Rapid Water Freezer Using Thermoelectric Module

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Abstract : In a refrigerator, water is cooled with the help of refrigerant, which is circulated around the freezer chamber. Typically, a refrigerator takes upto 5000 sec. (approx. 1.5hrs.) to freeze one liter of water from 40^0C. Thermoelectric Modules (TEMs), working on peltier effect can provide high cooling rates while operating on DC electric source. TEMs can achieve sub-zero surface temperatures within a few seconds. An attempt has been made to use TEM for freezing of water. Water can be frozen without any refrigerant with the help of such TEMs while remarkably reducing the freezing time to 3 mins. A design of a rapid icing machine working on thermoelectric effect has been discussed in this paper. To obtain rapid icing the optimum selection of TEM on the basis of cooling capacity and current consumption is discussed wherein, a 500ml cooling box is designed which provides icing in 1.5mins. The design results suggest that, for the rapid icing machine 16 TEMs (TEC1-12706) are required with 4 copper heat sinks of 26 fins each.

***Index Terms* – Thermoelectric, Peltier, TEC, TEM, Rapid Icing, Refrigeration, Refrigerant.**

NOTATIONS USED

Q_1 – Heat to be removed from water to reduce temperature from 40^0C to 0^0C, J
Q_2 – Heat to be removed from water to freeze at 0^0C, J
Q – Heat removal rate, W
Re – Reynolds Number
v – Air flow velocity, m/sec
ν – dynamic viscosity of air, Kg/m.s
Nu – Nusselts Number
Pr – Prandtl Number
L_c – Characteristic length of fin, m
K_{air} – Thermal conductivity of air, W/m^{2}K
A_c – Cross sectional area of fin, m^2
P – Perimeter of fin, m
Q_{oneFin} – Heat transfer rate from single fin, W
Q_{in} – Heat flow rate into copper heat sink, W

I. INTRODUCTION

Thermoelectric Modules (TEMs) are heat pumps which perform cooling function same as that of a vapour compression cycle refrigerator. These modules are entirely solid state with no moving parts. The base material for module construction is Bismuth Telluride with doping with various materials like antimony, tellurium, bismuth and selenium [1-3].

With application of DC voltage, the charge carriers in the bismuth telluride pellet absorb heat energy from one surface and dump in the other surface [2].

TEMs have Co-efficient Of Performance (COP) in the range of 0.25 to 0.4 and the heat pumping capacity reduces as the temperature difference between the cold and hot side increases. Due to this, TE devices cannot provide solution to every cooling problem, however, they are best considered when system requirement calls for high reliability, small size and rapid cooling[1].

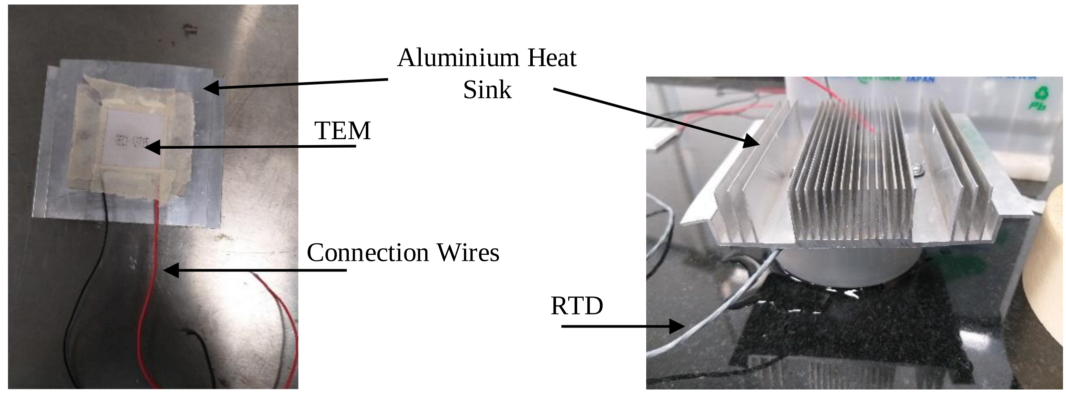
TEMs come with advantages like acoustically silent operation due to absence of moving parts, compact construction and high reliability[4].

In this paper, designing of rapid icing machine with the help of TEMs has been discussed. Optimum selection of TEM is performed considering the cooling capacity and current requirement of the module.

II. EXPERIMENTS

As shown in figure 2.1, the experimental setup consists of an assembly of TEM and heat sink. TEM is attached to heat sink by means of thermal paste. The paste acts as an adhesive between heat sink and TEM while reducing the contact resistance. The heat sink is cooled by forced air cooling using a fan mounted on top of the sink. TEM is powered by a 12V 48Ahr lead acid battery (not shown in figure).

This assembly of TEM is inserted into a cup containing water. It is ensured that there is no contact between heat sink and water inside the container. An RTD is inserted into the container to measure temperature of water. RTD is connected to a data logger and temperature indicator to measure and display water temperature.



(a) Thermoelectric Module Assembly (b) Experimental Setup

Figure 2.1 Experimental Setup for Water Cooling

Experiments were carried out,

1. To compare the cooling rates achieved by a refrigerator and two different TEMs.
2. To study the effect of cooling capacity of TEMs on cooling rate of water.

In all, three experiments were carried out, each with refrigerator, TEM 1 (TEC1-12706) and TEM 2 (TEC1-12715). Each trial experiment run was conducted thrice, and average temperature response was considered. Table 2.1 indicates the test parameters for all experiments.

Table 2.1 Test Parameters

Parameter	**Value**
Volume of Water	500cm^3
Test Duration	10min.
Temperature Sensor	RTD
Experimentation with Refrigerator	
Freezer Temperature	-7^{0}C
Experimentation with TEM 1 (TEC1-12706)	
Cooling Capacity	60W
Voltage Applied	12V
Current Drawn	6.1A
Experimentation with TEM 2 (TEC1-12715)	
Cooling Capacity	150W
Voltage Applied	12V
Current Drawn	15A

The comparison of average temperature response vs. time for water cooling corresponding to each experiment is shown in figure 2.2

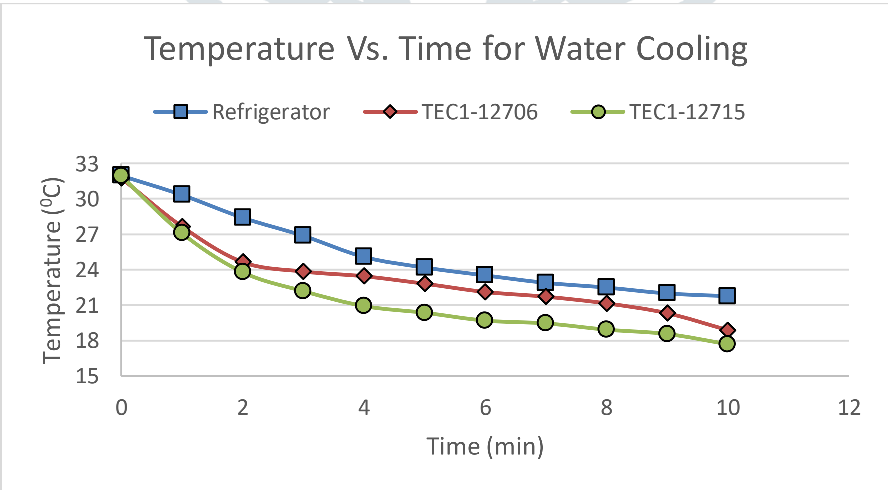


Figure 2.2 Temperature Vs. Time Plot for Water Cooling

From figure 2.2, it is observed that,

- Water cools at an average rate of heat transfer of 34W in the refrigerator. $((m \times C_p \times \Delta T)/ t) = (0.5 \times 4180 \times 10) /600)$
- With this rate, time required to freeze one litre of water at 40^{0}C in refrigerator will be 4900 sec.
- As the rate of heat removal of TE module increases, the rate of water-cooling increases. For same time period of 10 mins, TEC1-12715 cools 6.3% more than TEC1-12706.
- We can conclude that for same period of time TEC1-12706 cools 13% more than that of refrigerator.

- We can conclude that for same time period of 10mins, TEC1-12715 cools 19% more than refrigerator.
- Thus, we can conclude that, thermoelectric modules provide rapid cooling as compared to refrigerator.
- Moreover, the size of thermoelectric modules is small which makes it compact in construction as compared to a refrigerator.
- As the cooling capacity of thermoelectric module increases, the rate of cooling the water also increases. However, this is on the cost of higher current consumption.

III. NUMERICAL INVESTIGATION

3.1 Cooling load Calculations

For any refrigerating system, or any cooling system, cooling load calculations play an important role in the system design. With appropriate cooling load calculations, we can avoid overdesigning or under designing the freezer.

Following are the considerations for cooling load calculations:
1. Mass of Water to be Frozen = m = 0.5Kg
2. Specific Heat of Water = C_p = 4.2KJ/KgK
3. Initial Temperature of Water = T_1 = 40^0C
4. Final Temperature of Water = T_2 = 0^0C
5. Latent heat of Fusion of Water = H_g = 0.334 J/Kg
6. Target time for freezing using TEM = t = 1.5min = 90sec. (can be decided as per requirements)

<u>Step 1 –</u> Q_1 : Heat to Be Removed To Bring Water From 40^0C to 0^0C

$Q_1 = m \times C_p \times \Delta T = m \times C_p \times (T_1 – T_2)$
$= 0.5 \times 4200 \times (40 – 0)$
$= 84000$ J

<u>Step 2 –</u> Q_2 : Latent Heat to Be Removed To Freeze Water At 0^0C

$Q_2 = H_g \times m$
$= 0.334 \times 0.5$
$= 0.167$ J

The water is to be frozen within 1.5 mins.
Thus,
Q : Heat Removal Rate,

$Q = (Q_1 + Q_2) / \text{time}$
$= (84000+0.167) / 1.5 \times 60$
$= 933.334 = 934$ W
Hence,
Q = 934W….. (targeted cooling load)

3.2 Selection of Thermoelectric Module

For freezing of water, the total cooling rate achieved by the number of TEMs together, should be more than that of the required cooling load. Following table shows the number of TEMs required for the target calculated cooling load (Q).

Table 3.1 Required Thermoelectric Modules

Sr. No.	Available TEMs	Cooling Rate Per Module	No. of TEMs Required	Round Off
(1)	(2)	(3)	(4)=Q/(3)	(5)
1	TEC1-12706	61W	15.311	16
2	TEC1-12712	115W	8.12	9
3	TEC1-12715	150W	6.22	7

Table 3.2 Standard Power Requirement of TEMs

Sr. No.	Available TEMs	Voltage Requirement	Current Drawn
1	TEC1-12706	12V	6A
2	TEC1-12712	12V	12A
3	TEC1-12715	12V	15A

Table 3.3 Current Requirement for Available TEM

Sr. No.	Available TEMs	Current Drawn Per TEM	No. of TEMs Required	Total Current Consumption
1	TEC1-12706	6A	16	96A
2	TEC1-12712	12A	9	108A
3	TEC1-12715	15A	7	105A

For achieving same target cooling rate, we require different number of TEMs as per their individual cooling rates. If we use a TEM of higher cooling rate, the required number of modules reduces, however, the current consumption increases. Thus, we need to balance the number of modules required and the current required. Table 3.3 gives the details of total current consumption required corresponding to respective available TEMs for achieving 934W of cooling rate. Thus, for freezing of water within 1.5mins., referring to table 3.3, from the available TEMs, TEC1-12706 indicates minimum total current consumption with 16 number of modules. Hence, rapid water freezer using TEC1-12706 was proposed to be designed using 16 number of TEMs.

IV. DEVICE DESIGN

4.1 Introduction

The device is designed using 1mm thick aluminium plates, fabricated to form a box structure. Four TEMs per face are attached to four sides of the box. The box is insulted to avoid heat infiltration into water during cooling operations. Heat sink (one on each side, common for four modules) is attached on the TEMs to dissipate the heat extracted from water inside the container. The dimensions of TEC1-12706 are shown in figure 4.1.

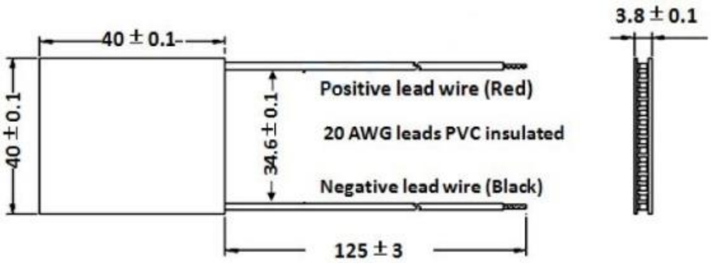


Fig 4.1 Dimensions of TE Module (All dimensions in mm) (courtesy : TEC1-12706 Datasheet)

4.2 Aluminium Box Design

The length and width of thermoelectric module is 4cm x 4cm. Thus, to accommodate 4 modules on one side of aluminium box, the required six side aluminium plate dimensions of the box are as below:
Length = 8 cm
Width = 8 cm
Thickness = 1mm

4.3 Heat Sink Design

The heat sink design includes heat sink sizing, computation of required number of fins and material selection of heat sink. Due to geometrical restrictions of the dimensions of aluminium plate for the box, the size of heat sink was restricted to 8cm x 8cm. Therefore, the material of the heatsink was iterated over to choose the material which will provide required heat transfer within the available dimensions.

With this, heat sink was designed using aluminium and copper. To obtain the required heat transfer, aluminium heat sink dimensions were oversized. But, copper heat sink dimensions were within the size limitations. Thus, the design of heat sink using copper material is as follows:

The dimensions of a single fin are:
Width of fin = w = 80mm = 80×10^{-3} m
Length of fin = l = 30mm = 30×10^{-3} m
Thickness of fin = t = 1mm = 10^{-3} m
Fin Material = Copper
Thermal conductivity of copper = K_{Cu} = 401 W/m^{2}K

a. Heat Transfer Co-efficient Computation

Reynolds number for a flow is given by [5],

$$Re = \frac{v \times l}{\nu}$$

$$= \frac{10 \times 80 \times 10^{-3}}{1.6 \times 10^{-5}}$$

Therefore,

Re = 50000 (Laminar Flow)

Nusselts Number for the flow is given by [5]

$\text{Nu} = 0.339 \text{ x } Re^{1/2} \text{x } Pr^{1/3}$

$\quad = 0.339 \text{ x } 50000^{1/2} \text{ x } 0.718^{1/3}$

Therefore,

<u>Nu = 67.87</u>

Now,

$$\text{Nu} = \frac{\text{h x Lc}}{\text{K}_{\text{air}}}$$

$$67.84 = \frac{\text{h x } 30 \text{ x } 10^{-3}}{24.35 \text{ x } 10^{-3}}$$

Therefore, the value of co-efficient of convective heat transfer between the cold side fins and the flowing air is,

<u>h = 55.09 W/m²K</u>

Therefore,

Ac = w x t

$\quad = 80 \text{ x } 10^{-3} \text{ x } 10^{-3} \text{ m}^2$

$\quad = 8 \text{ x } 10^{-5} \text{ m}^2$

And,

P = 2 x w

$\quad = 2 \text{ x } 80 \text{ x } 10^{-3}$ m

$\quad = 0.16$ m

Rate of heat transfer by fin depends on following three parameters [5]:

1. $\text{m} = \sqrt{\frac{\text{h x P}}{\text{Kcu x Ac}}}$

   $= \sqrt{\frac{55.09 \text{ x } 0.16}{401 \text{ x } 8 \text{ x } 10^{-5}}}$

   $= 16.57 \text{ m}^{-2}$

2. $\sqrt{\text{h x P x Kcu x Ac}} = \sqrt{55.09 \, x \, 0.16 \, x \, 401 \, x \, 8 \, x \, 10^{-5}}$

   $= \; 0.53$ W/K

3. $\tanh(\text{ml}) = \tanh(26.49 \text{ x } 30 \text{ x } 10^{-3})$

   $= \; 0.54$

4. $\text{Q}_{\text{oneFin}} = \sqrt{\text{h x P x Kcu x Ac}} \text{ x } \theta_0 \text{ x } \frac{\tanh(\text{ml})}{1 + \tanh(\text{ml})}$

   $= 0.53 \text{ x } (80 - 40) \text{ x } 0.54$

   $= 11.44$ W

Four thermoelectric module dump heat into one heat sink, thus heat flow into the heat sink is

$\text{Q}_{\text{in}} = \text{Q}_{\text{TE}} \text{ x } 4$

$\quad = 60 \text{ x } 4$

$\quad =$ **240W**

Number of fins (N) = $\text{Q}_{\text{in}} / \text{Q}_{\text{oneFin}}$ = 240 / 11.44 = 20.97

Considering a factor of safety of 20%,

Number of Fins = N x 1.2 = 20.97 x 1.2 = 25.17 = 26 (round off)

Figure 4.3 shows the final design of single heat sink wherein the fins are oriented vertically, to provide air flow to cool the sink. Cooling fans with air flow velocity of 10m/sec are provided on each heat sink for heat transfer. Blue arrow indicates the direction of inlet air onto cool the heat sink, while the red arrows indicate the air going out from the heat sink. Figure 4.4 shows the complete assembly of rapid icing machine. TEMs are sandwiched between aluminium plate and heat sink assembly on four sides of the box. Thermal paste is added between TEMs and aluminium box as well as TEMs and heat sink to reduce thermal contact resistance.

Outlet Air

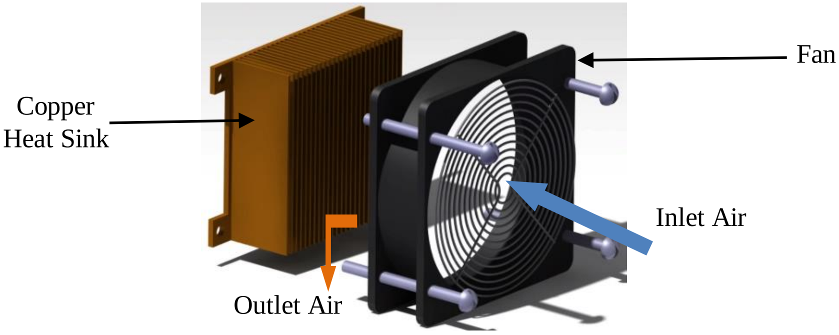


Figure 4.3 Air Flow Over Heat Sink

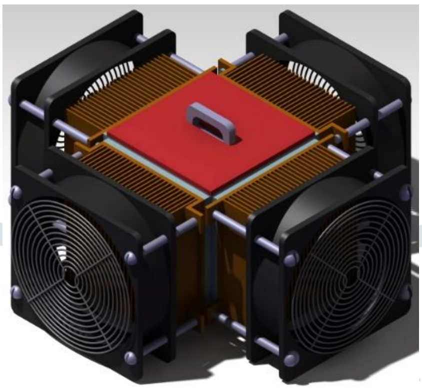


Figure 4.4 Final Thermoelectric Water Freezer

V. RESULTS AND DISCUSSION

Device COP

COP of a refrigerator or any heat removal device is the ratio of the amount of heat removed per unit time to the input power consumed per unit time to remove heat [5].

$$\text{COP} = \frac{\text{Heat Removed In watts}}{\text{Power Consumed In watts}}$$

As discussed in section 4, total number of 16 TEC1-12706 thermoelectric modules are used. As one TEC1-12706 consumes 6A current at 12V and provides 60W of cooling, total amount of current consumed by 16 TEC1-12706 at 12V is 96A and total heat removal achieved is 960W. Also, 4 cooling fans are required which consume 0.17A current operating at 12V. Thus, total input power is

$P_{in} = P_{TEC} + P_{fan}$
= (No. of TECs x Voltage x Current) + (No. of fans x Voltage x current)
= (16 x 12 x 6) + (4 x 12 x 1.7)
= 1152 + 81.6
= 1233.6 W

$$\therefore \textbf{COP} = \frac{\mathbf{960}}{\mathbf{1233.6}} = \mathbf{0.77}$$

VI. CONCLUSION

a. We can conclude that, the thermoelectric freezer can thus provide rapid icing. It can produce ice from 500ml of water within 1.5mins.
b. Further, for large volumes of water, performing similar numerical investigation as described in section 3.1, appropriate size of thermoelectric freezer can be developed for required volume of water.
c. The main drawback of the developed thermoelectric freezer is its COP. As compared to the COP of a convectional refrigerator of 3.31, COP of thermoelectric freezer (0.77) is very low. This restricts the usage of thermoelectric freezers at present.
d. With future development of high performing thermoelectric modules, this COP can be improved.
e. Currently, TE modules are manufactured using Bismuth Telluride (Bi_2Te_3). With improvements in the construction materials of TE modules, the cooling efficiency of TE module will increase. This will in-turn increase the efficiency of the thermoelectric water freezer.

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