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Solid State Heat Pipe Based Waste Heat Recovery System for Domestic Power Generation at Local Energy Emergencies

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ABSTRACT

Through this work, we have studied a thermoelectric generator-based waste heat recovery system with a low response time for fast energy generation under low and high direct normal solar radiations. Under direct normal radiation of 1000 W m^{-2}, a TEG voltage up to ~3 V has been observed within a saturation time of ~ 900 s. A large temperature gradient (15000 K/m) is produced between hot and cold ends of the TEG module under a simple application of solid-fluid convective heat exchanger. Our results show the potential of remote heating and heat transfer for TEG power generation for small scale power emergencies.

Keywords: Renewable energy, waste heat recovery systems, solid-state heat pipes, thermoelectric energy generation, transient heat diffusion.

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I. Introduction

Renewable energy (RE) systems can be presented as viable as well as most studied alternative for fossil fuel systems [1]. As one of the main advantages, RE systems provide complete green operation without emitting harmful compounds to global atmosphere by preserving ozone layer health [1].

Among many renewable energy systems available, a wide interest has shown in solar thermal engineering due to its versatility in energy extraction [2]–[4]. An active research is currently ongoing under areas of concentrative solar power harvesting technologies and other renewable energy technologies [2], [5].

To increase the efficiency of concentrative type solar power plants as well as conventional power plants, waste heat recovery systems (WHRS) are widely used to recover waste heat in many thermodynamic processes. Extracted waste heat include process heat dumped from fluid cooling, surface heat of heat exchanger vessels, radiative waste heat from solar concentrating operations etc. [6]. Few previous work on the development of WHRS include, [7] studied the potential of thermoelectric power generation from automobile waste heat applications. They have implemented the TEG modules to extract waste heat from the exhaust gases coming after combustion. They have implemented high efficiency heat exchangers to increase cooling in the cold end of the TEG modules to maximize output voltages. Reference [8] developed a WHRS using solid state heat pipe technology for general renewable power plant applications. They have soundly proved the feasibility of such systems using coupled thermal and fluid computational simulations also further as extended in this work. As a benchmark, the large-scale TEG based WHRS introduced by Biswas and Weerasekera was able to recover up to 8 kW of waste heat from a 300 kW concentrative type solar thermal power plant tremendously supporting the need of WHRS for modern power generating sector. Reference [9] utilized TEG WHRS to extract waste heat from cement rotary kilns. Rather than active cooling at the cold end, they have utilized passive cooling with extended surface heat exchangers to maintain a temperature gradient across the TEG modules. Reference [10] studied the application of cross flow heat exchangers for efficient cooling of cold end of the TEG modules. By using this approach, they were able to maintain temperature gradients near 1200 K/m for highly efficient TEG power generation. From the previous studies, it is evident that functional properties such as thermal conductivity, heat capacity etc. [11] plays a vital role in system performance.

Through this work, we extend the concept of application of WHRS to solid-state applications based on thermoelectric energy generation (TEG). From all previous work that has been studied are concentrated on attaching the TEG module hot end directly on the heat source. Due to this approach, a minor temperature gradient is being lost by the radiative energy from the heat source. To alleviate this problem, here with we introduce a concept of transferring heat from a remote heat source to a TEG module located far away from the heating location. Since TEG module voltage is dependent solely on the hot and cold end temperatures, locating the module far away from the high concentrated radiative source is necessary, since heat from the heating source can reduce the temperature gradient across the TEG module due to high surrounding temperature.

To implement remote heating, we have facilitated heat transfer to the TEG module using a high thermally conducting heat pipe arrangement to preserve giant thermal gradients across the TEG module.

II. Device Model and Governing Equations

We propose a device model consisting of a solid-state heat pipe made from high thermally conducting material with a high melting point as shown in Figure 1. We implement a commercially available TEG module with a well-known figure of merit (FOM) value to identify output voltage with respect to temperature gradient imposed in the TEG module.

As in Fig. 1, the arrangement of the device consists of a remote heating end which can be heated by any solar concentrating device (Fresnel lens etc.) or waste heat from an auxiliary process, a solid-state heat pipe to transfer remote heat to the TEG modules and TEG module with cold side heat exchanger. The cold side heat exchanger is implemented as a solid to fluid heat exchanger with a known convective heat transfer coefficient.

As per a real time situation, we have incorporated convective and radiative heat losses from a non-perfectly insulated device to ambient environment. The entire problem is modeled as a coupled system of conductive, convective and radiative heat transfer problem and defined by the governing equations presented subsequently.

Initially, heat flux incident on the remote heating end (Q_{in}) from a typical Fresnel lens with an optical efficiency of η can be given as [12],

$$Q_{in} = \eta I_n A \tag{1}$$

Where, I_n is the direct normal solar radiation incident on the Fresnel lens and A is the exposed surface area of the Fresnel lens.

The transfer of heat in the heat pipe and within the TEG module can be given using the 3-dimensional transient heat diffusion equation as [13], [14],

$$\frac{\partial T}{\partial t} = \alpha\left(\frac{\partial^2 T}{\partial x^2} + \frac{\partial^2 T}{\partial y^2} + \frac{\partial^2 T}{\partial z^2}\right) + \dot{q} \tag{2}$$

For x, y and z coordinate system, where, T is the temperature, t is the time, α is the thermal diffusivity and $\dot{q}$ is the internal heat generation rate.

The thermoelectric voltage (V) can be calculated using the Seebeck coefficient (S) specific to a TEG modules as [7],

$$V = S.\nabla T \tag{3}$$

Where, ∇T is the temperature gradient across the TEG module.

The convective heat loss to the surroundings for unit surface area can be given using Newton's law of cooling [15],

$$Q_{loss} = h.(T - T_{amb}) \tag{4}$$

Where, h is the convective heat transfer coefficient and T_{amb} is the ambient temperature.

Similarly, convective heat transfer to cold end thermal reservoir (Q_{cold}) can be given as,

$$Q_{cold} = h_{cold}.(T - T_{cold}) \tag{5}$$

Where, h_{cold} is the heat transfer coefficient associated with solid-fluid thermal reservoir and T_{cold} is the fluid temperature of the heat exchanger.

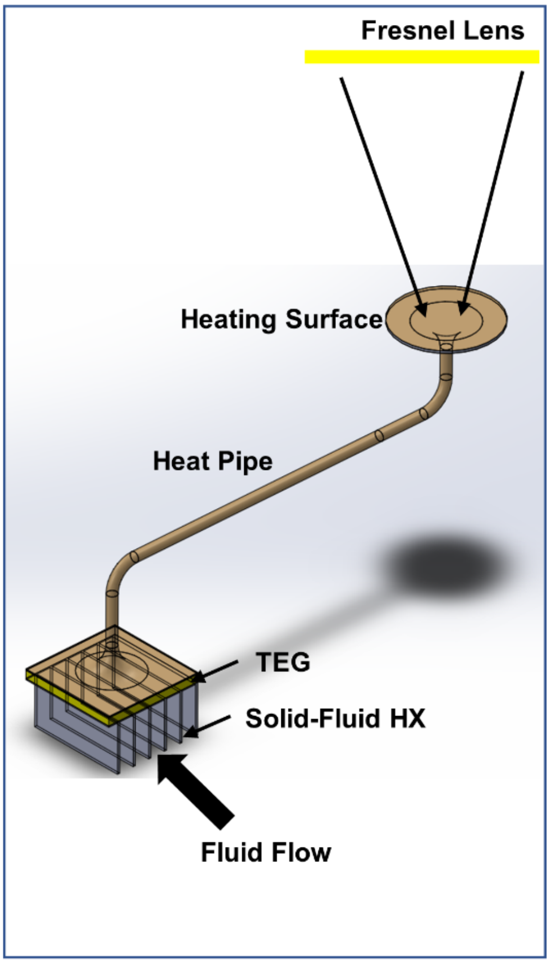

Fig. 1. Device model for simulations. Where, remote heating is performed using a solar concentrating device (Fresnel lens) and focused heat is transported through a high thermally conducting heat pipe to the TEG.

III. Parametric Analysis and Numerical Simulation Process

We performed parametric analysis based on varying heat flux conditions on remote heating end of the device arrangement using ANSYS software. Based on the available direct normal solar radiation in a typical summer day, we varied heat flux from 200 to 1200 W m^{-2} on the remote heating end. Two sets of finite element analysis (FEA) simulations are performed considering steady state and transient conditions. Steady state simulations are performed to analyze device performance after system reaches to steady state while transient simulations are used to evaluate system response time. Table I shows the values used for numerical simulation procedure.

TABLE I: OPERATING AND DESIGN PARAMETERS OF THE DEVICE ARRANGEMENT

Parameter	Value
Fresnel lens side length	0.4 m
Remote heating end diameter	0.05 m
Heat pipe length	1 m
Heat pipe diameter	0.008m
Thermal diffusivity of heat pipe material (α)	165.53 mm^2/s
Ambient loss convective heat transfer coefficient (h)	5 W/m/K
TEG dimension	4 cm*4 cm* 0.3 cm
TEG FOM value	1×10^{-6}
TEG Seebeck coefficient (S)	3.47×10^{-4} V/m
Solid-Fluid HX convective heat transfer coefficient (h_{cold})	200 W/m^2/K
Ambient Temperature (T_{amb})	293 K
Cold fluid temperature (T_{cold})	293 K

IV. RESULTS AND DISCUSSION

Fig. 2A shows the TEG voltage for different heat flux conditions in the remote heating end for the variation of direct normal solar radiation under steady state conditions. Fig. 2B shows the variation of hot and cold end temperature of the TEG module for the varying heat flux condition shown in Fig. 2A. Fig. 2C shows the temperature gradient across the TEG module under increase in heat flux on the heating end.

It is observable that TEG generated voltage has a positive impact on the incident heat flux. Furthermore, increase in incident heat flux produced an increase in temperature gradient across the TEG module with a higher rate of increasing temperature in the hot end. Based on the TEG FOM, an open circuit voltage value up to 3 V can be generated using a single TEG module.

Fig. 3A shows the response time analysis using transient FEA simulations performed up to 1500 s. For current arrangement, it is evident that system reaches steady state after ~800 s providing the peak voltage shown in the steady state simulations.

Fig. 4 presents the contour plots of transient time analysis performed on the TEG device arrangement. When focusing on temperature distribution on the entire device, it is observable that majority of the temperature gradient is present in the heat pipe section. Since convection loss to the surroundings is prevalent for a non-insulated heat pipe, majority of the heat energy is lost in this region of the device.

It is also observable that under steady state conditions, maximum temperature of the device at any cross section do not exceed 2500 K which shows safe operation at highest flux conditions under appropriate cooling at the cold end.

As a future implementation, parallelizing similar modules can increase the current output with a constant voltage and a low response time. In addition, series mode operation allows to increase output module voltage under constant single TEG current. However, at series conditions as the series circuit progresses, rapid reduction in TEG hot and cold end temperatures takes place. Therefore, greater decrease in output voltage of TEG modules from the end TEG modules can be observed. Parallelizing or series arrangement for current device design is under a scope of another research.

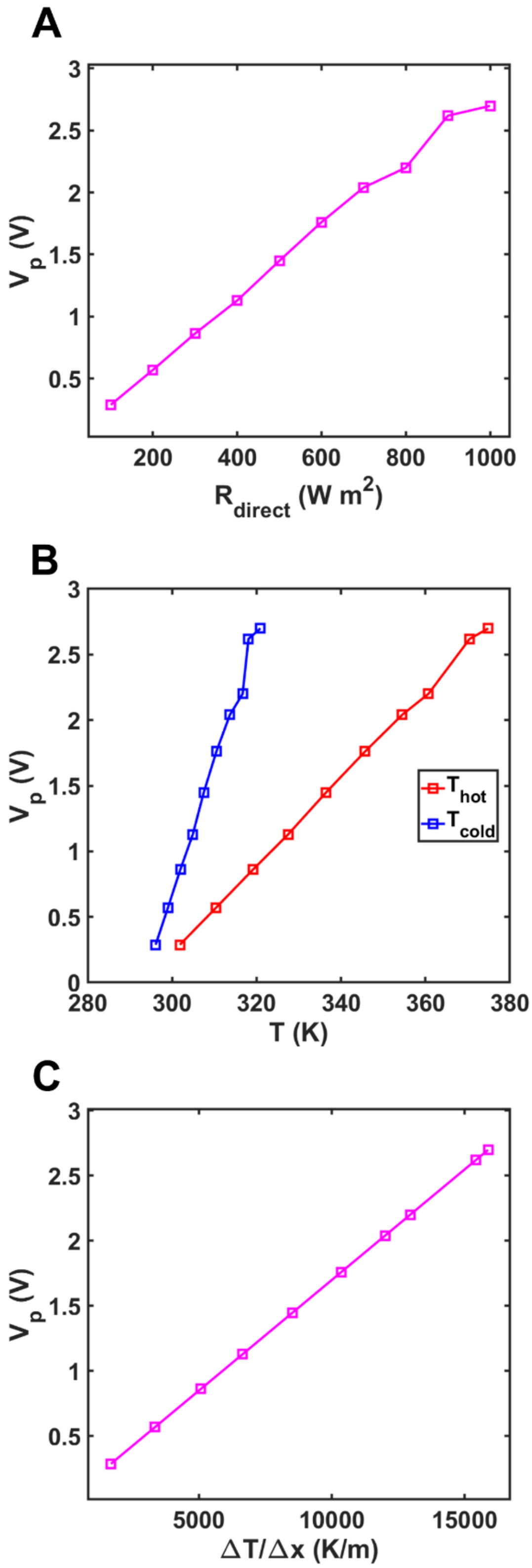

Fig. 2. Analysis of TEG induced voltage for multiple case studies. (A). TEG induced voltage with respect to direct normal solar radiation. (B). TEG induced voltage with respect to hot and cold side temperatures for constant direct normal solar radiation variation as studied in the analysis in subfigure A. (C). TEG induced voltage with respect to temperature gradient across the TEG module for the analysis of subfigure A.

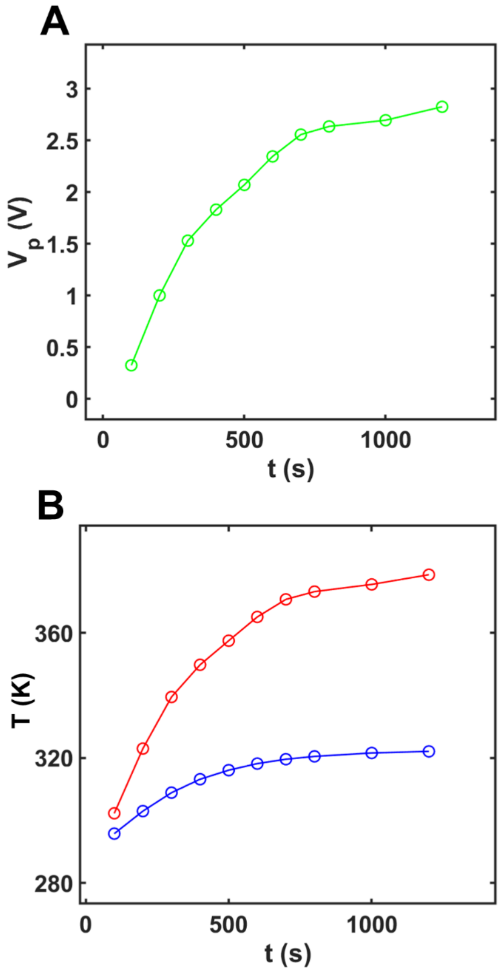

Fig. 3: Transient analysis of the device and response time analysis. (A). Saturation time analysis of the TEG module output voltage for constant direct normal solar radiation (1000 Wm^{-2}). (B). Saturation of hot and cold thermal reservoir temperatures with respect to time (red-hot end temperature, blue-cold end temperature).

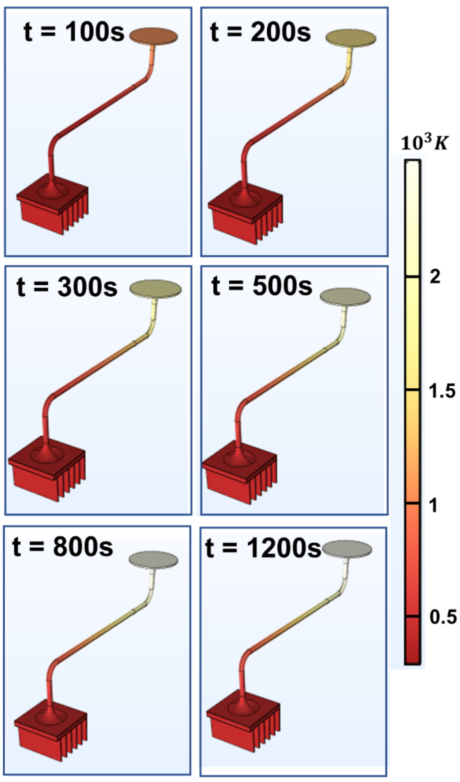

Fig. 4. Contour plots of temperature distribution utilized for saturation of the device arrangement with respect to time.

V. Conclusion

In this work, we have introduced a TEG based WHRS unit with a low response time to be effectively utilized at a local energy emergency. From device level simulations, we were able to reach maximum potential of TEG module to extract best FOM performance at a regular direct normal radiation values. The system demonstrated a saturation time less than 900 s with a large temperature gradients up to 15000 K/m. Therefore, we conclude that heat transfer through solid-state heat pipes is an efficient methodology for transfer remote heat to a TEG module within a low cost. The similar type of arrangement can be implemented for parallel and series TEG operation to increase power density and current density.

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Conflict of Interest

Authors declare that they do not have any conflict of interest.

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