which is commonly used as vaccine diluent.

C. Scope and Limitations

As stated in the DOH Vaccine, Cold Chain and Logistics Management Manual of Operations, there are National Immunization Program (NIP) vaccines like those for Polio; Measles, Mumps and Rubella (MMR); and Measles and Rubella (MR) can be either safely stored at negative storage temperature (at -15℃ to -25℃) or at positive storage temperature (at +2℃ to +8℃). Also, there are a good number of NIP vaccines that can be damaged by freezing [5]. On the other hand, Bacillus Calmette Guerin (BCG) vaccine may not be damaged by freezing but freezing temperature may break the ampoules.

This research was aimed at designing a vaccine carrier that can support in maintaining +2℃ to +8℃ vaccine temperature range, to be utilized in transporting vaccines from the health centers to other vaccination sites. To be able to safely maintain the +2℃ to +8℃ vaccine temperature range, the setting was +4℃ to +6℃.

II. METHODS AND MATERIALS

A. Literature and Research Materials Review

At the initial stage of this study, patent searches were done. This guided in the conceptual design of the proposed vaccine carrier. Existing features of prior art include embedded display for temperature monitoring; use of micro-controller; use polyurethane for insulation; can be a hand carried; use of built-in batteries; use of external charging port; use of low alarm system for temperature monitoring optimization; use of separate temperature sensors, among others.

B. Conceptual Design

With the design ideas gathered from patent searches, the conceptual design of the proposed vaccine carrier has an overall dimension of 0.36mX0.36mX0.51m with back compartment. The design is equipped with a handle, and internal battery compartment. Its capacity is five (5) liters. Both vaccine storage boxes and vaccine carriers can be classified into short or long range, however according to UNICEF, the latter’s capacity can be from 0.8 to 3.4 liters, which can make it easier to carry when on foot, than the former [6]. The conceptual design below shown in Figure 1 is illustrated using Solidworks.

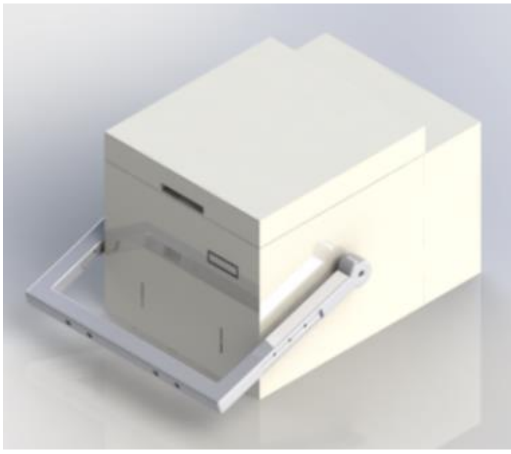


Fig. 1: Illustration drawing of vaccine refrigerator carrier

C. Consideration Design Calculation

Calculations on the heat that could be absorbed by the thermoelectric cooler were made. The heat to be considered are those that can be absorbed through the sides of the carrier by means of conduction, convection, solar radiation, and those absorbed as a result of cooling process of the interior part of the carrier and vaccines. Two (2) main calculations were done comprising: 1) initial cooling phase and the 2) actual cooling phase. The initial cooling phase is where the temperature inside the carrier is reduced from ambient air temperature to 5 ºC while the actual cooling phase is where the temperature is further reduced to 4 ºC. There were other necessary calculations that were considered which accounted for battery pack, heat sink and fasteners.

ISSN No:-2456-2165

There were assumptions when making the calculations. It is assumed that: the heat conduction through the wall is one-dimensional; the heat travels in a direction parallel to the thickness of the wall but perpendicular to the surface area; the ambient air temperature is constant at 38.9; the specific heat and density is constant at standard temperature and pressure (STP).

A material's thermal resistance measures the amount of heat flow that is resisted and is inversely proportional to U-factor [7]. This research mainly focused on the heat transfer into the vaccine carrier, considering only the absorbed as well as transmitted radiation which is considered negligible as the walls of the vaccine carrier are opaque [8]. All design computations are shown on Table 1, Table 2 and Table 3.

TABLE 1. SUMMARY OF DESIGN CALCULATIONS FOR COOLING LOAD

Actual Cooling Load Design Consideration	Equation	Values
Heat through vaccine box walls by conduction-convection	$Q_c = UA(t_{out} - t_{in})$	10.367334 W
Heat through vaccine box walls by radiation	$Q_{rad} = \alpha AI$	11.1762 W
Sensible heat gains due to infiltration of outside air	$Q_s = m_i C_p(t_{out} - t_{in})$	0.169847 W
Latent heat gains due to infiltration of outside air	$Q_l = m_i(W_{out} - W_{in})h_{fg}$	0.28905 W
Heat extracted from inside air	$Q_{air} = m_{air} C_p(t_{@6} - t_{@4})$	0.005734 W
Heat extracted from the vaccine	$Q_{vaccine} = m_{vaccine} C_p(t_{@6} - t_{@4})$	0.174458 W
Total cooling load with factor of safety	$Q_{total} = (Q_c + Q_{rad} + Q_s + Q_l + Q_{air} + Q_{vaccine})1.5$	33.2739 W

TABLE 2. SUMMARY OF DESIGN PLOTTING FOR TEC POWER SUPPLY

TEC Design Consideration	Plot
Using performance chart $T_h = 50°C$ @ΔT=35 and 35W	I=6A
Using performance chart $T_h = 50°C$ @ΔT=35 and 6A	V=7V

TABLE 3. SUMMARY OF DESIGN CALCULATIONS FOR HEAT SINK

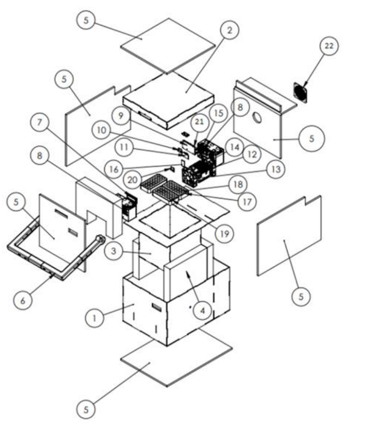
Fan with Heat Sink Design Consideration	Equation	Values
Heat load at hot side	$Q_h = 35W + VI$	77 W
Volume required for heat sink@100CFM fan	$V_r = \frac{volumetric\ thermal\ resistance}{required\ thermal\ resistance}$	1040.2219 cm^3

D. 3D Design and Air-Flow Simulation

The conceptual design of the vaccine carrier is made using Solidworks. With ideas from researches and conceptual design, and still with the use of Solidworks, the three-dimensional (3D) design was drawn with actual parts with actual dimension and sizes.

a) Parts Drawing and Assembly:
Each of the different parts of the vaccine carrier were drawn with actual dimensions and sizes using Solidworks. Parts drawing in exploded view with parts list is shown in the illustration below. All parts of the drawing were based according to the dimension of actual parts as they are sourced from supplier of materials and then assembled in Solidworks for viewing the contact and fitting of parts. This enabled of visualization of the different parts as they are assembled as one whole vaccine carrier.

As shown in Figure 2, parts assembly was done to facilitate the generation of parts list or Bill of Materials (BOM). Assembly drawings illustrate the full machine or system, together with the location and identification of each component. Assembly drawing's functions include item identification, identification of the assembly order, and other standard requirements. Assembly drawings also include technical details such as orthogonal plans, elevations, sections, mass, weight, Bill of Materials (BOM) and other information. and other information. Among technical persons, these drawings serve as a means to communicate, show and validate design ideas.



Part Number	Part Name
1	Acrylic Outer Layer
2	Acrylic Lid
3	Acrylic Inner Layer
4	Polyurethane
5	Insulation Foam
6	Handle
7	16x2 LCD Screen
8	12v 24 Ah Battery
9	Arduino Mega
10	Real-Time Clock Module
11	Motor Driver
12	TEC Module
13	CPU-Fan
14	Heat Sink
15	Hinge
16	SD Card Module
17	Vaccine Holder
18	Waterproof Temperature Sensor
19	Vaccine Vial
20	Thermal Sensor
21	Buzzer
22	Air Vent

Fig. 2: Exploded drawing with parts list

b) CFD (Computational Fluid Dynamics) Air-Flow Simulation:
The air flow trajectory of CFD simulation using Solidworks to visualize air direction, velocity and temperature profile inside and outside portion of the box, is shown below. However, today's flow simulation uses thermal analysis to forecast how well electronic components and other part that generate heat would cool down. This ability to simulate heat conduction with convective heat transfer that is generated by airflow over heatsinks and chip packages provides a high degree of confidence with projected temperature readings. This has been useful in determining fan capacity, flow and orientation as shown in Figure 3.

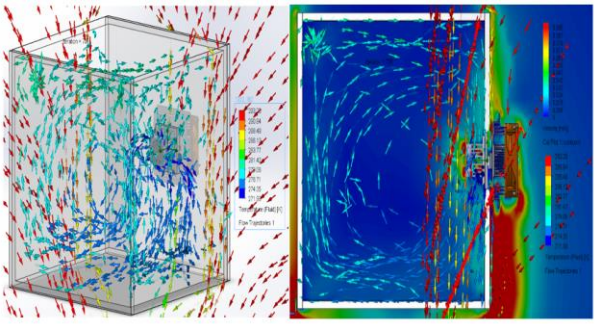


Fig. 3: Air Trajectory Profile and Cut Plots

E. Pre-Selection and Classification of Materials

There are three (3) main components and are classified as: 1) the vaccine box and insulation assembly; 2) the microcontroller assembly; and 3) the thermoelectric cooler assembly. The vaccine box and insulation assembly is made up of polyurethane, acrylic, insulation foam, glue hinges, bolts and nuts. The microcontroller assembly which comprised the Arduino-based programmable micro-controller (Mega), vaccine vial dummy with waterproof temperature sensor (DS18B20), ambient temperature sensor (DHT11), clock module (DS1307), piezo buzzer (4216), SD card module (SPI), voltage/current driver (VNH2SP30), LCD display (16x2). The thermoelectric cooler assembly includes thermo-electric cooler Peltier module (TEC1-12715), fans for hot and cold MT-6 Snowman for hot side, ice edge mini for cold side, battery packs use a lead acid battery and (18650), heat sink. Other sub components are stand-by battery, battery charger, mini SD and others.

Material selection was affected by limited availability, cost and time factor. The total cost of sourcing the parts amounted to Php 21, 324.87.

F. Fabrication and Actual Assembly

The fabrication has three (3) main components, vaccine box casing and insulation assembly, microcontroller assembly and thermoelectric cooler assembly. The basis for fabrication is the blue print of the 3d drawing, result of simulation, actual available parts and design calculation.

a) Vaccine Box Casing and Insulation Assembly:
As shown in Figure 4, the box is made up of insulation foam. The outer acrylic layer is processed by laser cutting. The polyurethane foam layer is formed by mixing chemicals and moulding. The inner acrylic layer by is processed by laser cutting. The hinged lid is attached to the box and the handle made by PLA (polylactide) printing is also being mounted using bolts and nuts. The back compartment houses the microcontroller, wires and batteries.

b) Microcontroller Pin Configuration Assembly and Coding:
Figure 5 illustrates the wiring between the microcontroller and temperature sensors or modules placed on the breadboard. This particular layout shows the current wiring for testing which was subequently transferred to PCB. Then coding was done using Arduino Software IDE.

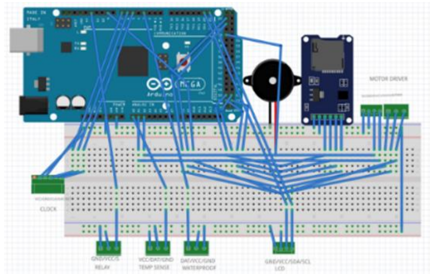


Fig. 5: Pin connections

c) Thermoelectric Cooler Assembly:
Figure 6 shows the final thermoelectric cooler (TEC) design. SNOWMAN M-T6 4PIN CPU cooler fan with heatsink is attached to the hot part of TEC. On the other hand, to circulate the cold air inside the vaccine carrier, a smaller DEEPCOOL DP-FDC-XF120 XFAN 120 mini fan is attached to the cold side. Figure 7 shows the fans which facilitates in ensuring that the temperature range inside the vaccine carrier is the same, regardless of the location. To increase the surface area coverage and subequently effect a wider cooling area of the mini fan, an aluminum heatsink is attached of the cold side of TEC.

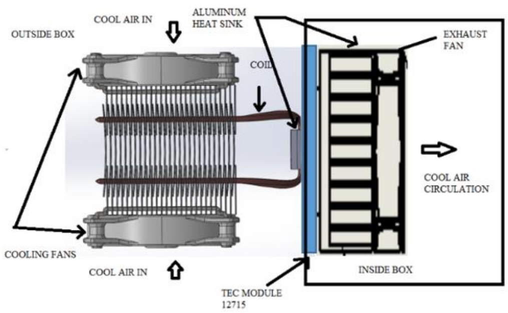


Fig. 6: Peltier module connected to heatsink and fan diagram

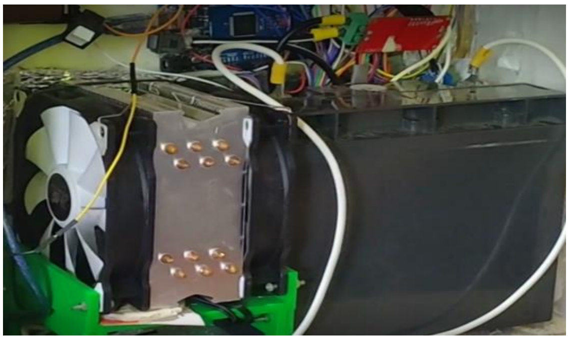
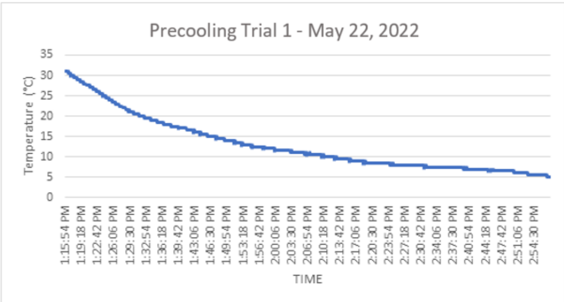


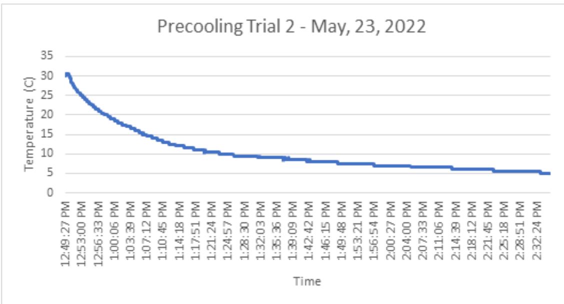
Fig. 7: Actual picture of fan, battery and the microcontroller

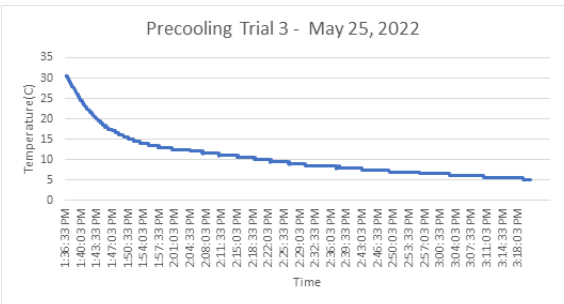
III. RESULTS AND DISCUSSIONS

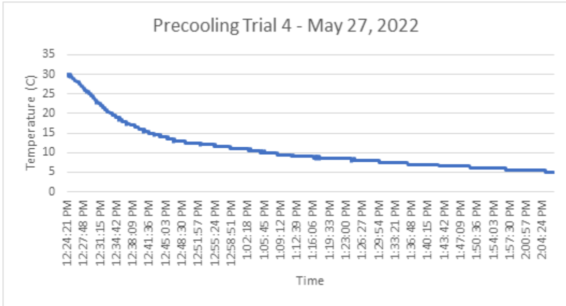
A. Precooling Results (using TEC with ice).

There are five trials made. The temperature data measured at a 3- second interval are recorded into the mini SD card and are plotted below.









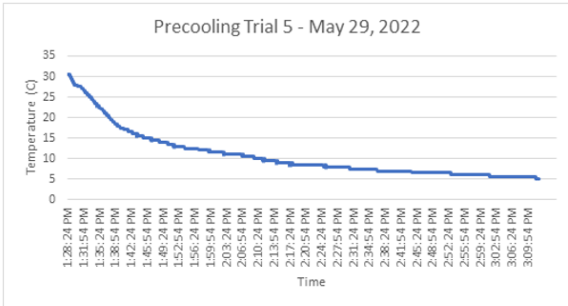
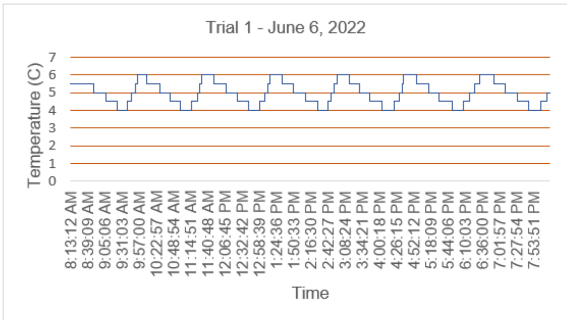


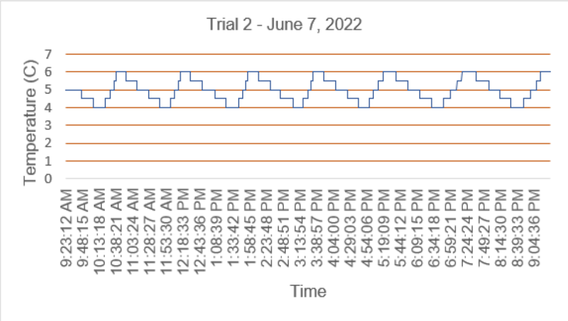
Fig. 8: Precooling data

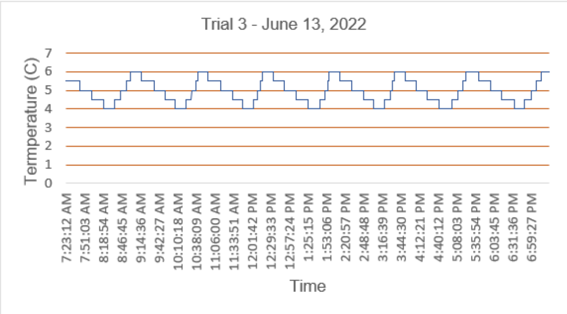
Based on testing, ice was used for pre-cooling to meet the cold chain requirement from dummy vial to vaccine. The dummy vial temperature quickly dropped to 5℃ as shown in Figure 8. Immediately after the pre-cooling phase, the ice cubes or chunks are then removed. This makes the TEC be the only factor that maintains the temperature of the vaccines to be within the 2-8℃ range during transport and delivery. The use of ice during transport and delivery is removed to reduce the weight of the vaccine carrier. It took about 101.9 minutes on the average to cool down the dummy vial to 5℃ from ambient temperature. Considering the five trials, the standard deviation was at 1.02896.

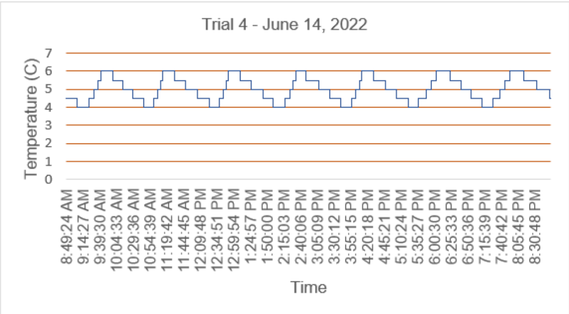
B. Actual Cooling Results (using TEC only).

The five (5) trials made indicating the cooling of the carrier is recorded at a 3-second interval.









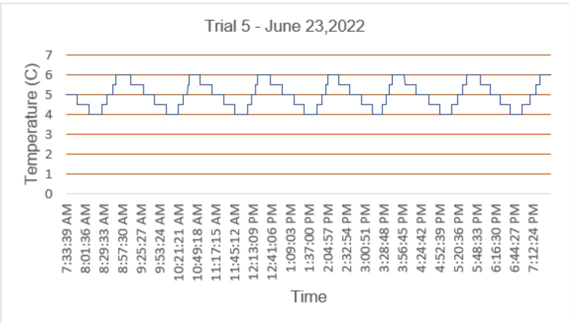


Fig. 9: 12-hr Cooling data

Here, the actual cooling test results are shown. During testing, the TEC was turned on with 7 volts and 6 Amperes. VRLA batteries were used as power source. Temperature readings were recorded all throughout the test at a three (3) second interval, with the sensor having an accuracy of +/- 0.5 ºC.

As shown in Figure 9, it can be noted that the cooling time is 8.2283 hrs, 7.8942 hrs, 7.9367 hrs, 8.0458 hrs, and 7.7783 hrs, for trials 1 to 5, respectively. Cooling time is 7.9767 hours on the average. Based on specification, the batteries used should not be drained and used beyond the recommended 80% DOD which is 9.1429 hrs. Since average cooling time is 7.9767 hours, two (2) battery units meet the requirement for a 12-hour period of vaccine carrier use.

The moment the ideal dummy temperature range is achieved, the carrier is ready for vaccine loading. Five trials were conducted to test if the carrier is capable of maintaining the desired temperature levels as designed (2℃ to 8℃) for 12 straight hours. Setting was at 4℃ to 6℃, and readings in the five trials were at 3.5℃ to 6.5℃, which is well within the target temperature levels at 2℃ to 8℃. This validates the design and functionality of use of the vaccine carrier. The vaccine carrier is also capable of monitoring and recording the temperature of the dummy at a 3-second interval for 12 straight hours. This means that the device complies with the WHO requirement of 30-minute interval temperature monitoring of the vaccine carrier.

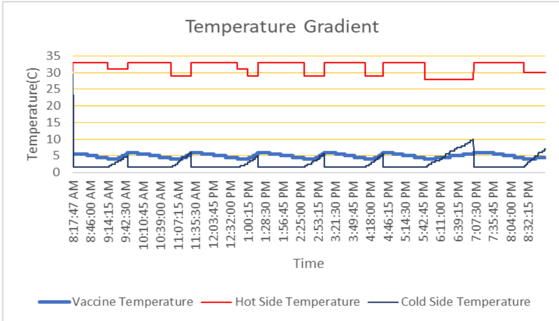


Fig. 10: 12-hr Cooling data of TEC on the hot and cold side with corresponding vaccine temperature

The vaccine carrier is equipped with TEC that provides the cooling mechanism. Here, TEC transfers heat from one side (cold side) of the carrier to the other side (hot side). Figure 10 shows the temperature on the hot and cold side of the carrier and the dummy which simulates that of the vaccine. The three temperature measurements were taken by the temperature sensor over a 12-hour period and recorded by the microcontroller. Results indicate that in the course of the 12-hour period, the hot side registered a much higher temperature than the cold side, yet the microcontroller was able to register vaccine dummy temperature reading of 3.5℃ to 6.5℃. The microcontroller setting was from 4℃ to 6℃ range since the target was for the vaccine's temperature to be within 2℃ to 8℃ temperature. The microcontroller functions similar to a switch, by turning on and off the TEC as the carrier reaches the temperature setting. The TEC was able to successfully extract heat from the space and vaccine dummy inside the carrier and dissipated that heat and released it outside of the carrier.

ISSN No:-2456-2165

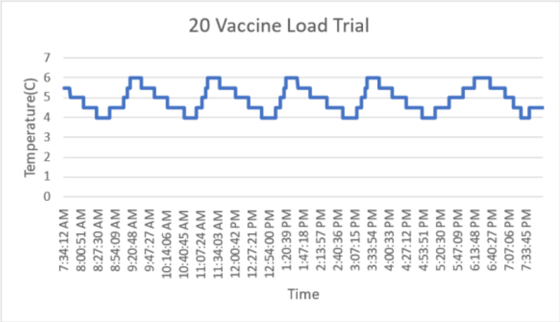


Fig. 11: 12-hr Cooling data for 20 vials

Figure 11 shows that the cooling time which was taken once (8.2975) when there 20 vials in the set up, exceeded the average cooling time, done in five (5) trials, when there were only 10 vials (7.9767). More vials meant longer cooling time.

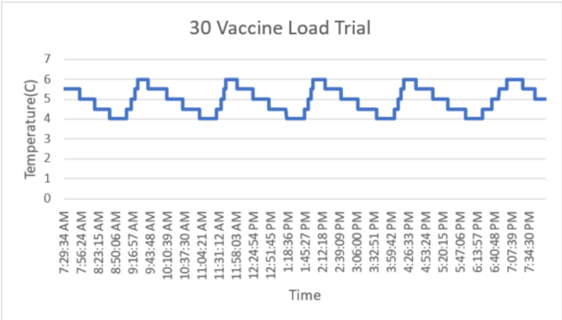


Fig. 12: 12-hr Cooling data for 30 vials

A single trial was done with 30 vials and cooling time was 8.5856 hrs, as shown in Figure 12. Expectedly, cooling 30 vials took the longest time. More vials to cool consequently took longer cooling time, and used up more energy.

C. Cooling Results (using ice only without TEC).

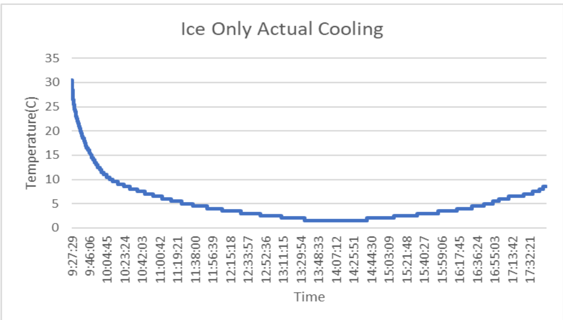


Fig. 13: Cooling data using ice only

Another test was done involving the use of ice only without TEC. Figure 13 shows the plotted temperature recording. Starting from when it was warmer, with the use of ice only, there was a drastic and faster drop in the temperature, but when the temperature has started to lower, the cooling rate has slowed down. In the course of this test, the temperature of the vaccine dummy went down to as much as 1.5℃, which is outside of the 2℃ to 8℃ temperature target. As the temperature reached 1.5℃, the temperature started to go up. Using ice only, pre-cooling temperature ended at 5 ℃, and enabled the carrier to maintain the target vaccine temperature 2℃ to 8℃ range for just 6 hours and 18 minutes. The TEC therefore was more effective at maintaining the 2℃ to 8℃ temperature range and can efficiently maintain within such range for a longer time.

IV. CONCLUSION

This research was able to design a portable vaccine carrier equipped and Arduino system that can effectively maintain the ideal vaccine temperature range during transport and delivery. Aside from the conceptual design, a vaccine carrier prototype was created and tested. The prototype is equipped with a water temperature sensor capable of accurately measuring the temperature of the water inside the vaccine dummy. Such temperature reading of the water inside the vaccine dummy provides a much closer estimate of the temperature of the vaccines than when taking readings anywhere from the internal portion of the vaccine carrier whether using a thermometer for instantaneous measurement or any continuous temperature monitoring device. Also, the vaccine carrier prototype is equipped with an LCD screen to show the current dummy vaccine temperature and an SD card module that can record the readings taken by the temperature sensor on the water inside the vaccine dummy, that are received by the Arduino system.

This research was able to produce a design and prototype that satisfies WHO requirement for a vaccine carrier that does not freeze the vaccine or effect damage as it can maintain a safe vaccine temperature range of 2 to 8 ºC. Based on testing, the prototype equipped with a thermoelectric cooler (TEC) system can maintain a temperature range of 2 to 8 ºC for at least 12 hours. Prior to maintaining the actual cooling temperature, pre-cooling was done using ice. This pre-cooling phase can be perfectly done at health centers and to speed up the cooling of the vaccine carrier interior from ambient temperature to about 5ºC, before the main and actual cooling phase using battery powered TEC. This prototype can be a good alternative to portable carrier and can be conveniently used in the transport and delivery of vaccines by foot to areas which are remote or hardly accessible by motor vehicle while keeping the vaccine within safe temperature levels effecting reduced damage caused by extreme temperatures.

ACKNOWLEDGMENT

This paper is an output a group of the aforementioned student researchers with technical guidance from faculty adviser/researcher. This has passed the research proposal and final presentation held and facilitated by the Mechanical Engineering Department of CIT-University.

ISSN No:-2456-2165

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