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Shafee SM
Asso. Prof, Department of Mechanical Engineering, Hindustan Institute of Technology & Science, Padur, Chennai, Tamil Nadu, India

K Gnanasekaran
Asst. Prof, Department of Mechanical Engineering, Hindustan University, Hindustan Institute of Technology & Science, Padur, Chennai, Tamil Nadu, India

S Johnson Samuel
Asst. Prof, Department of Mechanical Engineering, Hindustan University, Hindustan Institute of Technology & Science, Padur, Chennai, Tamil Nadu, India

Correspondence
Shafee SM
Asso. Prof, Department of Mechanical Engineering, Hindustan Institute of Technology & Science, Padur, Chennai, Tamil Nadu, India

Performance study on thermoelectric cooling and heating system with cascaded and integrated approach

Shafee SM, K Gnanasekaran and S Johnson Samuel

Abstract
The increase in demand for refrigeration globally in the field of air-conditioning, food preservation, medical services, vaccine storages, and for electronic components temperature control led to the production of more electricity. Thermoelectric cooling and heating is a new alternative because it can reduce the use of electricity to produce cooling effect and also meet today's energy challenges.
The main objective of this work is to develop a cascaded and integrated thermoelectric cooling and heating system and to study its performance.

Keywords: Peltier module, cascaded setup, integrated setup, figure of merit, coefficient of performance

1. Introduction
Thermoelectric coolers or Peltier coolers (TEC), are solid-state refrigeration devices that utilize the Peltier effect to provide cooling effect. These are active cooling devices (they require forced convention to remove heat). Conventional cooling devices like those used in refrigerators have a compressor and a working fluid for transferring heat. Peltier coolers have several advantages over the conventional systems they have no moving parts(they are quiet) are more compact and precise. Precise temperature control (< ± 0.1 °C) can be achieved with TEC. However, they have low coefficient of performance (COP) when compared to conventional systems. Their applications include equipment used by military, medical, industrial, consumer, scientific/laboratory. The uses vary from simple food and beverage coolers to extremely sophisticated temperature control systems in missiles and space vehicles. The device used in thermoelectric cooling and heating is based on the Seebeck Effect and Peltier Effect.

1.1 Seebeck Effect
When a temperature gradient is applied to a conductor, an electromotive force is produced. The voltage difference generated is proportional to the temperature difference across the thermoelectric module between the two junctions, the hot and the cold one.

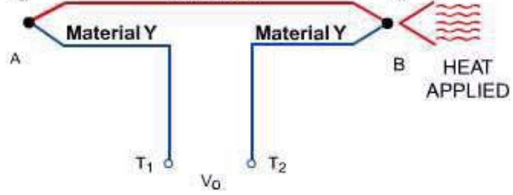

Fig 1: Seebeck Effect

1.2 Peltier Effect
The Peltier effect is the phenomenon that a potential difference applied across thermocouple causes a temperature difference between the junctions of the different materials in the thermo couple. It states that when an electric current flows across two dissimilar conductors, the junction of the conductors will either absorb or emit heat depending on the flow of the electric current.

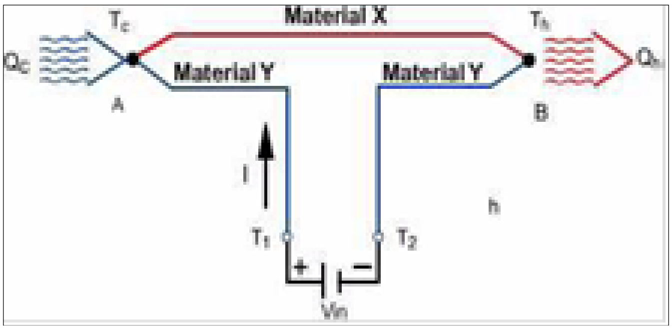

Fig 2: Peltier Effect

1.3 Operating principle of TE module

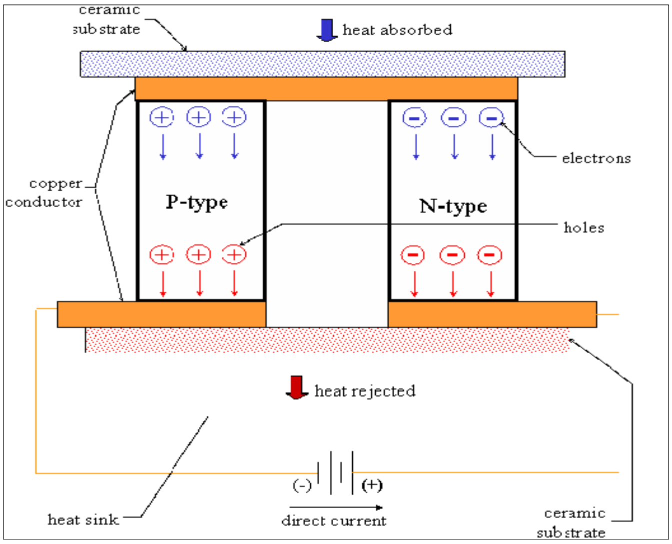

Fig 3: Operation

A typical thermoelectric cooling component is is made up of Bismuth telluride (a semiconductor) is sandwiched between two conductors, usually copper. A semiconductor (called a pellet) is used because they can be optimized for pumping heat and because the type of charge carriers within them can be chosen. The semiconductor is soldered to two conductive materials, like copper. When the voltage is applied, heat is transported in the direction of current flow.

A thermoelectric cooler consists of several N- type and P-type semiconductor junctions connected electrically in series by metallic interconnects (conducting strips) and thermally in parallel forming a single-stage cooler. when a low-voltage DC power source is applied to a thermoelectric cooler heat is transferred from one side of the thermoelectric cooler to the other side. Therefore, one side of the module is heated and other side of module is cooled. The quality of cooling depends on number of factors:

- The electric current applied at the couple of N-type and P- type.
- The thermal and electrical conductivities of the thermo-element.
- The thermal resistance of the heat sink on the hot side of the thermoelectric cooler.
- The number of thermoelectric modules.

The characteristics and performance of a thermoelectric refrigerator are described by parameters like the figure of merit, the cooling capacity and the coefficient of performance. Thermoelectric coolers can achieve both heating and cooling when applied an electric DC current from different directions. When the current flows in one direction, one of the Peltier cooler's plates is heated up while the other is cooled down. As the current reverses the direction, the TEC plates will reverse their thermal polarity accordingly. Common thermoelectric materials used as semi-conductors include bismuth telluride, lead telluride, silicon germanium, and bismuth-antimony alloys. Of this bismuth telluride is the most commonly used. Selection of the proper TE Cooler for a specific application requires an evaluation of the total system in which the cooler will be used. For most applications, it should be possible to use one of the standard module configurations while in certain cases a special design may be needed to meet stringent electrical, mechanical, or other requirements.

2. Literature review

Thermoelectric cooling is based on Peltier effect this cooling effect has been used in several fields. Various experiments were conducted to improve the COP, achieve a better cool down temperature. A review of some of the work done is discussed below.

Jiaheng Chen *et al.* [1] experimented on a integrated two-stage cascaded thermoelectric module (TTEM) operating with dual power source. The integrated TTEM contains two stages of thermocouples with identical semiconductor cross-sectional area but different leg lengths. An analytical model for the TTEM is developed, and the influences of the key parameters are theoretically investigated. The obtained results indicate that optimum two stage currents combination can maximize both the cooling capacity and coefficient of performance (COP).

Beiming Wang *et al.* [2] did mathematical analysis on thermoelectric cooling (TEC) module for enhancing the maximum coefficient of performance (COP) of TEC module. A significant novelty is that each stage thermoelectric couples have different leg lengths which decrease stage by stage from cold side to hot side of TEC module so that the lower stage can completely pump the heat dissipated by the upper stage.

Nandy Putra *et al.* [3] experimental investigation using a Peltier thermoelectric cooler (TEC) too cool down a cryoprobe for cryosurgerstage TEC modules were analyzed using a v exchanger configurations to obtain an optimum cold side temperature and temperature differences between sides of the modules. Using an electric voltage of 12 V and a CTB temperature of 273.55 K, a cryogenic temperature of 177.09 K and a temperature difference of 99.87 K were achieved. These results indicate that the TEC module can be an effective cooling source for cryosurgery.

Diana Enescu *et al.* [4] did a research on formulation of the parameters indicating the characteristics and performance of thermoelectric cooling devices, with particular reference to a number of recent publications. The specific aspects addressed include some practical considerations referring to the thermoelectric figure of merit, the characterization of the cooling capacity, and the assessment of the coefficient of performance (COP).

Riffat and Ma [5] review thermoelectric devices and their applications. They describe the importance of the thermoelectric coolers for niche applications (under 25 W) where the cooling demand is limited (e.g., cooler boxes) or the energy cost is not the main issue (e.g., military applications). Furthermore, thermoelectric devices are considered of interest for domestic refrigerators, in spite of their small COP, to replace other solutions with higher environmental impact.

Simons and Chu [6] discuss a review about thermo electric cooling and its application to the cooling of electronic equipment. They describe the modern developments and the definition of the main thermoelectric cooling equations, concluding that the thermoelectric coolers are not appropriate for high performance electronic cooling applications due to thermoelectric material shaving parameters like figure of merit Z and COP not good enough.

3. Materials and Components used for the experiment

3.1 Peltier Modules

Three Peltier modules are used for cascading as well as for integrated setup. The model number of the module is TEC1-12706. It is decided to select a TEC module which has a cooling power greater than the calculated cooling load. TEC1-12706 operates with an optimum voltage value of 12V. It has a maximum voltage of 15.4V.

Fig 4: TEC1-12706

3.2 Heat Sinks with Fan

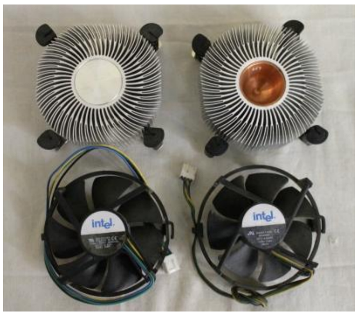

Fig 5: Heat sinks and Fan

The CPU exhaust fans and heat sinks are used for circulation of heat and chamber in the box. The heat sink material is made up of aluminium. Totally six heat sinks are used for integrated model and 2 for cascaded model.

3.3 Insulation Box

A 6.859 m^3 box is used as cooling and heating chamber. The insulation is provided by the Styrofoam sheets having a very low thermal conductivity of 0.033 W/m K. The box is made up of GI steel and arc welded.

Fig 6: Insulation box

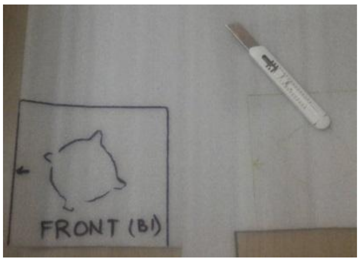

Fig 7: Styrofoam Sheet

3.4 Temperature Sensors

LM35 Temp Sensor along with its complimentary components is used. LCD shows temperature in °C. The temperature sensors display two temperatures; one is of cold side and other of hot side.

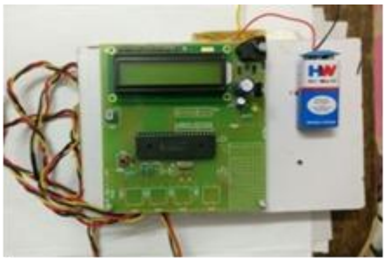

Fig 8: Temperature Sensor

3.5 Thermal Compound

Thermal compound also called CPU grease, heat paste, is a kind of thermally conductive (but usually electrically insulating) compound, which is commonly used as an interface between heat sinks and Peltier modules. The main role of thermal grease is to eliminate air gaps or spaces (which act as thermal insulator) from the interface area so as to maximize heat transfer.

Fig 9: Thermal Compound

3.6 Battery

A 12 V battery technology it will usually operate best with lead acid battery. It consists of combination of lead plates and electrolyte to convert electrical energy into potential chemical energy and vice versa. Lead acid battery is an electrical storage device that use as a chemical reaction to store and relies energy.

Fig 10: 12V DC Battery

3.7 Multimeter
A multimeter is used to measure the voltage and the current taken by the module at every step to do calculations and know the variations.

Fig 11: Multimeter

4. Experimental Setup
The experimental setup consists of two models. The theoretical analysis is done on both the models and figure of merit, cooling capacity and coefficient of performance is calculated.

4.1 Cascaded Model
The basic idea used over here is Peltier stacking also known as cascading. Three Peltier modules are stacked together in a fashion that the cold side of one is touching the hot junction of the other as shown in the figure below.

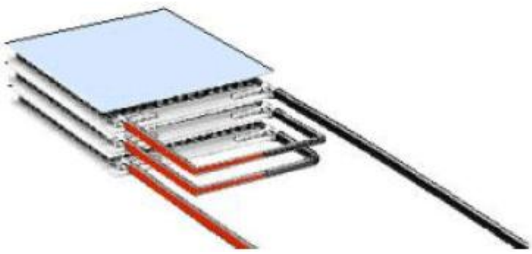

Fig 12: Peltier Stacking

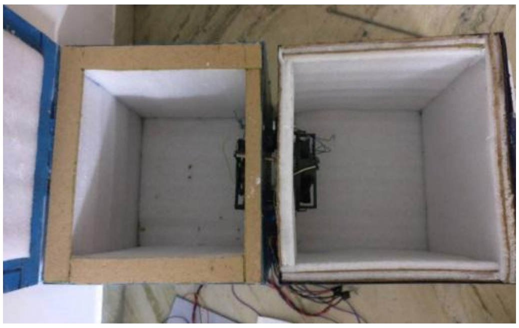

Fig 13: Cascaded Setup

Heat sinks are attached to both ends that are hot side as well as cool side. Exhaust fans are attached to the heat sinks in order to carry out heating and cooling effect in both the boxes as shown in the figure above.
This setup is used to carry out heat up and cool up test in order to find out the coefficient of performance and cooling capacity.

4.2 Integrated Model

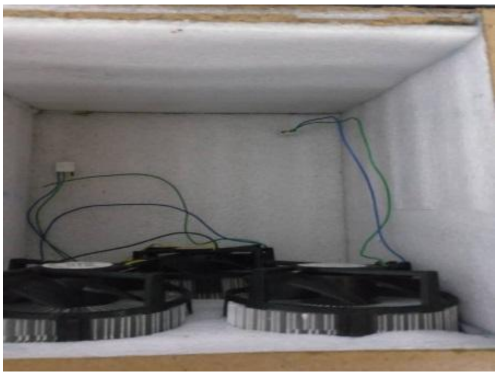

Fig 14: Fans and Heat Sink in Integrated setup

The idea used over here is that we have to connect three Peltier modules electrically in series in order to attain higher performance. Over here three Peltier modules are connected to six heat sinks and six exhaust fans with two heat sinks and two exhaust fan for each module. The attempt is made to cool and heat up the box through the power of three modules operating individually.
The three fans and three heats sinks for cooling and heating respectively as shown in the figure above.

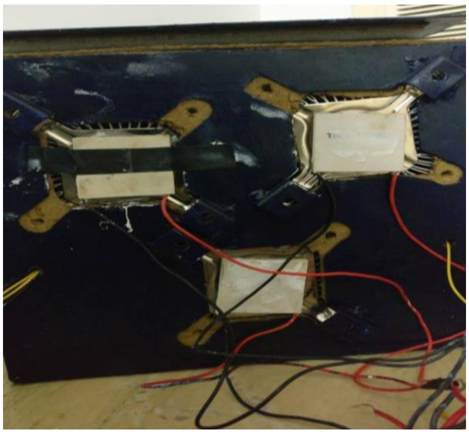

Fig 15: Module Setup

5. Formulae Used
5.1 Thermoelectric figure of merit

$$Z = \frac{\alpha^2}{\rho k} = \frac{\alpha^2 \sigma}{k} \quad (K^{-1})$$ [4]

The thermoelectric figure of merit Z indicates if a material is a good thermoelectric cooler. It depends on three material parameters that are electrical resistivity ρ (or electrical conductivity σ ¼ 1=ρ), Seebeck coefficient α and total thermal conductivity k between the cold and hot sides.
Z represents the efficiency of the N-type and P- type materials which compose a thermo element. A thermoelectric material having a higher figure of merit Z is more convenient, as it can carry out higher cooling power or temperature drop [4].
Current thermo electric devices:

- are considered to be efficient when Z is about 1
- able to recover waste heat when Z = 2
- able to match a refrigerator when Z = 4 or 5

5.2 Cooling Capacity

The cooling capacity Q_c results from the energy balance at the cold side of the thermoelectric refrigerator:

$$Q_c = Q_g - Q_d - \frac{1}{2} Q_j \qquad (W)$$

Q_g is the thermoelectric heat pumping at the cold junction, depending on the Seebeck coefficient.

$$Q_g = (\alpha * T_c * I_{max}) \qquad (W)$$

Q_d is the heat flow conducted from the hot junction to the cold junction which depends on the thermal conductance k of the thermoelements in parallel and it is given by

$$Q_d = k\Delta T \qquad (W)$$

Q_j is the Joule heat, which depends on the electrical resistance Re of the thermo elements in series and the maximum input current I.

$$Q_j = R_e I_{max}^{2} \qquad (W)$$

5.3 Coefficient of Performance

The coefficient of performance COP is the ratio between the cooling capacity Q_c and the electrical power consumption P_e.

$$COP = \frac{Q_c}{P_e}$$

where the electrical power consumption of the thermoelectric refrigerator is given by

$$P_e = R_e I_{max}^{2} + \alpha I_{max} \Delta T \qquad (W)$$

COP of 3 stage Cascaded Model is $COP_3 = \frac{1}{(1+COP^{-1})^3 - 1}$

6. Experimental Results

6.1 Cascaded Setup Results

The heating and cooling test were conducted on the cascaded model. The results are displayed below.

6.2 Cooling Test

Table 1: Cascaded cooling test

Ti Time (min)	Temperature (°C)	Voltage (V)	Current (Amp)
0	31	0	0
10	33	6.7	3.19
20	34	7.2	3.27
30	37	7.6	3.45
40	38	7.7	3.5
50	39	8.1	3.68
60	40	8	3.63
70	42	8.7	3.95
80	41	8.2	3.72
90	43	7.9	3.59
100	47	7.9	3.59
110	48	7.8	3.54
120	48	7.9	3.6

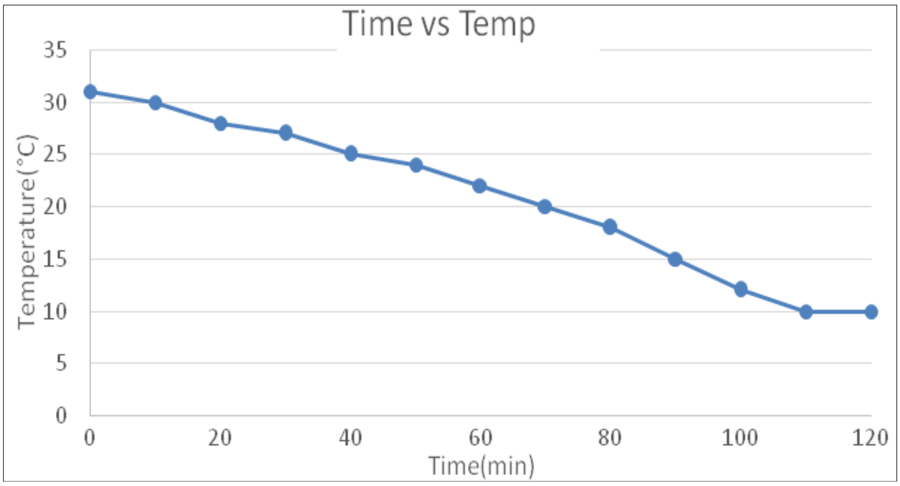

Fig 16: Cascaded Cooling Test

6.3 Heating Test

Table 2: Cascaded Heating Test

Time(min)	Temperature (°C)	Voltage(V)	Current(Amp)
0	31	0	0
10	33	6.7	3.19
20	34	7.2	3.27
30	37	7.6	3.45
40	38	7.7	3.5
50	39	8.1	3.68
60	40	8	3.63
70	42	8.7	3.95
80	41	8.2	3.72
90	43	7.9	3.59
100	47	7.9	3.59
110	48	7.8	3.54
120	48	7.9	3.6

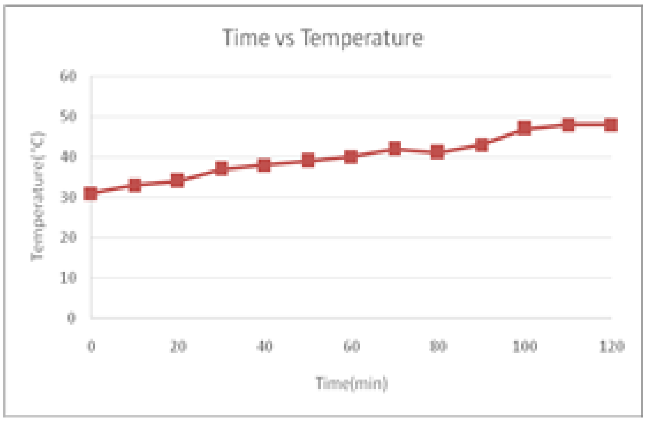

Fig 17: Cascaded Heating Test

6.4 Cop of Cascaded Model

V_{max} = 8.2 V
R_e = 2.2 Ω
I_{max} = 3.76 Amp
k = 1.20 W/mK
$\rho = R\frac{A}{l}$ = 0.352 Ωm
α = 0.215 V/K
Z = 0.1094 K^{-1}
Q_g =228.168 W
Q_j = 30.937 W
Q_d = 45.6 W
Q_c = 167.12 W
P_e = 184.725 W
For 3 Modules,
P_e = 554.175 W
COP = Q_c / P_e =0.34403
COP for 3 stage module setup,

$$COP_3 = \frac{1}{(1+COP^{-1})^3-1} = 0.0168$$

From the experiment done we conclude that the COP of Cascaded Model is around 0.02 which is very low.

6.5 Integrated Setup Results

The heating and cooling test were conducted on the integrated model. The results are displayed below.

6.6 Cooling Test

Table 3: Integrated Model Cooling Test

Time(min)	Temperature(°C)	Voltage(V)	Current(Amp)
0	30	0	0
10	28	6.17	2.8
20	26	6.35	2.88
30	25	6.5	2.95
40	24	6.7	3.04
50	22	6.64	3.16
60	21	6.85	3.11
70	18	6.7	3.04
80	16	6.81	3.09
90	15	6.73	3.05
100	14	6.92	3.14
110	14	6.83	3.1
120	14	6.91	3.14

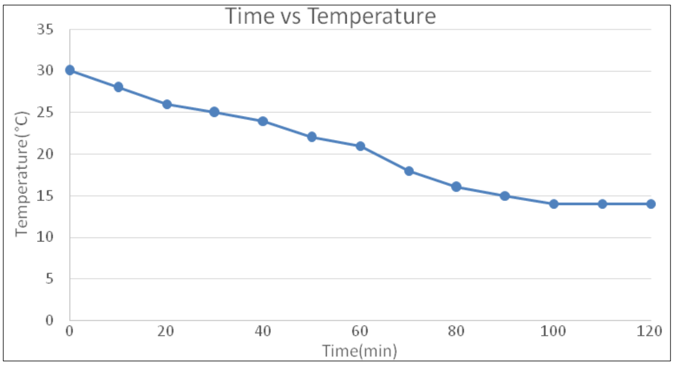

Fig 18: Integrated Cooling Test

6.7 Heating Test

Table 4: Integrated Heating Test

Time(min)	Temperature(°C)	Voltage(V)	Current(A)
0	30	0	0
10	32	6.3	2.86
20	34	6.1	8.9
30	37	6.5	2.95
40	40	6.71	3.05
50	43	6.73	3.2
60	45	6.72	3.05
70	47	6.51	3.1
80	50	6.91	3.14
90	51	6.84	3.07
100	51	6.85	3.09
110	50	6.84	3.11
120	51	6.89	3.13

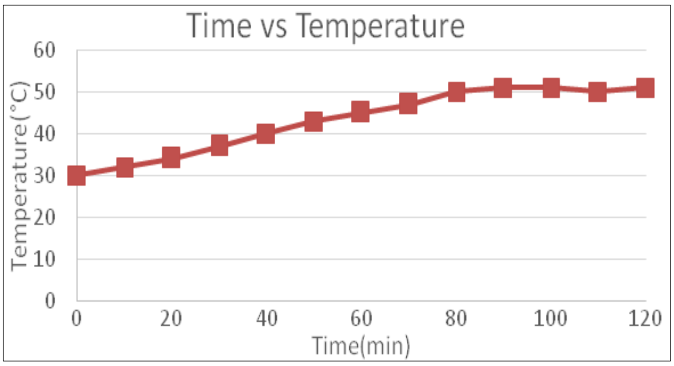

Fig 19: Integrated Heating Test

6.8 Cop of Integrated Model

V_{max} = 6.92 V
R_e = 2.2 Ω
I_{max} = 3.14 Amp
k = 1.20 W/mK
$\rho = R\frac{A}{l}$ = 0.352 Ωm
α = 0.1922 V/K
Z = 0.087 K^{-1}
Q_g =173.206 W
Q_j = 21.69 W
Q_d = 44.4 W
Q_c = 119.16 W
P_e = 134.73 W
For 3 Modules,
P_e = 404.19 W

COP = Q_c / P_e =0.294

It is found that the COP of integrated system is 0.294.

7. Conclusions

From the experiments and the analysis it is clear that even though lower and higher temperatures during cooling and heating test respectively are attained in cascade model than compared to integrated model, but it is found that performance and efficiency wise integrated model is better than cascaded model.

A common conclusion obtained from experiments conducted that the thermoelectric cooling and heating are not so effective if compared to refrigerators as the COP values obtained are very low and hence make it inefficient for daily purpose use.

Concerning performance aspects, for cooling applications in households conceived in a traditional way (e.g. refrigerators operating with a fixed temperature set point) the thermoelectric devices exhibit COP values typically below 0.5 for temperature differences of 20 K or higher. In this respect, thermoelectric refrigeration is not competitive with alternative solutions such as vapor-compression refrigerators (with COP of about 2.5). However, the interest in the use of thermoelectric refrigerators is increasing because of their useful controllability features. In fact, partial load operation is readily available by changing the electric current.

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