IOSR Journal of Mechanical and Civil Engineering (IOSR-JMCE)
e-ISSN: 2278-1684,p-ISSN: 2320-334X, Volume 16, Issue 4 Ser. I (Jul. - Aug. 2019), PP 68-75
www.iosrjournals.org

Development and Performance Evaluation of a Solar-powered Thermo-electric Water Dispenser

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Date of Submission: 01-07-2019 ate of acceptance: 16-07-2019

I. Introduction

Refrigeration is the science of providing and maintaining temperature below that of surrounding atmosphere, (Arora, 2008). There are many types of refrigeration systems but the commonest one is the vapour compression system. This system makes use of refrigerants that change phases in cyclic operation in order to achieve optimum performance of the equipment. The conventional refrigerants readily in use are classified into three; chlorofluorocarbons (CFCs), hydrochlorofluorocarbons (HCFCs) and hydrofluorocarbons (HFCs) refrigerants. The first two refrigerant classes have high depleting and global warming potentials while the third one meant to replace the CFCs and HCFCs has a very high global warming potential even though they do not deplete ozone. In essence all three refrigerant classes are greenhouse gases (GHGs).

In order to mitigate the effect of the ozone depletion and global warming, these refrigerants are to be phased out, and therefore alternative means of refrigeration has become a subject of great concern. Researchers are continuously making efforts for development of eco-friendly refrigeration technologies like thermoelectric, (Dai et al., 2003).

According to Mallikarjuna, (2015) the first and important discovery relating to thermo electricity occurred in 1823 when the German Scientist, Thomas Seebeck, found that an electric current would flow continuously in a closed circuit made up of two dissimilar metals provided that the junctions of the metals were maintained at two different temperatures. Some 12 years later French watchmaker, Jean Charles Athanase Peltier, discovered thermoelectric cooling effect, also known as Peltier cooling effect. Peltier discovered that the passage of current through a junction formed by two dissimilar conductors caused a temperature change. The true nature of Peltier effect was made clear by Emil Lenz in 1838. Lenz demonstrated that water could be frozen when placed on a bismuth-antimony junction by passage of electric current through the junction.

Thermoelectric refrigeration finds applications in electronic systems and computers to cool sensitive components such as power amplifiers and microprocessors; in a satellite or space application to control the extreme temperatures that occur in components on the sunlight side and to warm the components on the dark side; and to minimize thermal noise, thereby optimizing the sensitivity and image contrast as in digital cameras and charge coupled devices (CCDs) (Patil and Devade, 2015). It is also associated with thermoelectric generators and thermoelectric coolers which have no moving parts and requires little or no maintenance. The thermoelectric effect is the conversion of the thermal energy to electrical energy and vice versa due to the reversibility of the thermoelectric process. In the mode of the cooling or heating, a thermoelectric device (TED) converts the electrical energy to thermal energy, (HoSung, 2016).

Thermoelectric refrigeration system, is light, reliable, noiseless, rugged and low cost in mass production, uses electron rather than refrigerant as heat carrier, with low starting power and is feasible to be used in cooperation with solar cells (Saidur *et al.*, 2008). Han *et al.*, (2016) fabricated a small prototype of solar photovoltaic driven thermoelectric refrigerator for cold storage of food and medicines and carried out its experimental investigation for the analysis of system performance. The performance of the system depended on incoming solar isolation and the temperature difference between the hot and cold sides for thermoelectric cooler module.

Thermoelectric cooler works on the principle of Peltier effect, when a direct current is passed between two electrically dissimilar materials, heat is absorbed or liberated at the junction depends on the direction of current flow.

The direction of the heat flow depends on the direction of applied electric current and the relative seebeck coefficient of the two materials. Voltage is applied at the free ends of the two dissimilar metals, which causes temperature difference. This temperature difference, enables cooling due to peltier which causes heat to move from one end to another. Thermoelectric modules require heat sinks, fan, and cooling arrangement, (Manoj *et al.*, 2013).

Abdullah *et al*, (2009) carried out an experimental study on cooling performance of a developed hybrid Solar Thermoelectric-Adsorption cooling system. The developed system produced cooling via the Peltier effect during the day, by means of thermoelectric elements, and through adsorption (activated carbon-methanol) process at night. They reported that the evaluated coefficient of performance of the hybrid cooling system were 0.152 for thermoelectric system and about 0.131 for adsorption. Manoj *et al.*, (2016) developed experimental prototype with a refrigeration space of 1liter using four Peltier modules. They reported that, a reduction in temperature occurred from the initial temperature of 23 ^{o}C to 11$°C$ at no load within 120 minutes. It dropped to 9 $°C$ with 100 ml of water kept inside refrigeration space within 30 minutes. The COP of equipment was calculated to be 0.1. A solar thermoelectric refrigerator with modules was developed for the desert people living in Oman by Wahab *et al.*, (2009). The performance of the refrigerator with vaccines in the refrigerated space recorded a drop in temperature from 27°C to 5°C in approximately 44 min. The coefficient of performance of the refrigerator was calculated and found to be 0.16.

Darshan *et al.,* (2016) designed, fabricated and evaluated the performance of a thermoelectric refrigerator with four modules of 60 watts each. At no load condition, it took the system four minutes to reduce the temperature by 11$°C$. For load condition of 0.2736 litre of water it took 21 minutes to reduce the temperature by 8$°C$. The theoretical COP of the thermoelectric refrigeration system was found to be 0.548 while actual COP was 0.1939 for no load conditions and 0.03002 for the load conditions.

Totala *et al.*, (2014) studied and designed a Thermoelectric Air cooling and heating system for personal cooling and heating. Four TECs (TEC1-12706 of 48 W each) were used to achieve the cooling with a DC power supply through external power supply. Its results show that the cooling system is capable of cooling and heating the air when re-circulating the air with the help of blower.TEC cooling designed was able to cool an ambient air temperature from 32.5°C to 22.1°C with cross sectional area of 0.0054128 m^2 and volume flow rate was 0.02706 m^3 /s within ten minutes after the blower is turned on with a velocity of 2.5 m/s. They suggested the use of a single thermoelectric module of higher power of 200 W, a better cold side heat sink and a bigger heat sink for proper heat dissipation.

The input parameters in a thermoelectric refrigerating system affect its performance in various ways. For instance, Jaspalsinh *et al.*, (2012) found out that the COP of the system increased and attained an optimum with the application of increasing current to a certain level. Thereafter COP decreased as the current increased. The use of multi stage thermoelectric module, increased fin area of the heat sink and increased fan speed can improve the COP of a thermoelectric cooler (TEC) (Jatin Patel *et al*., 2016, Patiland Kulnarni, 2016). Adeyanju (2010), also reported that increase in number of thermoelectric modules and heat sinks increases the cooling rate for beverage chiller exponentially with time. The objective of this paper therefore is to develop and evaluate the performance of a solar-powered thermoelectric water dispenser.

II. Materials and Methodology

Calculations for the thermoelectric cooler module

The thermoelectric cooler module TEC 12706 has the following parameters as provided by the manufacturer:
The data sheet contains:
Temperature of the hot side $T_h = 50°C$; At $50°C$,

$$\Delta T_{max} = 76K, V_{max} = 16.8,\ I_{max} = 6.4,\ Q_c = 71.3W, T_h = 323K, T_c = 5°C\ = 278K$$

where, Q_c *is the rate of heat absorption at the cold junction;* T_h *is the hot junction temperature;* T_c *is the cold junction temperature;* I_{max} *is the maximum input current;* V_{max} *is the maximum direct current (DC) input voltage;* ΔT_{max} *is the maximum temperature difference at* I_{max} *and* V_{max}.

The SeeBeck Coefficient (α_m) of the thermoelectric cooling module is determined using equation (1) as suggested by (Rawat *et al*, 2013), and the value was fund to be 0.05201 V/K

$$\alpha_m = \frac{V_{max}}{T_h} \tag{1}$$

The thermoelectric module conductance (K_m) is calculated from equation (2),

$$K_m = \frac{(T_h - \Delta T_{max})V_{max} I_{max}}{2\Delta T_{max} T_h} \tag{2}$$

$$K_m = \frac{(323 - 76)16.8 \times 6.4}{2 \times 76 \times 323} = 0.5409W/K$$

The thermoelectric module resistance (R_m) of the module is calculated from equation (3) as given by (Rawat et al, 2013). The value was fund to be 2.007 Ω

$$R_m = \frac{(T_h - \Delta T_{max})V_{max}}{I_{max}T_h} \qquad (3)$$

The electrical current the module (I) used was calculated from equation (4), suggested by (Kaushik et al, 2016). The value was fund to be 4.81 A

$$I = \frac{(V - \alpha(T_h - T_c))}{R} \qquad (4)$$

The electrical input power (P_{in}) required by the thermoelectric cooler module is as stated in equation (5) (Kaushik et al, 2016). The estimated value is 57.69 W.

$$P_{in} = \alpha I(T_h - T_c) + I^2 R_m \qquad (5)$$

The cooling power (Q_c) of the thermoelectric cooler was calculated from equation (6) , (Rawat et al, 2013). The value was fund to be 21.99 W

$$Q_c = \left(\alpha I T_c - \frac{I^2 R_m}{2} - K_m(T_h - T_c)\right) (6)$$

The theoretical coefficient of performance (COP) of individual module is given as equation (7) (Kaushik et al, 2016), with average value of 0.381.

$$COP = \frac{Q_c}{P_{in}} \qquad (7)$$

Product Load Calculation

The amount of heat released by 4 kg of water which is assumed to be in the cooling chamber of the dispenser was calculated as stated in equation (8).

C_p of water is 4178 J/kg.K

$Starting\ Temperature\ is\ 30°C;\ Final\ Temperature\ is\ 5°C;\ \Delta T = 30 - 5 = 25°C$

Assuming a cooling time of 2 hours, then, $dt = 2hrs = 7200sec$

The product heat load (Q_1) is the heat removed from the mass of water which is inside the cooling chamber of the dispenser. The rate of heat removal is given in equation (8) (ASHRAE, 2001). The rate of heat removal was estimated to be 58.03 W.

$$Q_1 = \frac{mc_p\Delta T}{dt} \qquad (8)$$

Infiltration Load (Q_2)

This is calculated for the heat gain due to heat coming into the enclosed space of the dispenser through the lid as stated in equation (9) (ASHRAE, 2002)..

$$Q_2 = \dot{m}(h_0 - h_i) \qquad (9)$$

$$\dot{m} = \frac{4}{60} = 0.067L/s$$

From the steam Table, $h_o\ at\ 30°C$ = 100.006 kJ/kg; $h_1\ at\ 5°C$ = 18.639 kJ/kg

Therefore: $Q_2 = 0.000067(100.006 - 18.639) =$ 5.452 W

Transmission Load (Q_3)

The amount of heat that flows into the enclosed space of the storage tank of the dispenser is calculated from equation (10) (ASHRAE, 2001). The value was fund to be 1.99 W.

$$Q_3 = \frac{A\Delta T}{\frac{x}{k} + \frac{1}{h}} = \frac{hkA\Delta T}{hx + k} \qquad (10)$$

where: A = 0.25 x 0.25 = 0.0625m^2*;* ΔT *= 25°C; x = 0.03m; K = 0.044 W/m.K , h = inside conductance 10 W/m*^{2}*K* ***(ASHRAE, 2001)***

Safety Factor (Q_4)

This is calculated from equation (11) to be 13.09 W.

$$Q_4 = 20\% * (Q1 + Q2 + Q3) \qquad (11)$$

The total heat (Q_{TOTAL}) removed is calculated from equation (12)

$$Q_{TOTAL} = Q_1 + Q_2 + Q_3 + Q_4 \qquad (12)$$

$Q_{TOTAL} = 58.03 + 5.452 + 1.99 + 13.09$ = 78.562W

Number of module (N) used by the system was calculate as given in equation (13)

$$N = \frac{Q_{TOTAL}}{Q_C} \qquad (13)$$

$$N = \frac{78.562}{21.99} = 3.6$$

Therefore 4 units of Thermoelectric Cooler Module was adopted.

Power Consumption

Power (*P*) consumed by each module is obtained using equation (14), to be 57.72 W

$$P = IV \qquad (14)$$

The heat sink fan is selected based on the basis of the thermal resistance (R_{th}) as suggested by (Rawat *et al*, 2013) as given in equation (15).

$$R_{th}(for\ fan\ selection) = \frac{T_h - T_\infty}{Q_h} \qquad (15)$$

$$R_{th} = \frac{50 - 30}{57.72 + 46.13} = 0.193K/W$$

Four modules will be used for the work for faster cooling which was assumed to consume 230.88 W

The number of hours (N_s) (Battery life) the dispenser will run on battery as backup was determined using equation (16). The value was fund to be 5.6 hours.

$$\text{Number of Hours} = \frac{1\ x\ B_v\ x\ B_I}{Load\ Power} \qquad (16)$$

The amount of current (Bc) that will charge the battery is calculated from equation (17), to be 10.8 A.

$$Bc = \frac{1}{10}\ x\ Battery\ capacity \qquad (17)$$

Therefore two solar panels of 130 W each, will deliver a total of 260 W power to run the system and charge the battery.

Heat Sink Design Calculation

The heat sink used for this work was selected based on the design calculation to effectively dissipate heat away from the hot side of the thermoelectric cooler module to increase the overall coefficient of performance of the dispenser. Dimension of the heat sink used is as follow:

$l = 0.07$ m; W = 0.07 m; $t_f = 0.001$ m

The total heat transfer area (*A*) was calculated to be 3.246 m^2 using equation (18). The value was fund to be 3.246 m^2

$$A = n_f[2(l + t_f) + ls_f] \qquad (18)$$

The optimum spacing between the fins ($s_{f\,(opt)}$) was estimated using equation (19). The value was fund to be 8.6 mm

$$s_{f\,(opt)} = 2.714 \frac{l}{Ra^{1/4}} \qquad (19)$$

The properties of air evaluated at film temperature (T_f) is 313 K calculated from equation (20)

$$T_f = \frac{T_s + T_\infty}{2} \qquad (20)$$

$T_s = 50°C$; $T_\infty = 30°C$

$$T_f = \frac{50+30}{2} = \frac{80}{2} = 40°C = 313K$$

The properties of air are evaluated at the film temperature: k = 0.0299 W/mK; v = 20.94 x 10^{-6} m^2/s; Pr = 0.708

$$\beta = \frac{1}{T_f}$$

$$\beta = \frac{1}{313} = 0.003195/K$$

$$Ra = \frac{g\beta\,(T_s - T_\infty)l^3}{v^2} Pr \qquad (21)$$

$$Ra = \frac{9.8\ x\ 0.003195\,(50-30)0.07^3}{(20.94\ x\ 10^{-6})^2} 0.708 = 1.011\ x\ 10^6$$

The heat transfer coefficient (*h*) for optimum spacing was calculated to be 4.575 W/mK using equation (22)

$$h = 1.31 \frac{k}{s_{f\ (opt)}} \qquad (22)$$

The number of fins (n_f) for the heat sink was determined using equation (23)

$$n_f = \frac{w}{s_{f\ (opt)} + t_f} \qquad (23)$$

$$n_f = \frac{0.15}{0.00856 + 0.001} = 15.69 \approx 16 \text{ fins}$$

The rate of heat transfer (Q) was calculated from equation (24), and the value is 297.01 W

$$Q = hA(T_s - T_\infty) \qquad (24)$$

Table 1 gives the summary of the parameters calculated with the calculated value

The Coefficient of Performance of the System

The coefficient of performance of the system was calculated from equation (25)

$$COP = \frac{Q_a}{P_{in}} \qquad (25)$$

$$Q_a = \frac{mc_p\Delta T}{dt}$$

The COP of the system when 1.5 L of water was chilled for 405 mins (24,900 seconds) was calculated as

$$Q_c = \frac{0.5 \times 4178 \times (38 - 18)}{24900} = 1.67W$$

P = 29.87 W

$$\text{COP} = \frac{1.67}{29.87} = 0.06$$

The COP of the system when 1 L of water is chilled for 551 minutes (33,060 seconds) is 2.59 W for Power (P) of 29.87 W

$$Q_c = \frac{1 \times 4178 \times (38.5 - 18)}{33{,}060} = 2.59W$$

$$\text{COP} = \frac{2.59}{29.87} = 0.09$$

The overall COP of the system was calculated as (0.06 + 0.09)/2 = 0.08. Further explanation and calculations can be found in the work of Akande, (2019)

Table 1: Summary of the parameters and values used

S/n	Parameters	Equations	Estimated Value	Used Value
1	α_m	$\alpha_m = \frac{V_{max}}{T_h}$	0.05201 V/K	0.05201 V/K
2	K_m	$K_m = \frac{(T_h - \Delta T_{max})V_{max}I_{max}}{2\Delta T_{max}T_h}$	0.5409 W/K	0.5409 W/K
3	R_m	$R_m = \frac{(T_h - \Delta T_{max})V_{max}}{I_{max}T_h}$	2.007 Ω	2.0 Ω
4	I	$I = \frac{(V - \alpha(T_h - T_c))}{R}$	4.81 A	3.00 A
5	P_{in}	$P_{in} = \alpha I(T_h - T_c) + I^2R$	57.69 W	57.69 W
6	Q_c	$Q_c = \left(\alpha IT_c - \frac{I^2R_m}{2} - K_m(T_h - T_c)\right)$	21.99 W	21.99 W
7	Q_1	$Q_1 = \frac{mc_p\Delta T}{dt}$	58.03 W	58.03 W
8	Q_2	$Q_2 = \dot{m}(h_o - h_i)$	5.452 W	5.452 W
9	Q_3	$Q_3 = \frac{A\Delta T}{\frac{x}{k} + \frac{1}{h}} = \frac{hkA\Delta T}{hx + k}$	1.99 W	1.99 W
10	Q_4	$Q_4 = 20\%\ x\ (Q_1 + Q_2 + Q_3)$	13.09 W	13.09 W
11	N	$N = \frac{Q_{TOTAL}}{Q_c}$	3.6	4
12	A	$A = n_f[2(l + t_f) + ls_f]$	3.246 m^2	3.85 m^2

13	$s_f\ (opt)$	$s_{f\ (opt)} = 2.714 \frac{l}{Ra^{1/4}}$	8.6 mm	8.6 mm
14	n_f	$n_f = \frac{w}{s_{f\ (opt)} + t_f}$	16 fins	19 fins

III. Results and discussion

Energy from the sun was utilized to run the system which runs on 12 V DC power. The power consumption of the system changes with time (Fig. 1) based on the current drawn by the modules, fan and other components.

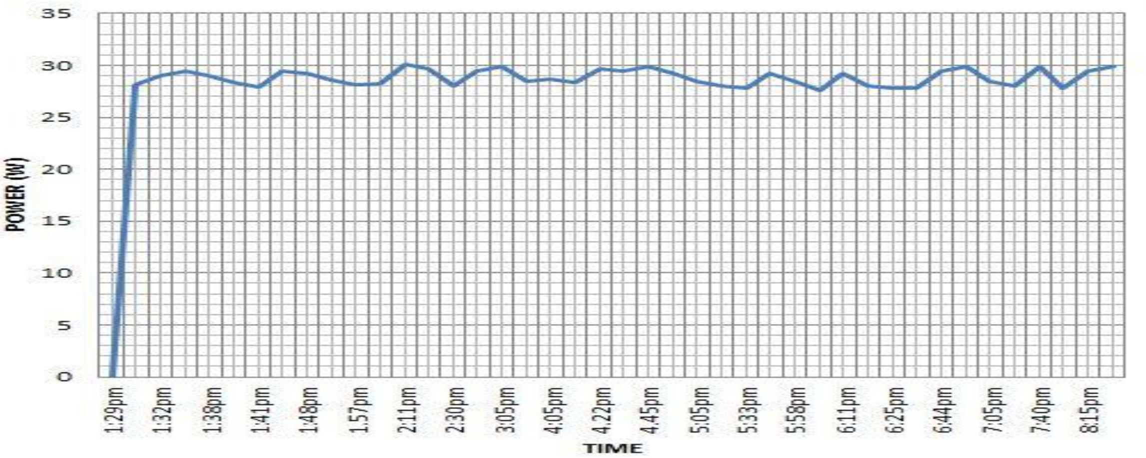

Fig. 1: Plot of power consumption of the system against time

Figure 1 shows the power consumption of the dispenser over the period of seven (7) hours. There are upward and downward variation of power consumption due to the cooling load and the current draw by the components in the system at different rates. The maximum power consumed by the dispenser during the experimentation was 29.87 W.

The plot of temperature variation with time interval is presented in Figure 2.

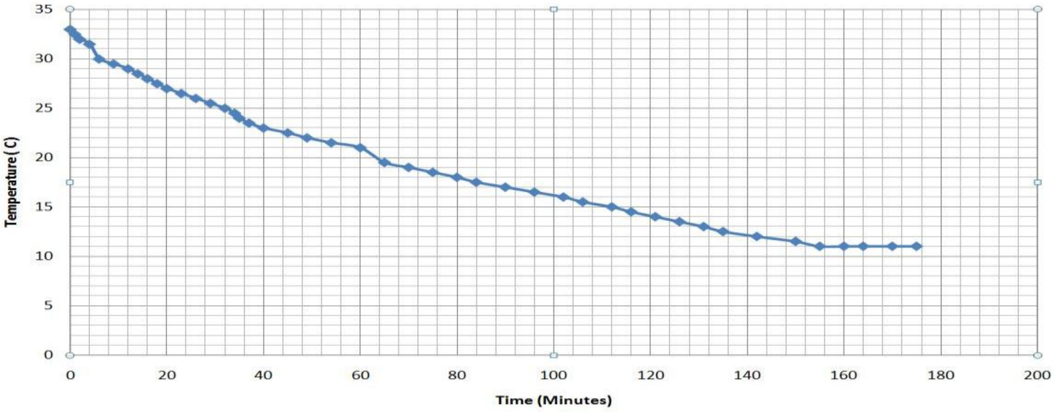

Fig. 2: Plot of temperature variation against time at no load

It shows that temperature fell from 33°C to about 11°C within 176 minutes in the thermoelectric water dispenser at no load condition. This inverse relationship of temperature with time agrees with the work of Rawat, *et al*. (2013).

Temperature change when 50 cl of water in the cooling tank

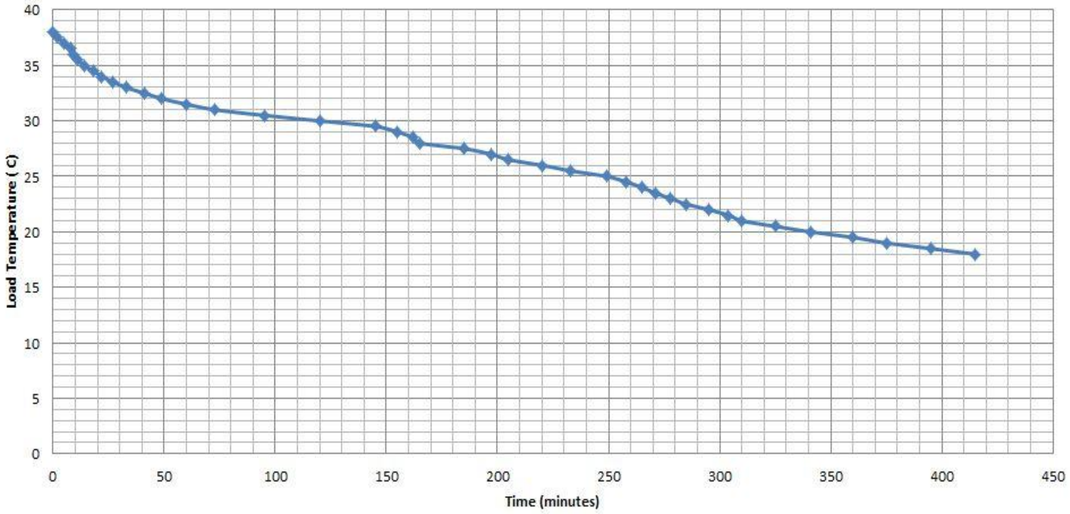

Fig. 3: Plot of temperature against time for 0.5 litre of water.

Figure 3 shows the temperature variation of 0.5 litres of water in the dispenser over a period of 415 minutes of operation. The initial temperature of the water was 38 °C. There was a temperature drop of 4 °C in 60 minutes as the cooling process progresses there was further drop in temperature of water to 18 °C after 360 minutes. The minimum temperature achieved after 7 hours of operation is 18 °C. There was a temperature difference of 20°C. The plot was similar to those obtained by Shetty *et al*. (2016).

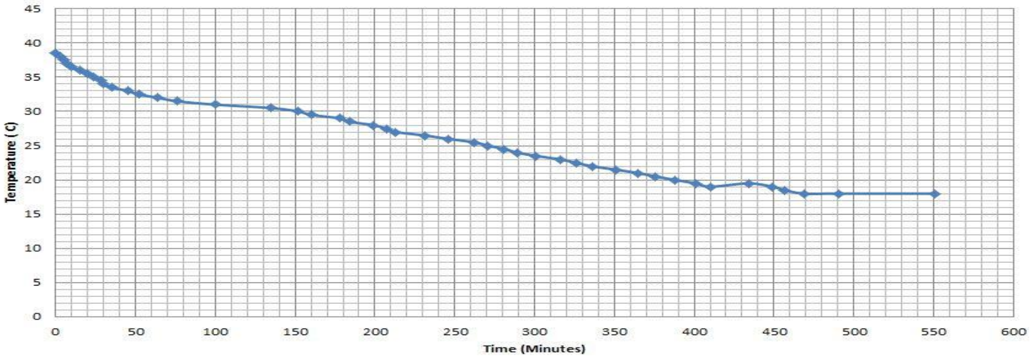

Fig. 4: Plot of temperature against time for 1 litre of water.

Figure 4 shows the temperature variation of one (1) litre of water for 551 minutes of operation of the dispenser. The minimum temperature achieved was 18°C.

IV. Conclusion

The thermoelectric water dispenser recorded power consumption within 27.90 W, being the lowest and 30.10 W, the highest. The dispenser at no load had a temperature drop of 11°C from the ambient 33 °C within seven hours. When it contained 0.5 litres of water, it took 415 minutes for the temperature to drop from 38 °C to 18 °C and 551 minutes for the dispenser to maintain this temperature with one litre of water in it. It is therefore concluded that the thermoelectric cooling system is a promising alternative to the vapour compression system in this regard.

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Akintunde, M. A. “Development and Performance Evaluation of a Solar-powered Thermo-electric Water Dispenser.” IOSR Journal of Mechanical and Civil Engineering (IOSR-JMCE) , vol. 16, no. 4, 2019, pp. 68-75.