Heat Think

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Made by:

Abdelrahman Ali
Ahmed Ibrahim
Ahmed Karam
Amr Mohamed
Azza Hassan
Dina Adel
Habiba Ahmed
Haidy Fathy
Kareem Hesham
Kareem Mohamed
Salma Mostafa
Tayseer Ashraf

Introduction

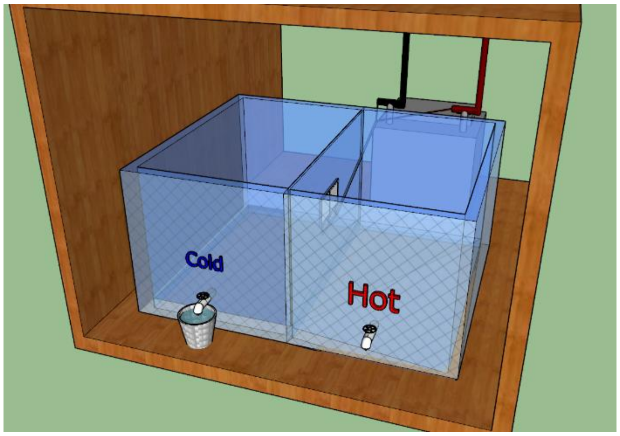
Hot and cold-water dispensers are such important devices in our daily life. In this project, a thermoelectric modules system is used to make a water dispenser instead of using the conventional cold-hot water dispenser with a compression refrigeration system. Thermoelectric modules provide several benefits, including reliability, environmental friendliness, and the absence of moving parts. Our project works with renewable energy as solar panels are used as the power source. solar panel works by generating electricity when particles of sunlight, or photons, knock electrons free from atoms, setting them in motion. This flow of electrons is electricity, and solar panels are designed to capture this flow, turning it into a usable electric current.

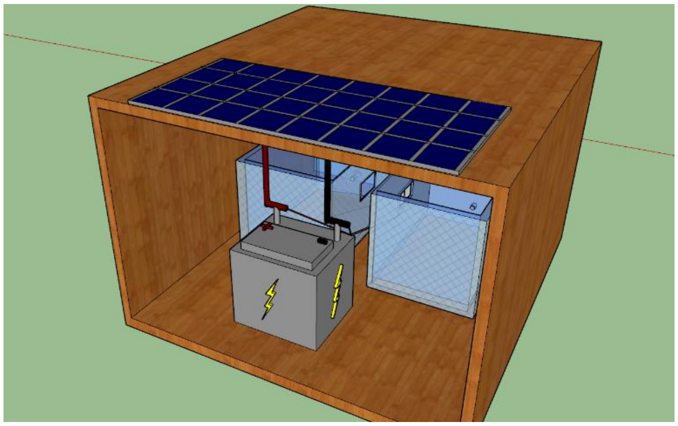
To design our prototype, prior solutions for water dispensers have been searched. One of the prior solutions used water pumps to pump water from an external source to the containers connected to Peltier. The problem with water pumps is that they consume enormous amounts of energy. To avoid this problem, our prototype is designed to contain the water in the containers connected to the Peltier directly. In the second prior solution cold and hot water systems were separated each one works independently, the problem in this solution is that there is a large amount of heat loss.

To avoid this problem, both systems are connected to each other to decrease the amount of heat loss. Our design requirements for this project are efficiency, portability, and low cost. Insulation material is used to decrease the amount of heat loss, so the efficiency will increase. Our prototype is designed to work well on a small scale which helped us minimize the project's cost. Appropriate material is used appropriate material in building our prototype to make it portable.

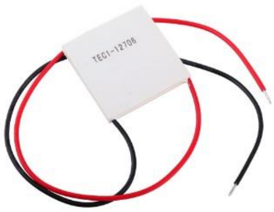
Idea Description

After viewing the prior solutions for the prototype and discussing each solution's advantages and disadvantages, it has come to decide the solution's design and characteristics. For the power supply part, the main source is the solar panel connected to a set of rechargeable batteries for portability. For the heat change, a thermoelectric cooler (TEC) is to be used. The initial design of the prototype is shown in the following figures.





First to be decided is the type and model of the thermoelectric cooler because its properties and power would be the base to build on it the characteristics needed in the other parts of the project. As the main idea of the project, which is gaining and losing heat, is achieved by the TEC, this made it the main part of the prototype. There are many models of TECs; they are different in their maximum operating temperatures, maximum temperature difference, input voltage, etc. It has been decided to use TEC1-12706, as it has the most suitable properties. Two heat sinks have been used in order to distribute the heat from the TEC to the containers.



TEC1-12706 picture

After deciding the model and properties needed for the heat generation and reduction, the rechargeable batteries should be chosen based on their power and lifetime. Lithium batteries have a medium but enough lifetime, in addition to the suitable voltage it provides and fast charging. Three of the 3.7V Lithium batteries have been used by connecting them in series to provide a voltage of 11.1V. A battery management system (BMS) is used to regulate the charging and discharge of the batteries.

3.7V Lithium batteries

Idea Description

The solar panel has been chosen based on the power needed to recharge the batteries. Hence the fully charged batteries should have 11.1V, it needed a power to provide the maximum possible efficiency needed for fast charging, so it was clear to use a 10W solar panel to provide such a power for the batteries.

After the main components have been carefully chosen, the decision is left for the design. Two containers are used: one for the cold water and the other for the hot water. Their material is polyethylene terephthalate (PET) plastic of a 1.5 Liters capacity. A hole of dimensions of (45x46) mm has been provided in each container for the heat sink to pass through the surface connecting the inner of the container with the TEC, along with another hole for each container for the water tap. The containers have been surrounded by an insulating material to reduce the heat loss as much as possible. There are different types of insulating materials regarding their thermal conductivity and properties. Nevertheless, the insulating material used is glass wool.

Analysis

In this section, the discussion is about the scientific bases and analysis for each component of the prototype.

Thermoelectric cooler (TEC):

The thermoelectric cooler is the main part of the dispenser, as it is the component responsible for causing the heat difference for water. The TEC's mechanism is so simple; it works by the Peltier effect. The electric component has two conductors connected. When an electric voltage is applied, a current flow through the junctions of the conductor causing heat to be deposited at one junction cooling the other junction. So, the effect is simply creating a temperature difference by transferring heat between two electric junctions.

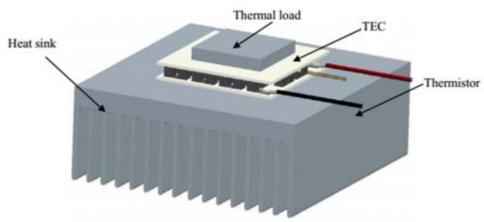
Performance Specifications

Hot Side Temperature (º C)	25º C	50º C
Qmax (Watts)	50	57
Delta Tmax (º C)	66	75
Imax (Amps)	6.4	6.4
Vmax (Volts)	14.4	16.4
Module Resistance (Ohms)	1.98	2.30

There are many different models for the thermoelectric cooler. Each model has its own code and datasheet with its properties and calculations. In this project, a TEC with high temperature difference and average voltage is needed. A suitable and commonly available TEC has been chosen; it is TEC1-12706 with the datasheet shown in *figure 1.* The TEC has a temperature difference between its sides referred to as Delta Tmax. There is a minimum difference of 66 ºC and a maximum difference of 75 ºC. So, the TEC model satisfies the required outcomes from it, in addition to its average voltage needed to make a noticeable heat difference.

Heat sink:

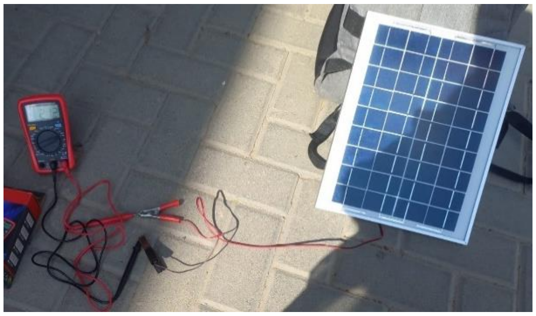
A thermoelectric cooler must be connected to a heat sink through a thermal paste. The heat sink absorbs heat from the cooler and distributes it. This feature helps in reducing the heat pressure on the cooler to prevent it from burning due to overheating on surface, and to distribute the heat from the cooler through the water to a larger surface area for faster heating and cooling.



The heat sink's dimensions were decided to be the same as the TEC dimensions or slightly wider. The wider the heat sink is from the cooler, the slower the heat transfer is. So, the surface dimensions of the two heat sinks -each one for a side of the TEC- are 45x46 mm. Thermal paste has been used to connect the TEC sides with the heat sinks adhesively. It allows the transfer of heat efficiently between the two components.

Analysis

Power sources (Solar panel and batteries):



For a green energy source, solar energy is the one to use. A solar panel has been used as the main source of power for the thermoelectric cooler and any other electronics could be used. There is a high risk of damaging the thermoelectric cooler if it was connected directly with the solar cell. This damage happens as the solar cell produces a voltage of 22V approximately, as shown in *figure 2,* while the cooler accepts 14.4V only and 16.4V at maximum performance. To avoid this damage, batteries have been used as a connection between the solar cell and cooler.

The batteries are rechargeable to still make the prototype portable. When choosing a rechargeable battery, there are some things that should be considered, such as voltage supplied, charge/discharge time, and lifetime. From the comparison shown in *figure 3* between the most common rechargeable batteries available, it shows that Lithium-ion has the highest voltage that can be supplied, as it supplies up to 3.7V per battery. A high energy density, which indicates it holds a high amount of energy compared to its size or weight. It has a high cycle life, which indicates a slow discharge.

	Nickel – Cadmium (NiCd)	Nickel Metal-Hydride (NiMH)	Sealed Lead Acid (SLA)	Lithium-Ion (Li-ion)
Anode	Cadmium	Hydrogen Alloy	Lead	Carbon/Graphite
Cathode	Nickel Oxyhydroxide	Nickel Ox hydroxide	Lead Dioxide	(See Table 2)
Electrolyte	Potassium Hydroxide	Potassium Hydroxide	Sulfuric Acid	Lithium Salt Solution
Voltage	1.2V	1.2V	2V	3.2V to 3.7V (See Table 2)
Energy Density	Medium	Medium	Low	High
Cycle Life	High	Medium	Low	High
Memory Effect (retains smaller capacity)	Yes	Yes	No	No
Maintenance Upkeep	High	High	High	Low
Environmental Concerns	High	Low	Very high due to Lead	Low

So, lithium batteries have been chosen due to their suitable and convenient properties. To supply an appropriate voltage, three batteries are connected in series to supply 11.1V for the cooler. The actual voltage shown in *figure 4*. But another issue caused by the high voltage produced from the solar cell is damaging the batteries through overcharging. So, in order to protect the batteries from overcharging which can result from the

high difference in the voltage of the solar cell (22V) and the batteries (11.1V), a BMS is used.

Analysis

Battery management systems (BMS) are electronic control circuits that monitor and regulate the charging and discharge of batteries. It also protects the battery from operating outside its safe area, calculates its state of charge, reports its data, and controls its environment. In this case, a BMS is a must to protect the batteries from any damage that can be caused by the solar cell.

Containers:

The containers' criteria focused on the material and capacity. A safe, flexible, and heat tolerant material was required for the containers. Safety and heat tolerance are important properties for the containers to hold clean and hot water. Flexibility is important just in the scope of this project to be able to cut through it for the heat sink, but for more professionality, a rigid and more fit container would be better.

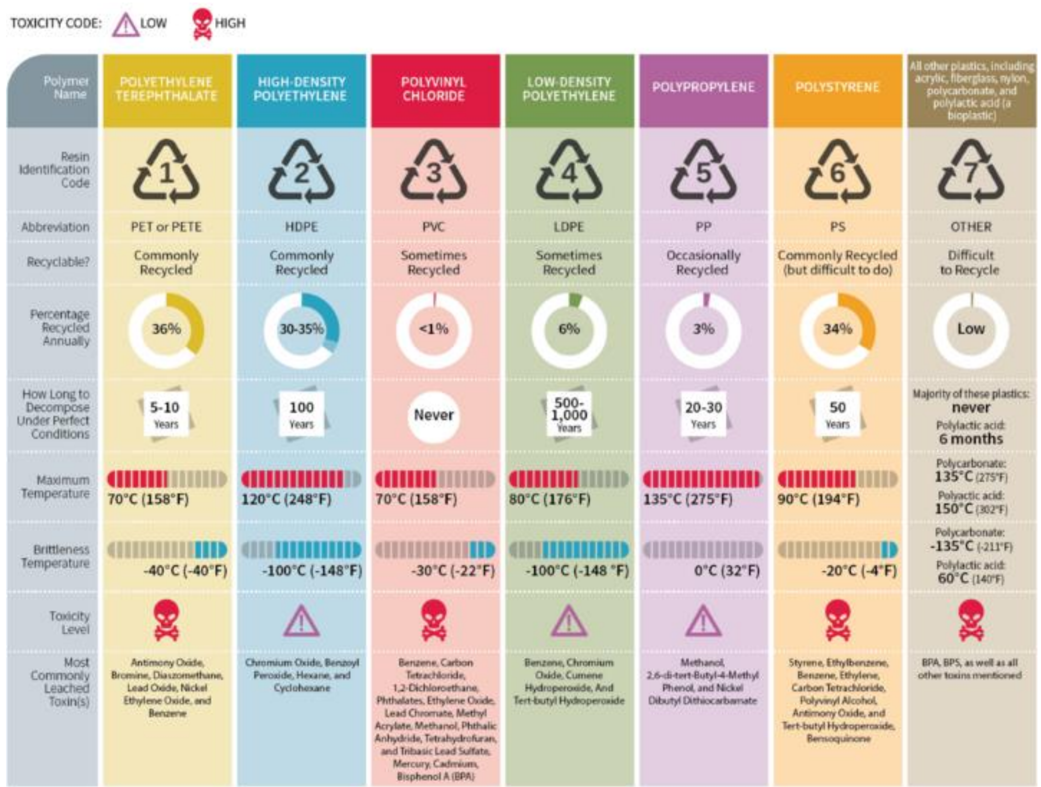
To meet the criteria, a plastic container has been chosen. There are many different types of plastic, as shown in *figure 5* that shows a comparison between them. From the quick comparison, the decision has been made to use PET plastic to satisfy all the required characteristics.

$$q = mC\Delta T$$

- q = heat transferred (in joules)
- m = mass (in grams)
- C = specific heat capacity
- ΔT = change in temperature

$\Delta T = T_{final} - T_{initial}$

The capacity of the containers is 1.5 liters, but only 475 mL approximately have been filled with water to just cover the heat sink. Using less water was derived from the desire to achieve maximum performance. So, in order to do this, the minimum amount of water was used to test. Using the heat/energy equation shown, it shows that as volume of water increases, its mass also increases, and causing the amount of heat required to cause a fixed temperature difference increase.



Analysis

Insulation:

During the process of heat transfer from heat sink to water, some of this heat is lost from water to the surrounding by radiation and convection through container's surface. Since the heat difference between room temperature and container's surface is low and convection coefficient of air is low, the heat loss caused by convection can be neglected in calculations. While the heat loss caused by radiation cannot be neglected as the temperature is biquadratic.

Materials	Picture	Manufacturing	Thermal conductivity (W/m.K)	Properties
Foam glass		Sand/limestone	0,038 to 0,055	- Non-combustible - Resistant to T°C > 430°C - Waterproof - Dimensional stability - Resistant to rodents, insects, acids
Glass wool		Silica and glass recovered by melting, then fibering and polymerization	0,03 to 0,04	- Resists up to 260°C - Non-flammable in the presence of a vapour barrier - Resistant to rodents - Root proof but blows over when humid
Rock wool		Basalt, fondant and coke	0,032 to 0,04	- Fire/heat resistant - Excellent compressive strength - Moisture resistant and vapour permeable (possibility of respiratory discomfort)
Perlite		Volcanic silica rock crushed and heated to 1200°C	0,05 to 0,06	- Hydrophilic (so it must be combined with a water repellent) - Durable and ecological but expensive - High compressive strength - Effective against bacteria, rodents - Non-combustible
Vermiculite		Magnesium silicate, a natural and abundant resource	0,06 to 0,08	- Expanded under the action of extreme heat (1000°C) or water vapour => water repellent treatment required - Non-combustible and rotproof - Not irritating - Resistant to rodents/insects - Good mechanical resistance
Expanded clay		Raw dried clay, reduced to flour, mixed with water and then heated	0,10 to 0,16	- Non-combustible and fire-resistant - Permeable to steam and water resistant but must dry to regain its properties - Rot-proof and resistant to corrosive/insect products

Analysis

In order to reduce this heat loss as much as possible, an insulating material must be used. Insulating materials efficiencies are compared by their thermal conductivity. The less the thermal conductivity, the better insulation offered by the material. The comparison shown in *figure 6* shows the different types of insulating materials along with the thermal conductivity of each type. We can tell that the least thermal conductivity is that of glass wool. So, glass wool has been used as an insulation for the system, as shown in *figure 7.*

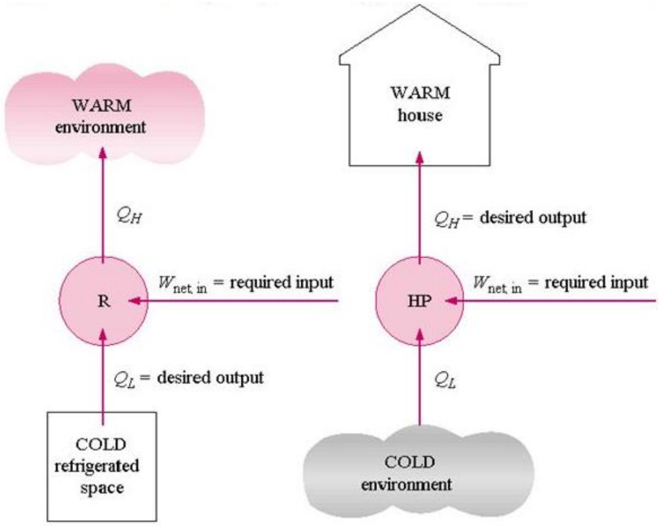
Learning outcomes:

This project helped each student who worked on it to understand the course's syllabus more practically. There are a lot of concepts and equations that facilitated working on the prototype and coming up with the best efficiency possible. In this section, it will get deeper in understanding and discussing those concepts.

1. Refrigeration cycle and heat pump

Studying cycles allowed us to know how the thermoelectric cooler works in a more scientific method and allowed us to come up with more scientific concepts to demonstrate the heating and cooling processes. The cycles that the TEC works with are the power consuming cycles: refrigeration cycle and heat pump.

The refrigeration cycle is a thermodynamic cycle that generates refrigerating effects with the use of mainly an evaporator, compressor, condenser & expansion valve. This process is basically a thermodynamic process where the working fluid absorbs the heat from the surrounding at a low temperature and rejects the heat to the atmosphere at a higher temperature. It works based on reversed Rankine cycle. In this process, heat flows from low temperature to high temperature. Besides this, we were able to calculate the coefficient of performance (COP) of the cold side:



(*a*) Refrigerator (*b*) Heat pump

$COP = \frac{\varphi_c}{\varphi_p}$, where φ_c is the heat transfer and φ_p is the power used by the TEC.

Analysis

Heat pumps operate by moving heat from lower temperature areas to higher temperature areas. They typically take advantage of an electrically driven compressor and a closed vapor compression cycle. Commercial-grade heat pumps come in many forms and can provide useful heating and cooling or simultaneously provide useful heating and cooling1. Technically, most refrigeration equipment can be classified as heat pumps, although the term is typically reserved for equipment that provides useful heat. Also, a coefficient of performance can be conducted for the hot side of the TEC:

$COP = \frac{Q_h}{W}$, where Q_h is the heat transfer and W is electric work consumed by TEC.

2. First law of thermodynamics

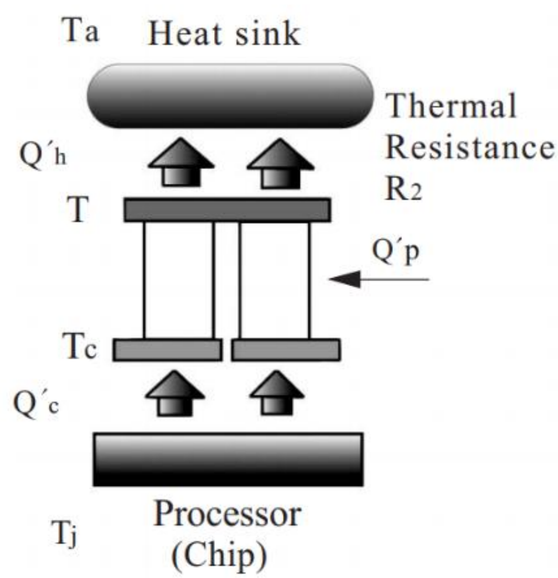
As mentioned, the main component was the thermoelectric cooler, so it was important to learn how it works and how to deal with it. By understanding the basic concepts of thermal engineering and semiconductors, we were able to define the TEC mechanism in the analysis section. Now to discuss the first law of thermodynamics analysis related to the connection and role of the TEC along with the heat sink.

From the schematic diagram shown, we conduct that Q'_c is the heat transfer rate of the absorbed heat from the cold side of the TEC, Q'_h is the heat transfer rate of the heat dissipated from the hot side of the TEC to the heat sink, Q'_p is the external power supplied (in this project case, it is the power supplied by the batteries).

The first law of thermodynamics allows us to distinguish the energy interactions that take place in the TEC and can be shown in the following equation:

$$Q'_c + Q'_p - Q'_h = \frac{dE}{dt}$$

Where $\frac{dE}{dt}$ represents the accumulation energy term of TEC.



Schematic diagram of a TEC

Analysis

3. Heat transfer

The diagram also shows that T_a is the surrounding temperature, T is the hot side temperature, T_c is the cold side temperature.
With these temperature readings, we can calculate heat lost due to convection and radiation by the following equations:

$$Q_{conv} = hA\Delta T$$

Where Q_{conv} is the heat lost by convection between containers surface and surrounding air of temperature T_a , h is convection heat-transfer coefficient of air, A is the surface area of container, and ΔT is the temperature difference between container's surface and air.

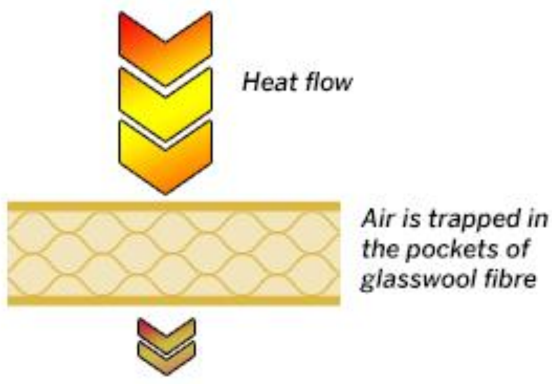
$$Q_{rad} = \varepsilon\sigma A\left({T_s}^4 - {T_{surr}}^4\right)$$

Where Q_{rad} is the heat lost by radiation from the container's surface to the surrounding, ε is the emissivity constant of surface, σ is the Boltzmann constant.

($\approx 5.67 \times 10^{-8}\, W \cdot m^{-2} \cdot k^{-4}$), A is the surface area of the container, T_s is the surface temperature, and T_{surr} is the temperature of the surrounding.
These equations helped in calculating the heat lost from the water containers before using the insulation.

4. Insulation

Thermal conductivity can be defined as the rate at which heat is transferred by conduction through a unit cross-section area of a material. After choosing glass wool to be the insulating material for having the least thermal conductivity available, the concept of insulation that has been taught in the course helped in knowing how it really insulates. Glass wool is primarily made from recycled glass. The glass is melted in a furnace then sent to a spinner to create fibers. The glass wool fibers create millions of tiny air pockets which trap the air. The air pockets make glass wool a poor conductor of heat, which allows it to insulate.



How glass wool insulation works

Results

Our observations during the experiment and the results we got are discussed in the following section.

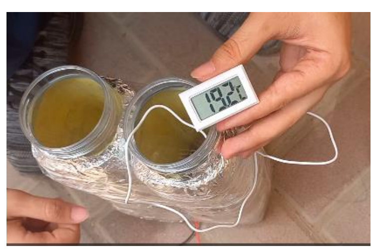
After the implementation of the mentioned design requirements, six trials were done to do the calculations precisely. The six trials are divided into two, 3 trials without the insulation material and 3 trials after the insulation material was added to the containers. The temperature difference between the hot and cold sides is observed and put in the following table:

Trials (Without insulation)	Applied voltage (volt)	T_{normal}	T_{hot}	T_{cold}	ΔT
1	9.5	24°C	27.3°C	22°C	5.3°C
2	10.35	23.5°C	27.9°C	20.3°C	7.6°C
3	11.1	22.7°C	28.3°C	19.1°C	9.2°C
Average	10.316	23.4°C	27.833	20.46	7.373°C

Table 1

Trials (With insulation)	Applied voltage (volt)	T_{normal}	T_{hot}	T_{cold}	ΔT
1	10.7	26°C	31°C	22°C	9°C
2	10.8	23.7°C	29°C	19.6°C	9.4°C
3	11.1	21.3°C	28.1°C	19°C	9.1°C
Average	10.933	23.66°C	29.366°C	20.2°C	9.16°C

Table 2

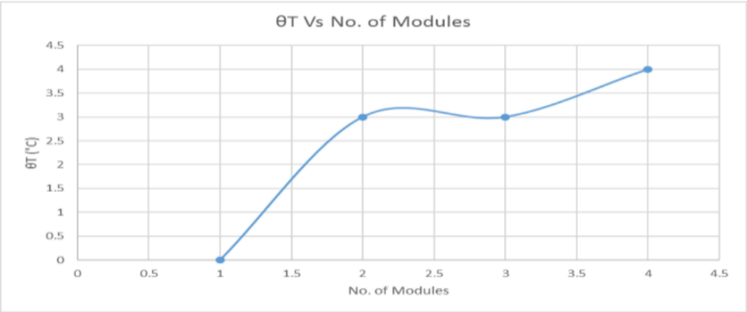


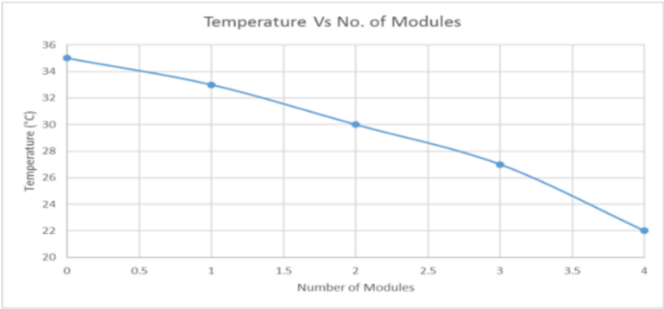
Results

From the above tables, some important relations are discussed:

1)Temperature Vs no of modules

In our project, one TEC module is being used. However, a statistic is made by comparing the results obtained from other projects that are using much more than one module. As the number of the used thermoelectric cooler modules increased, the temperature difference between the hot and cold side increases, and so does the efficiency of the system.

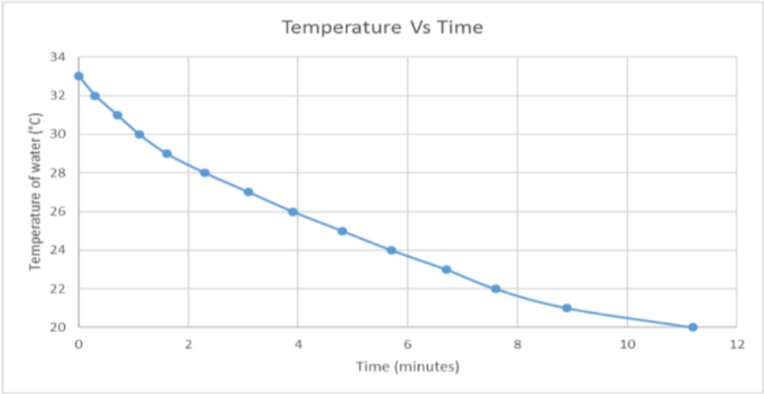




2)Temperature Vs time

By increasing the time interval that the (TEC) will be turned on at, the temperature difference between the hot and cold sides increases as shown in the following graph.

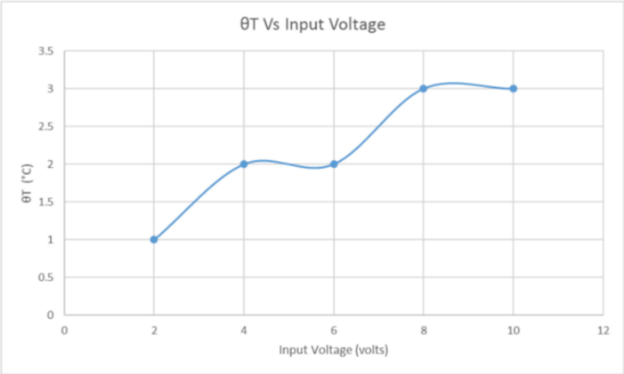
We can very clearly observe that the temperature of the water comes down in cold and increases in the hot side as the time increases for which the module is kept switched on. Graph 3 shows the temperature of the water in the cold container with time.

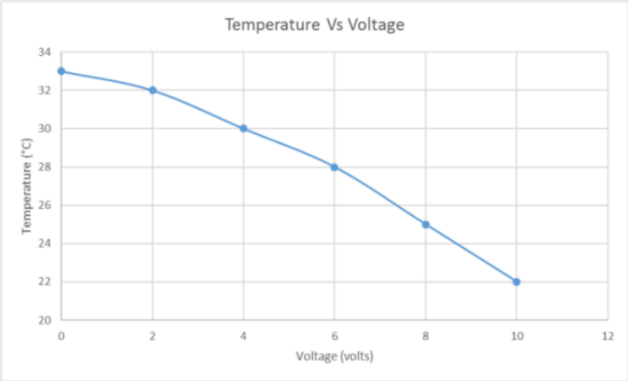


Results

3)Temperature Vs voltage

By increasing the power input to the TEC module, the module works efficiently, and the temperature difference obtained on both sides increases.





After collecting the above data, the power of the solar cell and Q for each subsystem was calculated by applying the first law of thermodynamics. To calculate the Q_{hot} and Q_{cold}, the temperature difference (θT°C) for each side was observed as shown in the following table:

Power of solar cell= 10 W

Atmospheric temperature = 27 °C

Initial temperature of water = 23.66 °C

Time interval = 8 minutes

Volume of water (for each container) = 475ml

Trials **Hot side**	Applied voltage(V)	θT(°C)
1	10.7	5
2	10.8	5.3
3	11.1	6.8
Average	10.866	5.7

Table 3

Trials **Cold side**	Applied voltage(V)	θT(°C)
1	10.7	4
2	10.8	4.1
3	11.1	2.3
Average	10.866	3.47

Table 4

Results

From the first law of thermodynamics Q= $m\, c_w\, \Delta T$

For the hot subsystem $Qh = 0.475 \times 4180 \times 5.7 = 11.317\ kJ$

For 8 minutes interval $Qh = \frac{11317.35}{8\times60} = 23.577w$

For the cold subsystem $Qc = 0.475 \times 4180 \times 3.47 = 6.889kJ$

For 8 minutes interval $Qc = \frac{6889.685}{8\times60} = 14.3535w$

$$\text{Cop} = \frac{Q}{W}$$

For the hot side $cop = \frac{Qh}{W} = \frac{23.577}{10} = 2.3577$

For the cold side $cop = \frac{Qc}{W} = \frac{14.3535}{10} = 1.4353$

Change in entropy (ΔS, hot) $= \frac{\Delta Q}{T} = \frac{23.4 \text{ x } 8 \text{ x } 60}{273+28} = 37.3$ J/K

Change in entropy (ΔS, cold) $= \frac{\Delta Q}{T} = -\frac{14.3 \text{ x } 8 \text{ x } 60}{273+28} = -22.8\ J/K$

Cost analysis

With the expansion of the water dispenser market, product demand is being driven by factors such as portability, ease of use and installation, and low maintenance costs. Cost was one of the design requirements that were aimed to be achieved. The used materials are discussed in the following table.

Item	No. used	Cost per item (L.E)	Picture
Battery Li-ion Battery Cell 3.7v (Used)	3	25	
Polycrystalline Solar Panels 10-Watt 18 Volt (34.5 * 25.5 CM)	1	250	
TEC1-12706(40x40mm)	1	130	

Results

BMS 3S 18650 Lithium Battery Protection Board (10A) 50x16x1mm	1	75	
Battery Holder (1×18650)	3	9	
Heatsink (L 50 x W 45 x D 18mm)	2	25	
Heatsink Plaster Thermal Silicon Adhesive Cooling Paste	1	20	
PET plastic containers(1.5 L)	2	20	
Glass wool (25 ×50)	1	25	
High Temperature Tape	1	40	
Tap	2	20	

Conclusion

After implementing the design requirements and perspectives, observing, testing, and recording the results, we can conclude that:

The cold and hot water dispenser is made using one thermoelectric cooler (TEC) in between the cold and the hot containers using solar panels as power supply, which produces 10 watts. To calculate the efficiency of the prototype, six trials were done, three trials without insulation and three with insulation. The amount of water tested is 475ml and the duration of the test was an average of 8 minutes. The average temperature difference between the hot and cold sides for these trials without insulation is 7.373C, and with insulation is 9.16C. The Q for each subsystem was calculated from the first law of thermodynamics and found to be 23.577 w for the hot side, and 14.33 for the cold side. The coefficient of performance of the hot side is 2.35, and that of the cold side is 1.43.

Recommendations

As the study progressed, a few parts are suggested to be developed to obtain a higher efficiency level in future studies. The recommendations are as follows:

- Using more TEC modules to obtain higher temperature differences in a short time.
- Using higher powering solar panels to reach maximum temperature on both sides, hot and cold.
- Using sufficient rechargeable batteries with higher storage capacities and low discharging rates as the implementation on a large scale will be consuming higher power.
- Using containers that have high insulation properties.
- Implementation of the design on a large scale to increase the amount of water being heated or cooled.

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