SIMULATION AND EXPERIMENTAL STUDY ON PERFORMANCE ANALYSIS OF SOLAR PHOTOVOLTAIC INTEGRATED THERMOELECTRIC COOLER USING MATLAB SIMULINK

by

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The present study investigates the performance of solar photovoltaic integrated thermoelectric cooler using MATLAB Simulink. The enhancement of efficiency has been achieved using an effective heat removal mechanism from the hot side heat sink. Since the hot side temperature is a crucial parameter. The intrinsic material properties like Seebeck coefficient, α, thermal conductance, K, and electrical resistance, R, of the thermoelectric module are carefully estimated using analytical method and reported. The MATLAB Simulink Peltier module is developed based on the estimated intrinsic properties. The effect of system voltage (V) and current (A) on the thermal parameters like cooling capacity, Q_C, and coefficient of performance has been investigated. The simulation study is validated by conducting a series of experimental analysis. The experimental model is equipped with a 100 Wp polycrystalline solar photovoltaic module to integrate and power the 12V/5A of the 60 W thermoelectric cooler. Moreover, the results reveal that there is a significant effect of ambient and hot side temperature on the thermoelectric cooler performance. The fin-type conductive mode of heat transfer mechanism is adopted along with the convective forced air-cooling system to achieve effective heat removal from the hot side. The infrared thermographic investigation is carried out for ascertaining effective heat removal.

Keywords: *thermoelectric cooler, solar photovoltaics, analytical method, thermal modelling, MATLAB simulink, infrared thermography*

Introduction

Renewable energy utilization is ensuring sustainability. The intervention of solar photovoltaic energy in refrigeration leads to green refrigeration [1]. In agriculture and dairy industry, the need for refrigeration is inevitable, this is because of the post-harvest treatment (removal of field heat), storage of agro produce, milk and meat cooling during transport. The conventional cold storage system has moving parts, which is the primary threat in reliable cold storage. However, the solid-state thermoelectric based micro cold storage will resolve the above issue.

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A thermoelectric module is made up of two or more elements of *N*-type and *P*-type doped semiconductor material. These elements are electrically connected in series to increase the voltage and thermally connected in parallel to reduce the overall thermal coefficient [2]. A variety of dissimilar profiles, substrate constituents, metallization designs, and mounting possibilities are available. Cooling capacity (heat dynamically pumped through the thermoelectric module) is proportional to the magnitude of the input DC electric current and the thermal conditions on each element's side. By varying the input current from minimum to maximum, it is possible to regulate the heat flow and control the surface temperature. The high electronic package thermoelectric cooler (TEC) performance analysis is carried out by the high power thermoelectric modules. The intrinsic design parameters like seebeck coefficient, α, thermal conductance, K, and electrical resistance, R, are essential for better performance of TEC. These data will not be disclosed by the manufacturer datasheets [3]. The iterative technique is adopted to overcome the issue of intrinsic design parameters of the TEC. The analytical method [3] is adopted for appropriate thermoelectric module selection in the MATLAB Simulink. The simulation design is highly recommended to reduce the design cycle [4, 5]. The performance analysis of the heat exchanger is carried out using MATLAB for better design consideration [6]. Effective heat removal can be achieved by the convective mode of heat transfer [7, 8].

Solar photovoltaic technology is a renewable energy technology and highly suitable for stand-alone power operation [9, 10]. Moreover, the solid-state operation, DC power output, reliability, and durability [11-13] (life span of 25 years) of solar photovoltaics are considered for the integration with the TEC. Solar photovoltaic power utilization and energy optimization is ensuring sustainability by the carbon emission reduction [14, 15]. Therefore, the development of a zero-emission refrigeration system using the Peltier effect is significant for sustainability.

The design and development of a solar photovoltaic integrated TEC are identified as a significant research gap. The MATLAB Simulink is developed for reducing the design cycle and helps in integrating solar photovoltaics with the TEC. The optimal operating point is identified through the simulation and it is validated through the experimental analysis.

Intrinsic properties of thermoelectric module selection

Generally, the quality of the thermoelectric materials is determined by their intrinsic properties of the material. To obtain high-quality thermoelectric element, high seebeck coefficient, high electrical conductivity, and low thermal conductivity are desirable properties of thermoelectric materials [2].The seebeck coefficient is a property of the material that determines the performance ability of the module. Thermoelectric devices require low thermal conductivity materials to reduce the parasitic transfer of heat across each leg [4]. Nanostructures are adopted for the autonomous control of electron and phonon transport [16]. The nanomaterials have extremely low thermal conductivity due to boundary scattering phenomena. In addition, thermoelectric materials are good electrical conductors [4]. The optimal value of electrical resistivity of the semiconductor materials will lies between the region of $10^{-3}\,\Omega$ m to $10^{-2}\,\Omega$ m [2]. The variation in the resistivity is based on the charge carrier concentration and mean free path of charge carrier by the surface scattering and reflection [17].

Methodology

The analytical methodology is adopted for obtaining the intrinsic properties like seebeck coefficient, thermal conductivity, and electrical resistance of the thermoelectric module. Based on the obtained intrinsic parameters the MATLAB Simulink based solar photovoltaic TEC is developed. The worst-case scenario is taken for the design of a solar photovoltaic module. The electrical and thermal performance studies are carried out using the MATLAB Simulink model. The various electrical parameters like operating voltage, operating current and operating power characteristics are obtained for the performance analysis of solar integrated TEC. Moreover, thermal parameters like cold side temperature, hot side temperature, ambient temperature, cooling capacity, and coefficient of performance are obtained for the thermal performance analysis. Finally, the relative error analysis is carried out for the simulation and experimental results for the validity of the Simulink model. In addition, the infrared thermographic technique is obtained to ensure effective heat removal from the hot side of the TEC. The intrinsic properties were estimated by iterative approach. The analytical modelling eqs. (1)-(3) are adopted for obtaining the parameters from the manufacture datasheet. The required data is obtained from the manufacturer datasheet:

$$R_\mathrm{m} = \frac{\left(T_\mathrm{ho} - \Delta T_\mathrm{max}\right) V_\mathrm{max}}{T_\mathrm{ho} I_\mathrm{max}} \tag{1}$$

$$K_\mathrm{m} = \frac{\left(T_\mathrm{ho} - \Delta T_\mathrm{max}\right) V_\mathrm{max}\, I_\mathrm{max}}{2 T_\mathrm{ho} I_\mathrm{max}} \tag{2}$$

$$S_\mathrm{m} = \frac{V_\mathrm{max}}{T_\mathrm{ho}} \tag{3}$$

The Peltier device of MATLAB Simulink is developed based on the following heat flow governing equations. The ceramic thermal port A and thermal port B are developed by eqs. (4) and (5), respectively. The cooling capacity, Q_C, and COP of the Peltier device are calculated using Eqs. (6) and (7), respectively. The percentage error analysis is a measure of accuracy. Equation (8) gives the formula to carry out the error analysis for validation:

$$Q_\mathrm{A} = \alpha T_\mathrm{A} I - \frac{1}{2} I^2 R + K\left(T_\mathrm{A} - T_\mathrm{B}\right) \tag{4}$$

$$Q_\mathrm{B} = -\alpha T_\mathrm{B} I - \frac{1}{2} I^2 R + K\left(T_\mathrm{B} - T_\mathrm{A}\right) \tag{5}$$

$$Q_C = \frac{m C_p\, \Delta T}{\Delta t} \tag{6}$$

$$COP = \frac{Q_C}{P_\mathrm{in}} \tag{7}$$

$$\text{Percentage error} = \left(\frac{\text{Experimental result} - \text{Simulated result}}{\text{Experimental result}}\right)100 \tag{8}$$

Simulation analysis of solar photovoltaic integrated thermoelectric cooler

The MATLAB Simulink based solar photovoltaic integrated TEC modelling is carried out by the electrical and thermal energy conversion equations in the MATLAB simscape and shown in fig.1. The solar photovoltaic module, the Peltier device and its control blocks are the significant component involved in the modelling block [5]. The solar photovoltaic module block modelling is carried out by the series configuration of 36 number of solar cells. Each solar cell characteristics is parametrized with the quality factor varies from 1 to 2. The solar photovoltaic integrated TEC configuration is designed using MATLAB Simulink.

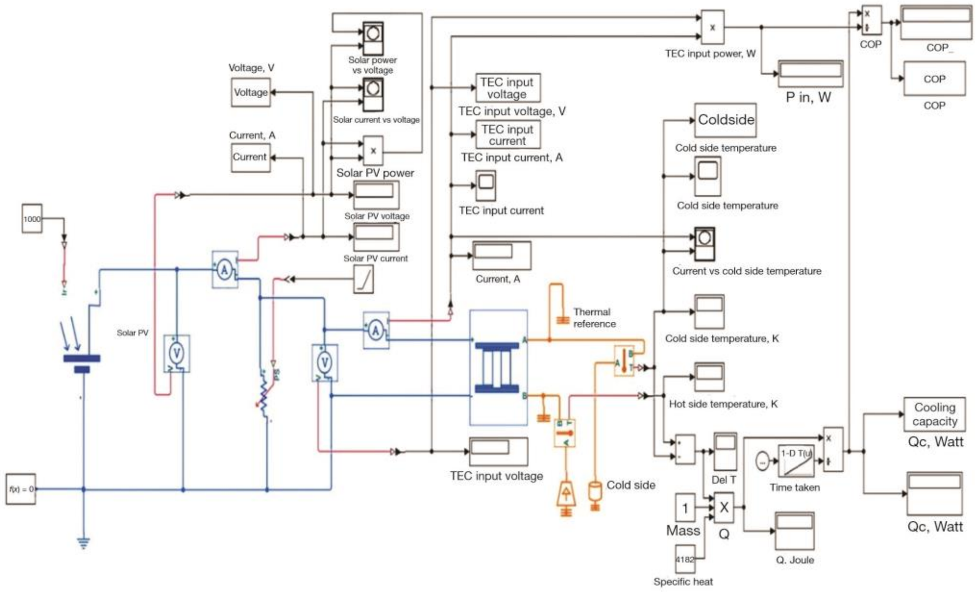

Figure 1. The MATLAB Simulink model of solar photovoltaic integrated TEC

Results and discussion of simulation analysis

The fig. 2(a) illustrates the current *vs*. voltage characteristics curve of generated solar photovoltaic power. The solar light energy is converted into direct electrical power. The maximum power point is achieved by considering the TEC. The voltage *vs*. power characteristics curve illustrated the amount of power input to the TEC in the fig. 2(b).

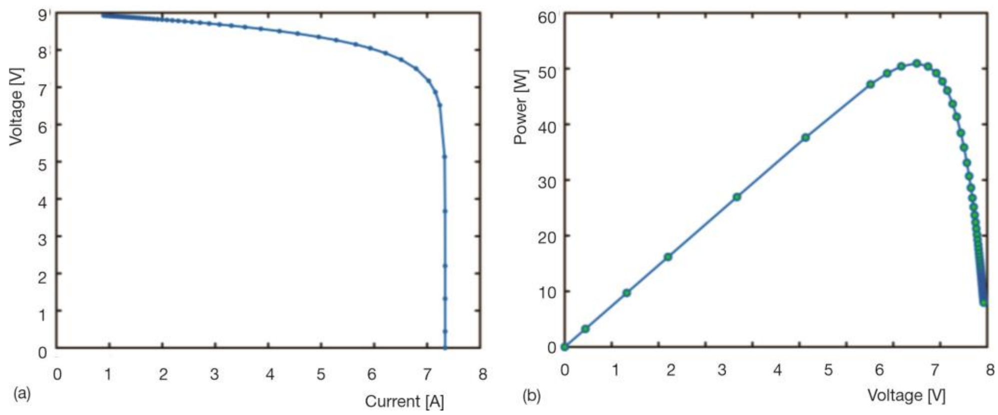

Figure 2. IV Characteristics (a) and power characteristics (b) of solar photovoltaic module

According to the Peltier effect, the amount of current flow is directly proportional to the cooling capacity. The fig. 3(a) illustrates the operating current *vs*. the cooling capacity of the solar integrated TEC. Here, the maximum cooling capacity of 70 W is achieved during the simulation. Moreover, the fig. 3(b) illustrate the operating current *vs*. COP. This describes the efficiency of the solar integrated TEC. The COP depends on driving power, change in temperature, and efficiency of the module [3]. Higher COP can be achieved at lower ΔT only. The optimal operating point is necessary for better COP and cooling capacity.

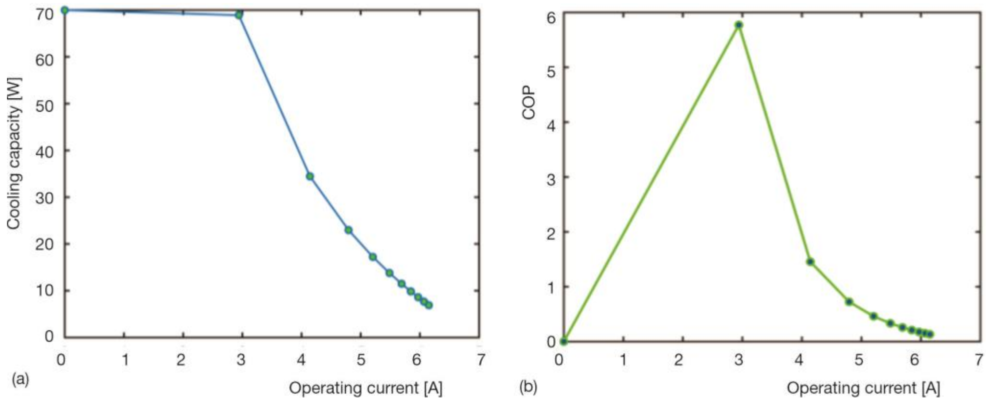

Figure 3. Cooling capacity (a) and COP (b) of solar integrated TEC

The fig. 4(a) illustrates the input power characteristics of TEC. Here, the operating current and operating voltage of the solar integrated TEC is highly significant and consuming 55 W of power. The input electrical power is fed directly for the better operation of the TEC. The fig. 4(b) gives the thermal output characteristic of the TEC. The cooling capacity is a measure of effective workout and the coefficient of performance is a measure of the efficiency of the system. The optimal operating point is essential for the better performance of TEC. It is impossible to achieve maximum values of cooling capacity and COP simultaneously.

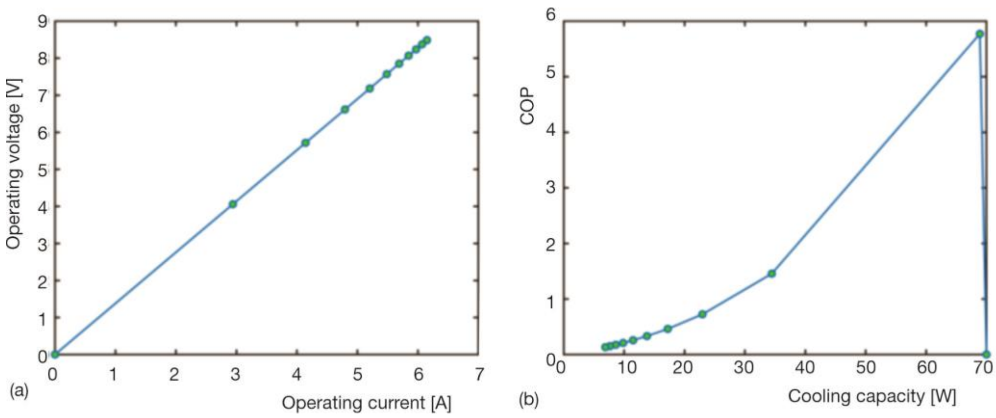

Figure 4. Operating power characteristics (a) and thermal output characteristics (b) of solar integrated TEC

Experimental analysis of solar photovoltaic integrated thermoelectric cooler

The selection of thermoelectric element is a crucial phase of designing the cooler. The optimum match between the design requirement and material's properties should be ensured while selecting the module's material. The materials should have a high Seebeck coefficient, high electrical conductivity, and low thermal conductivity for the significant figure of merit and power factor [2]. In addition to that, the material should possess the following criteria, chemically, thermally, and structural stability must withstand the vibrations and thermal cycle with no noteworthy degradation in the life span of about 5 to 10 years at the industrial operating condition in a cost-effective manner [18].

The TEC experimental set-up is powered by a carefully chosen thermoelectric element based on the precise design shown in fig. 5. The TEC is having the potential of operating at any rugged operating condition with the proper polyurethane foam insulated container. The *K*-type thermocouple is employed in the data logging phase of one minute once the sampling interval is programmed in the data logger. The set-up is equipped to conduct the thermal and electrical performance analysis of the solar photovoltaic integrated TEC and shown in fig. 6. The set-up is powered with the 100 W_p solar photovoltaic module with the Pulse Width Modulation based 12V/8A charge controller for effective integration. A lead-acid battery of 35 Ah is coupled with the set-up for the stable operation of the TEC. The hot side of the Peltier element is equipped with an Al-based heat sink. The heat sink overall dimension is 100 × 100 × 20 mm. In addition, the 3 W 12V/0.25A cooling fan is installed over the heat sink for the convective mode of heat transfer.

Figure 5. Experimental set-up of the solar photovoltaic integrated TEC

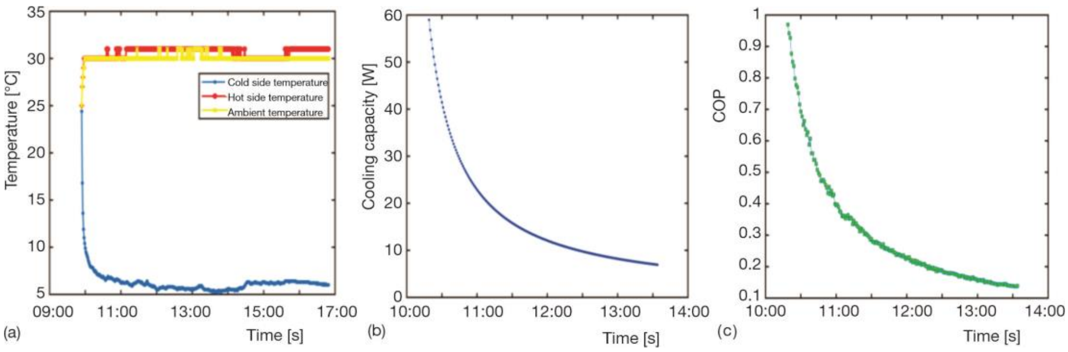

Figure 6. Thermal performance of the solar photovoltaic integrated TEC; (a) temperature characteristics, (b) cooling capacity, and (c) COP

Results and discussion of experimental analysis

The fig. 6(a) illustrates the time *vs.* temperature of the TEC. The cold side temperature reduction of 6 °C is achieved during the experimental phase. The heat sink temperature result reveals that the amount of heat liberated at the hot side of the thermoelectric module and its effective removal. The cold chamber temperature is highly influenced by the hot side temperature generation and ambient temperature. Therefore, thermal performance increases as the hot side temperature decrease. The time *vs.* cooling capacity, Q_C, of TEC is shown in the fig. 6(b). The maximum cooling capacity is indicating the maximum work output to remove the heat from the cold side. The reduction of cold side temperature is ensuring the reduction in cooling capacity with respect to time. The maximum cooling capacity of 58.15 W is achieved during the experimental phase. The fig. 6(c) illustrates the time *vs.* COP of TEC. The maximum COP is achieved during the initial work output of heat removal from the cold side of the TEC. The drop in the cold side temperature and maximum change in temperature, ΔT, leads to the maximum COP reduction. The maximum COP of 0.97 is achieved during the experimental phase.

The percentage error analysis is carried out for the simulation and experimental results. The percentage error gives the level of accuracy. The 0.68% and 11.16% deviation are calculated for cooling capacity and COP of the experimental and simulation results.

The infrared thermographic result shown in the left image of fig. 7(a) illustrates the natural draught cooling mechanism *i.e.* natural air-cooling technique is employed for the heat sink. In addition, the fig. 7(b) illustrates the forced air circulation technique for effective heat removal from the hot side heat sink. The maximum heat removal of 33.41% is achieved by reducing the hot side temperature from 55.1 °C to 41.3 °C.

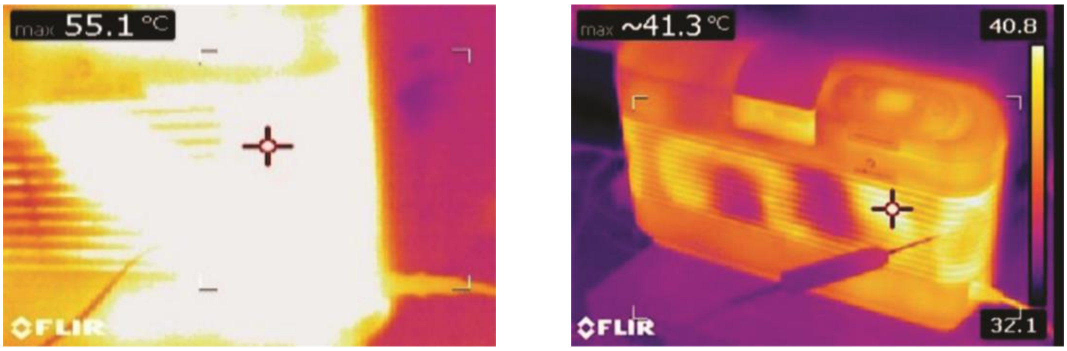

Figure 7. Infrared thermography of natural cooling (a) and forced air cooling system (b)

Conclusions

The analytical method of performance analysis on the solar integrated TEC is carried out using the MATLAB Simulink and simulation is validated by conducting an experimental analysis. The percentage error analysis is carried out for ensuring the validity of the simulated model. The effect of input voltage and current is having a significant effect on solar integrated TEC cooling capacity and COP.

In the experimental analysis, the cooling capacity of 6.94 W and COP of 0.15 is achieved with respect to the time taken for cold side temperature to reach 6 °C. In the simulation analysis, the maximum COP of 0.13 and cooling capacity of 6.89 W is achieved. The maximum temperature reduction is achieved during the input current of 4.9 A. The optimal current is essential for the better performance of the solar integrated TEC. The percentage error value is calculated as 0.68% for cooling capacity and 11.16% for COP. Therefore, the analytical method of performance analysis is highly significant.

The infrared thermography reveals that 33.41% of maximum heat removal is achieved in the forced convective mode of the heat transfer mechanism. The effective heat removal from the hot side of the TEC ensures the thermal performance of the TEC by the reduction of cold side temperature. Therefore, the effect of hot side temperature and ambient temperature are highly significant in cold side temperature reduction.

From the analysis, the solar energy integrated TEC can be used for various refrigeration application like storage of tropical agro produce. Renewable energy utilization paves a way for a green refrigeration system.

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Nomenclature

Cp	– specific heat, [Jkg^{-1}K^{-1}]
ΔT	– change in temperature, [K or °C]
Δt	– change in time, [second]
V	– voltage given in manufacturer's datasheet, [V]
I	– current given in manufacturer's datasheet, [A]
K	– thermal conductivity of the TEC module, [Wm^{-1}K^{-1}]
m	– mass of the loaded substance in the TEC, [kg]
P	– operating thermoelectric power, [W]
Q	– heat flow of the Peltier device [W]
Q_C	– cooling capacity, [W]
R	– electrical resistance of TEC module, [Ω]
S	– Seebeck coefficient of TEC module, [VK^{-1}]
T	– temperature of the Peltier device [K or °C]

Greek symbols

α	-Seebeck coefficient, [VK^{-1}]

Subscripts

A	– thermal port A
B	– thermal port B
ho	– hot side of the module
in	– input
m	– module
max	– maximum given capacity

Acronym

TEC	– thermoelectric cooler

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