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Performance evaluation of a thermally concentrated solar thermo-electric generator without optical concentration

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ABSTRACT

Recent research has shown the use of solar thermoelectric generators (STEG) to be an alternative method of harnessing solar energy. They comprise of a spectrally selective absorber coupled to thermoelectric materials to generate power as governed by the Seebeck effect. Since output power generated is dependent on thermal gradient in the STEG, it is important to maximize this parameter. This can be done by increasing energy absorbed from the sun and minimizing energy lost from the system. Herein, the former has been achieved using thermal concentration by area while the latter has been addressed by use of a vacuum enclosure. The effect of varying enclosure pressure on convective heat loss from the solar selective substrate ($\alpha = 0.90$, $\varepsilon = 0.15$, area: 22.4 cm × 12 cm) was studied. It was observed that at 100 mbar enclosure pressure, convective heat transfer coefficient as low as 0.6 W/m^2 °C (cf., 10 W/m^2 °C at atmospheric pressure) was obtained. This resulted in the rise of substrate temperature from 97 °C at ambient pressure to 142 °C at 100 mbar enclosure pressure, an observation validated by simulations. Further study was conducted where open circuit voltage (OCV) and output power were observed and efficiency was calculated at different enclosure pressures. In these tests the effect of using a large area absorber was also studied. It was observed that decreasing the enclosure pressure increased the OCV, output power and efficiency of the STEG setup. It was also noted that using a large surface area absorber further increased the OCV and output power of the setup. During the course of the study, a maximum OCV of 823 mV, output power of 44.2 mW, and an efficiency of 0.82% were achieved by the setup at an enclosure pressure of 100 mbar and thermal concentration ratio of 22. The results show that the present setup may be used as an alternative to optically concentrated STEGs which require a power consuming solar tracking system.

1. Introduction

The need for researching alternative sources of energy has arisen due to the growing demand for power and also the detrimental impact of the use of conventional fuels [1]. The sun being the most widespread and abundant source of energy is therefore the most viable option [2]. Photovoltaics and large-scale solar thermal power systems are currently the most used means of harnessing solar energy [3,4]. Recent research shows that spectrally selective absorbers coupled with thermoelectric materials can serve as an alternative solar energy harnessing technique for micro-power applications [5]. Focus on the latter has increased in recent years since further growth in the field of photovoltaics is now limited [6].

Thermo-electrics generate an electrical potential gradient from a thermal gradient as governed by the Seebeck effect [7] expressed as:

$$V_{OC} = (S_p - S_n)(T_H - T_C) \tag{1}$$

where $\boldsymbol{S_p}$ and $\boldsymbol{S_n}$ are Seebeck coefficient of the 'p' and 'n' junctions and $\boldsymbol{T_H}$ and $\boldsymbol{T_C}$ are temperatures of the hot and cold junctions.

Thermo-electrics are mostly used as waste-heat recovery systems but can be coupled with spectrally selective substrates to harness solar energy. These arrangements are called solar thermoelectric generators (STEGs). The growing interest in STEGs is due to the fact that they require no working fluid and have no movable parts, which greatly reduce, if not eliminate, the need for regular maintenance [8,9]. This would be particularly beneficial for power generation in remote locations where logistics would make regular maintenance unviable.

Efficiency is critical for every energy system. Improving STEG power generation efficiency can be done by increasing the thermal gradient across the hot and cold junctions of the thermo-electric modules, by improving the absorber (application of solar selective

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coatings) and module efficiencies (which can only be increased by improving TEG figure of merit [5]). Maria Telkes had used optical concentration using a Fresnel lens and achieved a system efficiency of 3.36% way back in 1954 [10] and was one of the pioneers of STEG research. Other work on STEG comes from Nattestad et al. [11], who achieved only 2.42% system efficiency. Further work was done by Olsen et al. [12] in 2013 where they sought to demonstrate near 15% efficiency from their setup far outstripping the performance of the former. Aside from using optical concentration and vacuum enclosure, they also used a water cooling system to cool the cold junction of the STEG module.

The main drawback in the above setups, which prevents their widespread use, is the need for a solar tracking system. Such a system is required due to the fact that maximum transmittance of a Fresnel lens occurs when solar flux is incident along its principal axis [13]. The tracking system also feeds off the already minimal power generated by the STEGs, therefore, making the system unviable for micro-power applications. Daniel Kraemer et al. had come up with an alternative to the above setup and achieved better efficiencies (4.46%) without the use of optical concentration by using vacuum, a nano-structured absorber coating and cooling system instead [14]. Nanostructured absorbers show higher absorptance and lower emittance than other coatings, improving absorber efficiency and therefore hot junction temperature. By placing the module in vacuum, they managed to minimize heat loss from the hot end by convection, while the cooling system served to lower cold junction temperature. The aggregate effect was the increase of the temperature gradient in the module and thus higher system efficiency.

Experiments recently conducted by Candadai et al. saw them achieve an efficiency of 1.2% at an optical concentration ratio of 65 using commercial Bi_2Te_3 modules by coupling to solar selective substrates [15]. Wan et al. [16] on the other hand, coupled STEGs with photovoltaics to get improved system efficiency of 13% in a very innovative design. The research into TEGs has created such excitement in the world of research with new innovative designs such as the Flexible Thin Film TEG [17], opening new avenues for applications. It must be noted, however, that applications are restricted by feasibility, particularly economicity of the setup, which is one focus of this experiment, i.e., to create a maintenance free setup with easily available components.

In the present work we demonstrate the use of thermal concentration in the STEG device. The first part of the present study is to understand the impact of enclosure pressure on the convective heat transfer coefficient (h) in the setup. Since convective heat transfer is the main cause of energy loss from the hot junction, minimizing this factor would significantly improve system efficiency. This is an implication of the study conducted by Hosseini and Saidi [18], one of the few researchers to study the impact of enclosure pressure on the convective heat transfer coefficient. This study also serves to test the solar selective coating performance as well as the ability of the enclosure to create and maintain vacuum. The coefficient of convective heat transfer in this assembly is also measured. The latter part of the study is the application of the results achieved from the above performance tests to determine the power and efficiency of the STEG setup in the enclosure conditions. It also helps to evaluate the impact of thermal concentration by area.

2. Theory

2.1. Solar selectivity

The solar spectrum is comprised of three major regions – Ultra-Violet, Visible and Infra-Red, each of which contributes to the energy from the sun. Most of the energy is contained in the wavelength range of 0.4–2.5 μm [19]. In order to draw maximum energy from the sun, the absorber should ideally be almost entirely absorptive in this range and have very low emittance. This can be achieved by means of certain coatings atop metal substrates. In the experiments that follow, an AlTiN/AlTiON/AlTiO based absorber coating with $\alpha = 0.90$ and $\varepsilon = 0.15$ on an aluminium substrate was used [15]. The angular dependence of optical properties of the spectrally selective absorber coating can be found elsewhere [20,21]. The efficiency of the absorber given by Eq. (2) [22] critically affects the efficiency of the STEG setup.

$$\eta_{abs} = \alpha - \frac{\sigma \epsilon T_{abs}^4}{q} \tag{2}$$

2.2. Convective heat transfer

It is the form of heat transfer in occurring in fluid medium. It is one of the primary causes of heat loss in the STEG setup. Exposure of hot surfaces to the atmosphere leads to heat exchange between the surface and the medium causing a cooling. The heat exchange by convection is expressed as follows [23]:

$$\dot{Q}_{conv} = hA\frac{dT}{dt} \tag{3}$$

The term ‘h’, is dependent on the conditions of the fluid medium. It must also be noted that convective heat loss rate is also proportional to the term dT/dt, i.e., the rate of change of surface temperature. This term is higher for hotter surfaces and lesser for colder ones. In other words, the hotter junction of the STEG system would cool faster than the colder junction, which would mean that the temperature gradient across the STEG would drop at a very quick rate. The principle behind the present experiment is to reduce the heat loss by convection by varying ambient conditions, i.e., ‘h’ rather than dT/dt since the former is intrinsic to the material and its surroundings while the latter is dependent on the temperature of the system which cannot be compromised. The impact of ambient pressure on ‘h’ has been previously studied by Hosseini and Saidi [18] where they found that the heat loss rate decreased with enclosure pressure.

The above phenomenon can be understood mathematically by the means of the following expressions. Decreasing the enclosure pressure, can be viewed as a decrease in density of enclosure gas. Eqs. (4)–(7) show that decreasing pressure decreases the value of ‘h’, which in turn decreases the heat lost by a surface (Eq. (3)) [24].

$$P = \rho RT \tag{4}$$

where P is pressure of gas, ρ is its density, R is the gas constant and T is the temperature of the gas.

$$Ra = \rho \times Gr \tag{5}$$

The density of the gas affects Ra which is the Rayleigh's number. Gr in the above equation is Grashof's number.

$$Nu = \left[Nu_0^{\frac{1}{2}} + Ra^{\frac{1}{6}} \left(\frac{f_4}{300}(\mathrm{Pr}) \right)^{\frac{1}{6}} \right]^2 \tag{6}$$

Ra in turn affects Nu which is the Nusselt's number while $f_4(Pr)$ is a function of the Prandtl's number.

$$Nu = \frac{hL}{k} \tag{7}$$

This directly impacts ‘h’ as shown in the above equation where L is dimension factor while k is the coefficient of thermal conduction of the fluid. The estimation of ‘h’ is carried out by the use of the following heat balance equation which takes into account heat loss by convection and radiation. Conduction has been