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Finite element analysis on solar energy harvesting using ferroelectric polymer

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Abstract

Solar energy harvesting through pyroelectric effect has been under the scrutiny of researchers since the past few years. However, the low energy density coupled with requirement of rapid temperature fluctuations has hindered any successful commercial ventures in this field. This study is an attempt towards eliminating these drawbacks associated with pyroelectric energy generation using ferroelectric polymers. Langmuir–Blodgett Polyvinylidene difluoride copolymer–Trifluoroethylene–Chlorofluoroethylene P(VDF–TrFE–CFE) thin films were used in conjunction with pyroelectric effect and forced cooling to simultaneously increase energy and power density. In this regard, a two faceted approach of linear pyroelectric harvesting and harvesting through Ericsson cycle have been analyzed and compared. The models for the same have been developed and analyzed using finite-element method. Two separate cases of air cooling and water cooling were investigated. Peak values of power density for water cooling and air cooling processes (direct pyroelectric effect) are found to be 0.437 μW/cm^3 and 0.2 μW/cm^3, respectively. These values are obtained at optimized value of load resistance and load capacitance ($R_L = 7$ MΩ and $C_L = 2$ μF for water cooling while $R_L = 14$ MΩ and $C_L = 2$ μF for air cooling). The maximum values of power density that can be obtained from water and air cooling process are 19.65 mW/cm^3 and 16.35 mW/cm^3 (using Ericsson cycle) at 0.013 and 0.011 Hz frequency, respectively. It was also observed that water cooling is more efficient than air cooling for energy harvesting. This study can lead to growth in the field of solar energy harvesting using pyroelectric effect.

Keywords: Pyroelectric; Ferroelectric; Olsen cycle; Energy harvesting

1. Introduction

Solar energy has been projected as a prominent source of renewable energy for future energy requirements. The solar radiation can be directly utilized as an energy source for powering many devices and systems. There are numerous ways to harvest solar energy including photovoltaic cells, solar thermal power plant and solar thermoelectric generators. Photovoltaic cells convert sunlight directly into electricity using suitable band-gap semiconductor materials such as Silicon and Gallium Arsenide (Grätzel, 2005; Mickey, 1981). Solar thermoelectric generators produce electro-motive force using the Seebeck effect employing heterogeneous metallic junctions and fixed thermal gradients (Telkes, 1954; Chen, 1996). However, solar energy harvesting can also be achieved using pyroelectric materials.

The change produced in the spontaneous polarization of a non-centrosymmetric dielectric material, as a consequence of the change in its temperature, is termed as pyroelectric effect. Pyroelectric materials form a subset of the piezoelectric materials and contain all ferroelectric

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Nomenclature

F_{ss}	angle factor between surface and sky
α_m	absorption coefficient of pyroelectric material
α_g	absorption coefficient of glass plate
ρ_m	density of pyroelectric material
ρ_g	density of glass plate
I_D	direct solar radiation
I_d	diffused solar radiation
ε_g	emissivity of glass plate
ε_m	emissivity of material surface
T_g	glass temperature
h_g	glass thickness
k_g	glass thermal conductivity
Q_s	heat supplied to the material in heating
Q_R	heat released from the material in cooling
H_{ab}	heat absorption rate of material by solar radiation
I_{solar}	intensity of solar radiation
I_n	intensity of solar radiation normal direction
C_L	load capacitance
R_L	load resistance
T_m	material temperature
h_m	material thickness
k_m	material thermal conductivity
C_m	material capacitance
R_m	electric resistance of material
I_P	pyroelectric current
p	pyroelectric coefficient
α	solar azimuth angle
β	solar altitude angle
Φ	surface inclination to the vertical
c_m	specific heat capacity of pyroelectric material
c_g	specific heat capacity of pyroelectric material
A_g	surface area of glass
A_m	surface area of material
T_t	time dependent temperature profile of pyroelectric material
T_o	temperature of ambient air
T^f	final time of cycle
t	time period of cycle
t^h	heating duration
t^c	cooling duration
h_a	thermal convective coefficient of air
h_w	thermal convective coefficient of water
V_m	volume of pyroelectric material
V_g	volume of glass plate

materials. The change in polarization stems from the shift in the degree of non-centrosymmetry owing to thermal lattice vibrations corresponding to different temperatures. This change in polarization can be used for generation of electric current and subsequently electric power by using suitable means. Direction of the pyroelectric current changes with changing nature of thermal gradient. As the materials temperature increases ($dT/dt > 0$) polarization decreases due to re-orientation of dipole moment. It results in the generation of an electrical current in external circuit. On the contrary, in case of material's cooling ($dT/dt < 0$) polarization increases as dipoles gain their orientation, causing flow of current in reverse direction. Utilization of pyroelectric effect for energy generation from solar temporal variations offers to be a promising prospect. Literature reveals a number of studies discussing the pyroelectric effect and its possible applications for energy harvesting (Yang et al., 2012; Harb, 2011; Cuadras et al., 2010; Sebald et al., 2009; Fang et al., 2010). However, attempts at commercialization of linear pyroelectric harvesters have been limited owing to the low energy and power density associated with such methods of harvesting. However, this drawback can be easily offset by the sheer economics of operation associated with a pyroelectric generator. Pyroelectric harvesting technology employs solid state conversion mechanism through pyroelectric phenomenon involving little or no moving parts. Additionally, these systems are essentially autonomous and require little to no maintenance when generating heat from transient temporal gradients. Lastly, when employing polymer thin films, the commercial benefits associated with installing and operation of a pyroelectric conversion system is expected to be high when compared to either semiconductor-based solar cells or hetero-junction based thermo-electric generators.

In order to further reduce the cycle time and increase power output, cooling using various natural and artificial sources has been proposed. Studies have been reported where a fraction of the generated energy is redirected to pump a coolant for rapid heat exchange (Navid et al., 2010). Additionally, Olsen and co-workers have proposed an Ericsson-like cycle for enhanced thermal energy harvesting by successfully utilizing induced pyroelectricity (Fang et al., 2010). Olsen cycle involves high field energy harvesting and uses induced polarization by means of electric field. We have also investigated thermal energy harvesting through Olsen cycle in our previous studies (Chauhan et al., 2014; Vats et al., 2014; Patel et al., 2014). The present study is an attempt to harvest solar energy with use of ferroelectric polymers (direct pyroelectric effect and Ericsson/Olsen cycle). Two separate case studies have been discussed, one each for direct pyroelectric effect and for enhanced conversion using Ericsson cycle. A comparative analysis has been provided to compare the power and energy outputs obtained from both the techniques. The approach involves investigating energy harvesting while employing cooling through external means. A suitable system was designed and analyzed for each of the cases