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Design of Solar Powered Thermo-Electric Refrigeration System

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ABSTRACT –

This paper presents the design and development of a solar-powered thermoelectric refrigeration system as an eco-friendly and sustainable cooling solution. The system utilizes thermoelectric modules driven by solar energy and incorporates a water-cooled heat exchanger for effective heat dissipation. The thermoelectric cooling principle, selection of materials, heat exchanger design, and solar integration are discussed. An experimental setup is described to evaluate the system's cooling capacity, coefficient of performance, and energy efficiency under various operating conditions. The proposed portable system addresses cooling needs in remote areas with limited grid access while minimizing environmental impact by eliminating harmful refrigerants. Potential applications across residential, commercial, healthcare, and agricultural sectors are highlighted, along with limitations and future research directions for performance improvements.

Keywords *- water block, heatsink, TEC-12706 module, cooler box*

1. INTRODUCTION

The utilization of thermoelectric modules for eco-friendly cooling applications has gained traction due to their solid-state operation based on the Peltier effect, enabling precise temperature control without refrigerants or moving parts. However, effective heat dissipation through efficient heat sinks is crucial for optimal performance, especially in liquid-cooling systems.

Driven by environmental concerns over traditional refrigerants, researchers have been exploring sustainable alternatives like thermoelectric, adsorption, magnetic, and thermoacoustic refrigeration. In this context, the design of a Solar Powered Thermoelectric Refrigeration System emerges as a pioneering solution, leveraging solar energy to drive thermoelectric cooler modules.

The primary objective is to create a portable prototype capable of reliable cooling, targeting remote areas with limited access to essentials like vaccine and insulin storage. Thermoelectric cooling offers a solid-state heat pump solution devoid of moving parts, ensuring reliability and durability where traditional methods face challenges.

Integrating thermoelectric cooling with solar energy presents a sustainable approach to address cooling needs while reducing environmental impact. By incorporating water-cooled heat exchangers, the proposed system aims to achieve precise temperature control and overcome limitations of conventional refrigeration.

This research paper focuses on the design, development, and experimental validation of a solar-powered thermoelectric refrigeration system. The potential applications, limitations, and future research directions are discussed, highlighting the system's contributions to sustainable cooling solutions.

2. THEORETICAL BACKGROUND

I. Peltier Module –

The Peltier effect describes the temperature difference created when an electric current flows through two dissimilar conductors or semiconductors. Peltier modules exploit this effect for cooling and heating applications. They consist of alternating n-type and p-type semiconductor layers connected electrically in series and thermally in parallel. Metallic contacts facilitate current flow, while ceramic plates provide structure and thermal isolation. Thermal interface materials enhance heat transfer between the module, heat source, and heat sink. When a DC current passes through, electrons move across the semiconductor junctions, creating a temperature gradient that enables cooling or heating depending on the current direction.

II. Design Parameters –

The system design aimed to optimize the thermal difference between the hot and cool sides of the Peltier chip while ensuring portability, efficient cooling, and effective use of solar power. A large heatsink coupled with a high static pressure fan was used to enhance cooling efficiency on the cold side. The compact size (≤1 cubic foot) and internal thermal insulation maintained the desired temperature and portability. Solar panels were strategically selected and placed to capture maximum sunlight for powering the system. A solar charge controller managed battery charging and provided outputs for other voltage requirements, extending usability beyond portable refrigeration.

III. Parameters affecting COP –

The Coefficient of Performance (COP) is crucial for the efficiency of thermoelectric refrigeration. Key factors affecting COP include input current, input power, temperature difference between hot and cold sides, cooling capacity (heat absorbed at cold side), Figure of Merit (ZT) of thermoelectric materials, and heat exchanger design. Optimizing these parameters through appropriate current levels, energy-efficient components, thermal management, material selection, and heat exchanger optimization can significantly improve cooling performance and energy efficiency.

3. MATERIALS AND METHODS

I. Materials –

The cooler box performance experimentation uses a thermoelectric Peltier module of TEC-12706, as shown in Fig.1. Such a module requires a nominal voltage of 12V direct current (DC) and a maximum current at 6 A. The module surface with a printed number is marked as the cold side. The cold side absorbs heat from the inner of the cooler box. The opposite surface, namely the hot side, releases the heat out of the module through the heatsink.

Fig. 1 – Peltier Module

Fig.2. shows a heatsink construction with a brushless DC fan (12 V/0.14 A, 90 x 90 mm) attached on the cold side of the Peltier module. The cold side heat sink dimension is 100 x 40 mm (12 fins, 30 mm height) made from aluminium alloy. The cold side heatsink is located on the heat load to enhance heat absorption. The fan can provide uniform distribution of the cold air temperature in the cooler box.

Fig. 2 - Cold side heatsink with DC fan

Fig.3. shows a copper water block heatsink composed of the mini channels to be attached on the hot side of the Peltier module. The water with a high heat capacity is used for heat exchange medium in the heatsink block. The water flows through the heatsink block inlet to capture heat from the hot side of the module. Therefore, the temperature difference between the cold and hot sides of the module can be adequately maintained.

Fig. 3 – Water block heatsink

Fig. 4 - Air-cooled radiator

The Air-cooled radiator is a heat exchanger painted in black colour (300 x 300 mm) with aluminium alloy fins, as seen in Fig.4. The radiator removes the heat of water flowing from the heatsink block. Thereby, the temperature of the water coming from the radiator to the water storage is kept constant.

A circulating pump is used to flow the water back and forth through the mini channel of the heatsink block. Fig.5. shows a 12 V DC submersible water pump (JT-500 model). The pump delivers a nominal 600 L/h flow rate at a maximum head of 5 m.

Fig. 5 – DC water

II. Experimental Setup –

The experimental investigation employed a Peltier cooler box integrated with a water block heatsink and water circulation system. Fig. 6, depicts the schematic representation of the experimental setup, while Fig. 7 provides an actual view of the experimental rig utilized in this study. The setup comprised crucial components, including a thermoelectric module, cold side heatsink coupled with a fan, water block heat sink, fan-cooled radiator, water circulating pump, water cooling storage unit, and a DC power supply. For the cooling chamber and product load testing, a commercial cooler box with an inner volume of 19.25 L (350 mm × 250 mm × 220 mm) served as the platform.

Fig. 6 – Experimental Setup

All the operational components, such as fans, the water circulating pump, and the Peltier module, were interconnected and drew electrical power from a DC power supply unit rated at 30 V/10 A. To gauge the water flow rate through the water block heatsink, a rotameter with a maximum scale of 7 L/min was employed. However, during the initial water pumping assessment, the maximum flow rate achieved by the pump was 2.5 L/min, primarily due to significant hydraulic losses encountered along the 9 mm diameter transparent plastic hose circuit.

Subsequent to the preliminary tests, the experimental performance evaluation of the Peltier cooler box was conducted under standardized conditions with a constant 2.5 L/min water cooling flow rate and a 1.5 L water load. The cooler box operated on a 12 V constant voltage setting provided by the DC power supply unit. The data monitored and recorded included DC power system parameters (voltage, current, power, and energy), water load temperatures, air temperature and ambient air temperature.

III. Experimental Coefficient of Performance of the Peltier Cooler Box

The coefficient of performance (COP) was calculated as the ratio of cooling capacity (Qc) to electrical power input (Pe), as expressed in Eq. (5). Water, with its high thermal mass, served as the product load. A total of 500 ml (500 g) of water was placed in four plastic bottles. The cooling capacity (Qc) was determined using Eq. (3), which accounts for the water mass (m), specific heat capacity of water (Cp), initial water temperature (Ti), final water temperature (Tf), and the cooling time interval (Δt). The electrical power input (Pe) to the cooler box was calculated as the product of applied voltage (V) and current (I), as shown in Eq. (4).

$$Actual\ COP\ = \frac{Desired\ Output}{Power\ Input} \qquad (1)$$

$$= \frac{\text{Cooling Capacity } (\mathrm{Q_c})}{\text{Electrical Power Input } (\mathrm{Pe})} \qquad (2)$$

$$\text{Cooling Capacity } \mathrm{Q_c} = \frac{\mathrm{m.c_p.(T_i - T_f)}}{\triangle\ \mathrm{t}} \qquad (3)$$

$$P_e\ = V.I \qquad (4)$$

$$Actual\ COP\ = \frac{Q_c}{P_e} \qquad (5)$$

4. RESULTS AND DISCUSSION

The test voltage to the Peltier cooler box is set at 12 V on the DC power supply unit. The actual applied voltage under loading over 45 minutes experiment is presented in Fig.7. The voltage is stable at around 11.34 V. However, the applied current starts high at 5.74 A, gradually decreasing and more stable circa 5.55 A after 90 minutes of the experiment running.

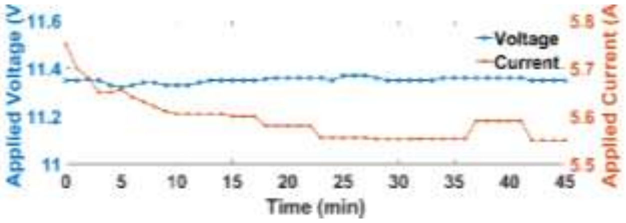

Fig. 7 - Profile of applied voltage and current

Fig.8. shows the power and energy consumption of the Peltier cooler box. The power consumption gradually decreased from 65 W to 63 W. The total energy consumption during the test period of 45 min is 48 Wh. It seems that heat pumping power is affected by the temperature cooling down rates inside the cooler box.

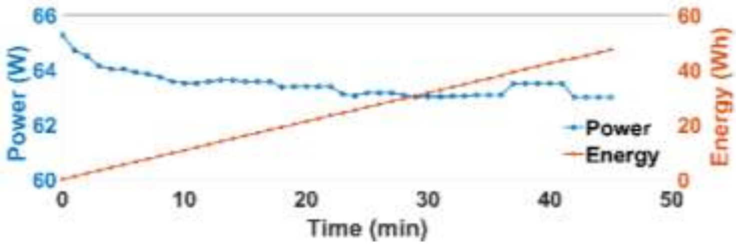

Fig. 8 - Power and energy consumption of a Peltier cooler box

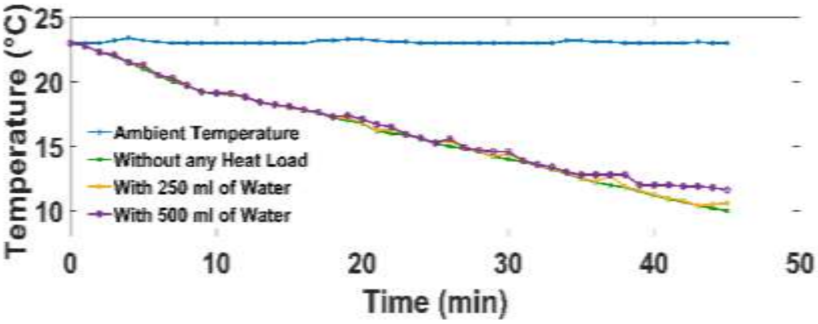

Fig. 9 - Temperature trend of a Peltier cooler box versus time

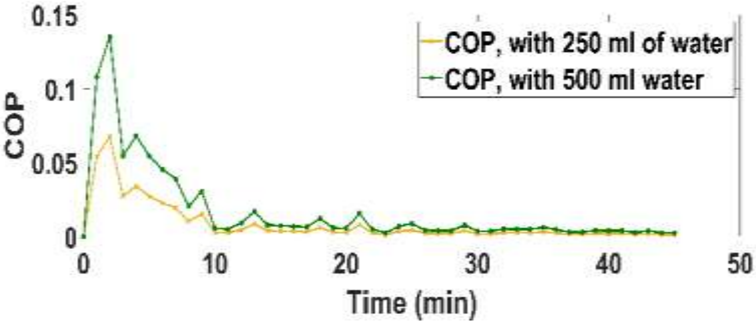

Fig. 10 - Experimental COP versus time

Fig.10. shows the trend of the changes of the COP and the average water load temperature of the Peltier cooler box with time. The COP of the Peltier cooler box decreases as the water load temperature decreases. The COP obtained is 0.203 at a water load temperature of 11.18 ºC.

5. CONCLUSION

The successful development and testing of a Peltier cooler box prototype demonstrated the feasibility and potential of thermoelectric refrigeration technology. Key achievements include attaining a coefficient of performance (COP) of 0.1422 when the water load temperature reached 11.18°C after 45 minutes of operation, and a total electrical power consumption of 64 W and energy consumption of 48 Wh for the cooler box components. These findings lay the groundwork for future advancements and optimizations in thermoelectric refrigeration systems, particularly for solar power-driven applications, while also highlighting areas for further improvement and exploration.

6. FUTURE SCOPE

Future endeavours encompass parametric optimization studies, development of advanced thermoelectric materials, system integration with complementary technologies (PCMs, thermal diodes, control algorithms), seamless renewable energy integration, scalability assessments, and cost-effective manufacturing exploration. Interdisciplinary collaborations driving innovations are vital for realizing the full potential of sustainable and energy-efficient thermoelectric refrigeration solutions across diverse applications.

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