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Experimental investigation of thermoelectric refrigeration system running on solar energy and development of mathematical model

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ABSTRACT

Experimental investigation of thermoelectric refrigeration system running on solar energy has been explained in detail also mathematical and theoretical characteristics of thermoelectric cooling model (Peltier module) designed and used in this research. In conventional refrigeration system use some rotating or mechanical part like compressor, evopourator, expansion valve etc. due to this rotating part, system is very complicated and some vibrations and noise are produced. But in thermoelectric refrigeration system all mechanical part are eliminated and it replaced by thermoelectric module. A thermoelectric module works on peltier effect to create a hot side and cold side, the cold side of thermoelectric module is used in refrigerator space for cooling purpose and hot side is used to rejection of heat to the atmosphere by using heat sink.

The developed experimental investigation having a refrigeration load of 0.5 liter capacity is refrigerated by using two number of Peltier module (TEC 1-12706) and heat sink fan assembly (MODEL NO. – REC 9225 A 12 MW) used to increase heat dissipation rate from hot side of peltier module. Experiments were conducted on developed prototype and mathematical model of thermoelectric refrigeration system and results obtained a temperature reduction of 24^{0} C in 7 minutes with respect to 32 ^{0}C ambient temperature. The coefficient of performance of thermoelectric refrigeration system was calculated and found to be about 0.35 to 0.69

Keywords -. **Thermoelectric refrigeration (TER), Peltier module, figure of merit, solar energy, coefficient of performance (COP).**

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I. INTRODUCTION

With the increase awareness towards environmental degradation due to the production, use and disposal of Chloro Fluoro Carbons (CFCs) and Hydro Chlorofluorocarbons (HCFCs) as heat carrier fluids in conventional refrigeration and air conditioning systems. Thermoelectric refrigeration is new alternative because it can convert waste electricity into useful cooling, is expected to play an important role in today's energy challenges. It does not require working fluids or any moving parts, which is friendly to the environment and it simply uses electrons rather than refrigerants as a heat carrier. Continuous efforts are given by researchers for development of thermo electric materials with increase figure of merit may provide a potential commercial use of thermoelectric refrigeration system.

Proposed work concentrates on development of renewable energy (solar) based TER system and its performance evaluation along with mathematical modeling. Efforts can be made to increase the COP of the system by increasing the rate of convectional heat transfer and selection of thermoelectric module with higher figure of merits. The development of renewable energy based TER system and proposed design and development an experimental thermoelectric refrigeration system having a refrigeration space of 0.5 liter is cooling by numbers of thermoelectric cooling module and a heat sink fan assembly for each thermoelectric module used to increase heat dissipation rate also time required attaining the cooling after a solar power is applied. Proposed prototype consists of a thermoelectric module, array of solar cell, controller, storage battery and heat sink fan. The proposed work for increase COP is possible through improvements in module contact resistances, thermal interfaces the surface area of the fins should increase also the increase the rate of convectional heat transfer and the higher the figure of merits of the thermoelectric module.

Therefore, thermoelectric refrigeration is greatly needed, particularly for developing countries where long life and low maintenance are needed. Generally the COP of a thermoelectric refrigerator is found to be 0.35-0.69 for a typical operating temperature of 8 ^{0}C with ambient at 32 ^{0}C.

II. LITERATURE REVIEW

Solar refrigeration may be accomplished by using one of the following refrigeration systems: vapor compression, sorption or thermoelectric refrigeration systems. The first two systems need high and low pressure sides of a working fluid to complete the refrigeration cycle, and are somewhat difficult to be developed into a portable and light solar device used outside. The thermoelectric refrigeration system, which has the merits of being light, reliable, noiseless, rugged, and low cost in mass production, uses electrons rather than refrigerant as a heat carrier, and is feasible for outdoor purposes in cooperation with solar cells, in spite of the fact that its coefficient performance is not as high as for a vapor compression cycle [1]. In past years, much work has been reported on thermoelectric cooling [2–6]. The thermoelectric refrigeration system is having potential application of storage and transportation of life saving drugs and biological materials at remote areas of our country where grid power is unavailable. P.K. Bansal [7] has compared the performance of vapor compression, thermoelectric and absorption refrigerators. T. Hara [8] investigated a solar cell driven, thermoelectric cooling prototype headgear for outside personal cooling. V.C. Mei [9] studied a solar assisted automobile thermoelectric air-conditioner. Dai et al. [10] developed a thermoelectric refrigeration system powered by solar cells and carried out experimental investigation and analysis. Researchers developed a prototype which consists of a thermoelectric module, array of solar cell, controller, storage battery and rectifier. The studied refrigerator can maintain the temperature in refrigerated space at 5–10^{o}C, and has a COP about 0.3 under given conditions. Wahab et al. [11] have designed and developed an affordable solar thermoelectric refrigerator for the desert people living in Oman where electricity is not available. In this study, they used 10 nos. of thermoelectric module in design of refrigerator. The experimental results indicated that the temperature of the refrigeration was reduced from 27^{0}C to 5^{0}C in approximately 44 min. The coefficient of performance of the refrigerator was calculated and found to be about 0.16. Abdullah et al. [12] have 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 evaluate the coefficient of performance by using derived equations, the average COP values of the hybrid cooling system were found about 0.152 for thermoelectric system and about 0.131 for adsorption. Thermoelectric cooling 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. The direction of the heat flow depends on the direction of applied electric current and the relative Seebeck coefficient of the two materials. The thermoelectric refrigerator is a unique cooling device, in which the electron gas serves as the working fluid. In recent years, concerns of environmental pollution due to the use of CFCs in conventional domestic refrigerators have encouraged increasing activities in research and development of domestic refrigerators using Peltier modules. Moreover, recent progress in thermoelectric and related fields have led to significant reductions in fabrication costs of Peltier modules and heat exchangers together with moderate improvements in the module performance. It is now possible to develop an economically-viable thermoelectric refrigerator which has improved performances and the inherent advantages of environmentally-friendly silent operation, high reliability, and ability to operate in any orientation. Although the COP of a Peltier module is lower than that of conventional compressor unit, efforts have been made to develop thermoelectric domestic refrigerators to exploit the advantages associated with this solid-state energy-conversion technology (Min and Rowe, 2006).[13]

For utilizing solar energy efficiently and cost effectively, proper design of reliable solar devices and system have to be attempted to suit the radiation climate and socioeconomic conditions. From this perspective, sizing of PV system involves finding the cheapest combination of array size and storage capacity that will meet the anticipated load requirement with the minimum acceptable level of security. The information required is including the daily or hourly load requirement, peak current and voltage characteristics of the solar module, the number of autonomous days, the estimated percentage of energy losses in the battery and power conditioning equipment, and the estimated losses in the array due to module mismatch, cable, dust and shading (Bhuiyan and Asgar, 2003; Kaushika et al., 2005).[14-15] Francis et al.[16] evaluated the performance of thermoelectric refrigerator. The research focused on simulation of a thermoelectric refrigerator maintained at 4oC. The performance of the refrigerator was simulated using Matlab under varying operating conditions. The system consisted of the refrigeration chamber, thermoelectric modules, heat source and heat sink. Results show that the coefficient of performance (C.O.P) which is a criterion of performance of such device is a function of the temperature between the source and sink. For maximum efficiency the temperature difference is to be kept to the barest minimum.

Rawat et al.[17] presented the Design and developmental methodology of thermoelectric refrigeration in detail also the theoretical physical characteristics of thermoelectric cooling module used in his research work have been investigated. Authors have been designed and developed an experimental prototype of thermoelectric refrigeration system working on solar photo voltaic cells generated DC voltage. The developed experimental prototype having a refrigeration space of 1 liter capacity is refrigerated by using four numbers of Peltier module (Super cool : PE-063-10-13, Qmax=19W) and a heat sink fan assembly used (Model No: TDEX6015/TH/12/G, Rth=1.157 ^{0}C /W) to increase heat dissipation rate from hot side of Peltier module. The experimental result shows a temperature reduction of 11^0C without any heat load and 9^0C with 100 ml water kept inside refrigeration space in 30 minute with respect to 23^0C ambient temperature. Also the COP of refrigeration cabinet has been calculated and it is 0.1.

III.THERMO PRINCIPLE OF WORKING

Thermoelectric modules are solid-state heat pumps that operate on the Peltier effect. A thermoelectric module consists of an array of p and n-type semiconductor elements that are heavily doped with electrical carriers. The elements are arranged into array that is electrically connected in series but thermally connected in parallel. This array is then affixed to two ceramic substrates, one on each side of the element. The p-type semiconductor is doped with certain atoms that have fewer electrons than necessary to complete the atomic bonds within the crystal lattice. When a voltage is applied, there is a tendency for conduction electrons to complete the atomic bonds. When conduction electrons do this, they leave “holes” which essentially are atoms within the crystal lattice that now have local positive charges. Electrons are then continually dropping in and being bumped out of the holes and moving on to the next available hole [8]. In effect, it is the holes that are acting as the electrical carriers.

Now, electrons move much more easily in the copper conductors but not so easily in the semiconductors. When electrons leave the p-type and enter into the copper on the cold-side, holes are created in the p-type as the electrons jump out to a higher energy level to match the energy level of the electrons already moving in the copper. The extra energy to create these holes comes by absorbing heat. Meanwhile, the newly created holes travel downwards to the copper on the hot side. Electrons from the hot-side copper move into the p-type and drop into the holes, releasing the excess energy in the form of heat.

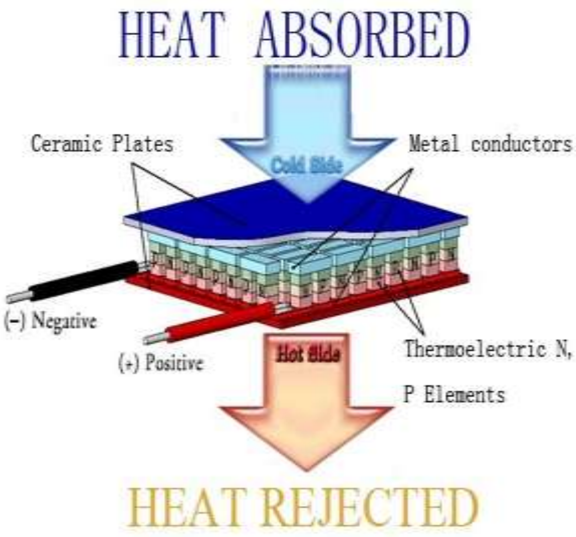


Fig. No.1 working principle of TE module[ ]

The n-type semiconductor is doped with atoms that provide more electrons than necessary to complete the atomic bonds within the crystal lattice. When a voltage is applied, these extra electrons are easily moved into the conduction band. However, additional energy is required to get the n-type electrons to match the energy level of the incoming electrons from the cold-side copper. The extra energy comes by absorbing heat. Finally, when the electrons leave the hot-side of the n-type, they once again can move freely in the copper. They drop down to a lower energy level, and release heat in the process.

IV. NOMENCLATURE

A	Cross sectional area
COP	Coefficient of performance
Δ E	EMF output
I	Current
K	Thermal conductivity
L	Length
Le&Lph	Dimensionless Lorenz number
NS	Dimensionless entropy generation
Q	heating and cooling rate
q_h	Heat rejection
q_c	heat absorption
R	Electric Resistance
R_f	heat sink resistance factor
Sg	Entropy generation rate
T	Temperature
Δ T	Temperature Difference
TER	Thermoelectric refrigerator
TEC	TEC Thermoelectric cooler
U	Overall conductance
UA	cabinet thermal conductance
P	power consumption
Z	Figure of merit

Greek letters

A	See beck coefficient
τ	Thomsion coefficient

ρ Specific resistance
π_{ab} Peltier coefficient
ε ideal coefficient of performance

V. EXPERIMENTAL SETUP

Design and developed an experimental thermoelectric refrigeration system with a refrigeration space of 0.5Liter capacity with outer casing of MS sheet and for thermal insulation a Glass wool sheet has been provided inside the box to prevent reversal of heat flow. A thin aluminium sheet (0.4mm) box has been fixed inside the MS box for uniform distribution of temperature.

Two numbers of thermoelectric modules (TEC1-12706) have been used to reduce inside temperature of refrigeration space. Cold side of TEM mounted on Aluminium sheet and hot side of modules were fixed with heat sink fan assembly. Two numbers of fin heat sink fan assembly (MODEL NO. – REC 9225 A 12 MW) were used for each module to enhance the heat dissipation rate.

System design calculations:

- Desired temperature of cold compartment:8°C
- Ambient temperature : 32^0C
- Required time for desired cooling:7 minutes
- Mass of water to be cooled : 0.5 Kg

Using Newton's law of cooling:

qc= mCp× (Tamb-Tc)

= 0.5×4180(32 - 8)

qc =50232 J

qc=50232 / (7 x 60)

qc =119.6 watt

Dimensions of cabinet is 10cm x10cm x 15cm And thermal conductivity of aluminium is 167 W/M k, To find hot side temperature of TE Modules, Th; keeping heat sink at 150C above ambient temperature:

Th = Tamb+15^0C = 32 + 15 = 47^0C

Now, temperature difference ΔT across the TE module can be calculated as follows,

ΔT= (Th-Tc) = 47 – 8 = 39^0C

So, 39^0C will be used for design calculations parameters to be used for TE module selection,

Q = 60 W, ΔT = 39^0C

TABLE I
Specification of TE module

Type	I_{max} (A)	V_{max} (v)	Q_{max} (w)	ΔT (^{0}C)	R (ohms)
TEC1-12706	6.4	14.4	60	39	1.98

Thermal resistance e of heat sink,

$$R_{hs} = \frac{T_h - T_a}{VI + Q_{Tec}}$$

R_{hs} = 0.049 K/W

A heat sink of rating 0.049 k/w or less must be use with each TEC module.

TABLE II
Specification of heat sink fan

Model	Voltage (V)	Current (I)	Input power (W)	Speed (rpm)	Air flow (CFM)
9225 A12MW	12	0.14	1.68	2600	46

Selection of solar panel first we have to need calculation of total load:-

In solar panel two loads are act is given below

Total power consume by module-

= 60 per module × (use two modules)

= 60 × 2= 120 watt

Power required to drive fan=1.68 × Two fans

= **3.36 watt**

Total power / load on the system = Total power consume by module + Power required to drive a fan

Total power load on the system = 120 watt + 3.36 watt

Total power /load on the system = **123.36 watt**

To design a solar panel at **123.36 watt** load

1 cell produce 1.8 watt power

Hence no. of cell required = total load on the system/1.8

= 123.36/1.8

No. of cell required = **68 cell**

125 W solar panel as per standard

Fig. no. 2 Experimental setup of proposed system

Testing the performance of the thermoelectric refrigeration:

When designed prototype was tested, it was found that the inner temperature of the refrigeration area was reduced from 32^0C to 8^0C in approximately 7minutes, i.e. 240C. Following example shows how the coefficient of performance was calculated. It was assumed that the refrigerator used to cool a 0.5 L from 320C to 80C in 7 Min.

Calculate COP;

COP = Qc / Win

Where, Qc=119.6 W

Win = VI = 14.4 X 6.4

Win = 92.16 W

Win = 92.16 X 2 (no. of module) = 184.32 J

COP = 119.6 / 184.32

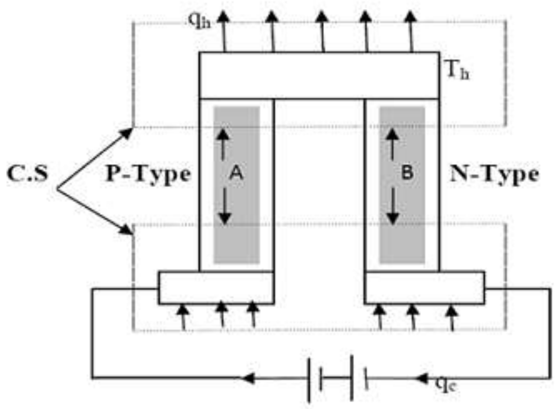
COP = 0.648

VI. MATHEMATICAL MODELING

For analyzing the system to obtain refrigeration effect, cop, etc. Following assumptions are made:

1. Heat transfer takes place through semiconductors at the end only.
2. No energy exchange between elements through space separating them.
3. Property such as conductivity, resistance etc. Are invariant with temperature

A



(a)

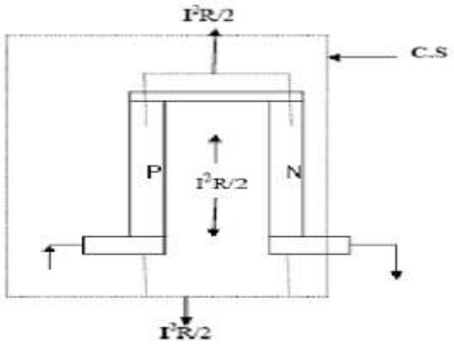


Fig. (a) & (b) Energy transfer in thermoelectric system

Now cooling and heating due to thermoelectric effect is given

$$q_c = \alpha_{ab}\, IT_c$$

$$q_h = \alpha_{ab}\, IT_h$$

As the Fig (b) Shown the heat generation in the absence of other effects will lead to beat transfer from both hot and cold ends equal to1/2 I2R. The conduction effect along the element leads to heat transfer at the cold junction from hot one.

And for cooling junction,

$$q_c + U(T_h - T_c) + \frac{RI^2}{2} = \alpha_{ab}\, I\, T_c$$

And for hot junction,

$$q_h + U(T_h - T_c) = \alpha_{ab}\, I\, T_h + 0.5\, I^2R$$

Thus the thermoelectric cooling is,

$$q_c = N[\alpha_{ab}\, IT c - U(T_h - T_c)$$

And for heating

$$q_h = N[\alpha_{ab}\, IT_h + \frac{RI^2}{2} - U(T_h - T_c)$$

Now using first law, one obtains energy input to the system from outside as:

$$q_{net} = -[\alpha_{ab}\, I(T_h - T_c) + \frac{RI^2}{2}]$$

Where negative sign indicates energy supplied to the system,

The required COP is:

$$Cop = \frac{qc}{energy\ suplied}$$

$$COP = \frac{[\alpha_{ab}\, IT_h - \frac{RI^2}{2} - U(T_h - T_c)}{[\alpha_{ab}\, I(T_h - T_c) + \frac{RI^2}{2}\,]}$$

VII. RESULT AND DISCUSSION

First experiments were conducted for performance evolution of above specified two thermoelectric cooling modules. The performance of TEM was evoluted at variable input electrical current conditions. In this section, we are discusses the analysis of thermoelectric refrigeration system by varying the various parameters like current and time.

The experimental results figure (c) shows that variation cold side temperature with respect to time. It shows that change in cold side temperature decreases with time exponentially.

The experimental results figure (d) shows that variation cold side temperature with respect to current. It shows that change in cold side temperature decreases with time exponentially.

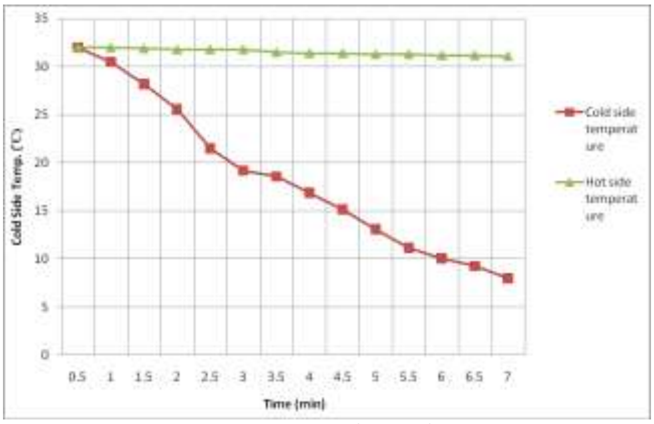


Fig.(c)Relaionship between temprature of sides of thermoelectric module & time

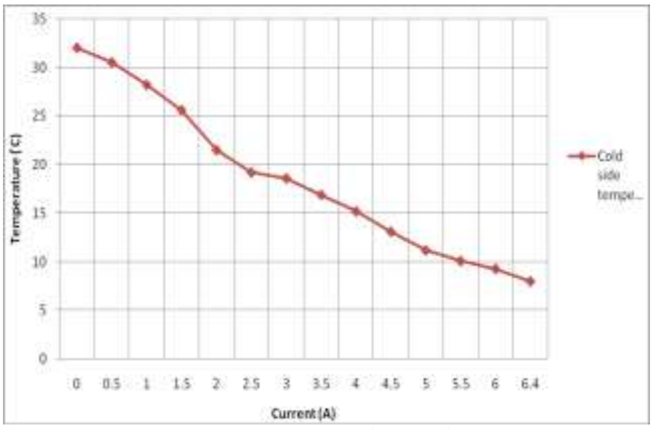


Fig.(d) Relaionship between temprature of sides of thermoelectric module & Current

VIII. CONCLUSION

Present study developes a design of thermoelectric cooler (Peltier module) and suggest a suitable data required to thermoelectric cooler also determine physical properties and performance of thermoelectric refrigeration system. Present study also developes and optimization design method for thermoelectric refrigerator. The proposed simple model in used in the optimization of real thermoelectric refrigerator. Thermo electrical analysis results have indicated that under given condition, there are optimal allocation ratio of the total thermal conductance that can maximize that TEC cooling capacity and COP respectively. The energy efficiency of thermoelectric refrigerators, based on currently available materials and technology, is still lower than its compressor counterparts. However, a marketable thermoelectric refrigerator can be made with an acceptable COP.

Further improvement in the COP may be possible through improving module contact resistance, thermal interfaces and heat exchanger. With its environmental benefit, thermoelectric refrigerator provides an alternative to consumer who is environmentally conscious and willing to spend a little bit more money to enjoy their quiet operation, and more precise and stable temperature control.

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REFRENCES

[1] [1] Sofrata H. Heat rejection alternatives for thermoelectric refrigerators. Energy Conversion and Management 1996;37(3):269–80.

[2] Min Gao, Rowe DM. Cooling performance of integrated thermoelectric microcooler. Solid-State Electronics 1999;43:923–9.

[3] Khedari J, Maneewan S, Pratinthong N et al. Domestic hot water system combining solar and waste heat from thermoelectric air-conditioner. International Journal of Ambient Energy 2001;22(1):19–28.

[4] Chen K, William SBB. An analysis of the heat transfer rate and efficiency of thermoelectric cooling systems. International Journal of Energy Research 1996; 20:399–417.

[5] Chen J, Andresen B. The maximum coefficient of performance of thermoelectric cooling systems. International Journal of Ambient Energy 1996;17:22–8.

[6] Winder EJ, Ellis AB. Thermoelectric devices: solid-state refrigerators and electrical generators in the classroom. Journal of Chemical Education 1996; 73(10):940–6.

[7] Bansal PK, Martin A. Comparative study of vapor compression, thermoelectric and absorption refrigerators. International Journal of Energy Research 2000; 24:93–107.

[8] Hara T, Azum H. Cooling performance of solar cell driven, thermoelectric cooling prototype headgear. Applied Thermal Engineering 1998; 18:1159–69.

[9] Mei VC, Chen FC, Mathiprakasam B, Heenan P. Study of solar-assisted thermoelectric technology for automobile air conditioning. Journal of Solar Energy Engineering, Transactions of the ASME 1993;115(4):200–5.

[10] Wang RZ, Dai YJ. Solar thermoelectric refrigerator, 2001, Patent, No. 01239142.5, China.

[11] Abdul-Wahab Sabah A., Elkamel A., Al-Damkhi Ali M., Al-Habsi Is'haq A., Al-Rubai'ey' Hilal S., Al-Battashi Abdulaziz K., Al-Tamimi Ali R., Al-Mamari Khamis H. & Chutani Muhammad U., Design and experimental investigation of portable solar thermoelectric refrigerator, Renewable Energy, 34(1), 2009, 30-34

[12] .Abdullah M. O., Ngui J. L., Hamid K. Abd., Leo S. L., & Tie S. H., Cooling Performance of a Combined Solar Thermoelectric-Adsorption Cooling System: An Experimental Study, Energy Fuels, 23, 2009, 5677-568

[13] Min, G., Rowe, D.M. (2006) Experimental evaluation of prototype thermoelectric domestic-refrigerator. Applied Energy. 83. 133-152.

[14] Bhuiyan, M.H.H., Asgar M.A. (2003). Sizing of a standalone photovoltaic power system at Dhaka. Renewable Energy. 28. 929-938.

[15] Kaushika, N.D., Gautam, N.K., Kaushik, K. (2005). Simulation model for sizing of stand-alone solar PV system with interconnected array. Solar Energy Material & Solar Cells. 85. 499-519.

[16] Onoroh Francis, Chukuneke Jeremiah Lekwuwa, Itoje Harrison John," Performance Evaluation of a Thermoelectric Refrigerator" International Journal of Engineering and Innovative Technology (IJEIT) Volume 2, Issue 7, January 2013.

[17] Manoj Kumar Rawat, Prasanta Kumar Sen, Himadri Chattopadhyay, Subhasis Neogi, " Developmental and Experimental Study of Solar Powered Thermoelectric Refrigeration System",International Journal of Engineering Research and Applications (IJERA) ISSN: 2248-9622 Vol. 3, Issue 4, Jul-Aug 2013, pp.2543-2547.