Enhancement of Pyroelectric Generation from Solar Energy

J. Sunilkumar[1], V. Saranya[2]
Assistant Professor[1, 2]
Department of EEE
United Institute of Technology, Coimbatore
Corresponding Authors' email id: *sunil.cbe@gmail.com[1], niketha.sree@gmail.com[2]*

Abstract

Pyroelectric thermal energy harvesters are intriguing alternatives to thermoelectric devices due to their high thermodynamic efficiency and reduced heat sink requirements. Thermoelectric generators use see beck effect to generate voltage from a spatial thermal gradient. Instead the temporal changes of the thermal energy can be captured by means of Pyroelectricity. Non-Olsen cycle method of pyroelectricity generation enables the usage of renewable energy sources such as solar energy and wind energy. The aim of this work is to study the ability of harvesting energy using a Lead-zirconate-titanate (PZT-5H) pyroelectric material using Non-Olsen cycle method. The PZT-5H is exposed to solar radiation and a periodic temperature change in the material is obtained by using the mechanical setup. The mechanical setup consists of a rotating chopper disc and a vertical axis wind turbine (savonious type).The savonious wind turbine provides mechanical input to the chopper disc such that it periodically allows the solar irradiation to fall on the PZT-5H material and will provide a time varying temperature. This method proves to be economical than Olsen cycle method as the time varying temperature can be obtained from the naturally available sources such as solar and wind energy. To maximize the output, optical concentrators are used to intensify the solar irradiation.

Keywords: *Pyroelectricity, optical concentrator, PZT.*

I. INTRODUCTION

Over the entire world with the development of modern industry, the problems of energy shortage and environment pollution become emergent. Solar energy as a renewable and environment friendly energy source is becoming more and more important. Solar energy can be harvested in many ways like, solar thermal power plants, solar thermoelectric generators and photovoltaic. The latter two are more advantageous than the solar thermal power plants because they provide direct electrical output and are sustainable for small scale installations. Solar thermoelectric generators use seebeck effect to generate voltage from a spatial thermal gradient. These are based on temperature gradients leading to heat flow through the thermoelectric generator, and a small percentage of the heat flow is converted to electrical energy. It requires simultaneous heating and cooling phase which is difficult to setup and maintain. A new category of ferromaterials which can be the perfect substitute for the thermoelectricity is the Pyroelectricity.

Pyroelectricity is the ability of certain materials to generate a temporary voltage when they are heated or cooled. The change in temperature modifies the positions of the atoms slightly within the crystal structure, such that the polarization of the material changes. This polarization change gives rise to a voltage across the crystal. If the temperature stays constant at its new value, the pyroelectric voltage gradually disappears due to leakage.

A pyroelectric can be repeatedly heated and cooled to generate usable electrical power. Possible advantages of pyroelectric generators for generating electricity (as compared to the conventional heat engine plus electrical generator) include potentially lower operating temperatures, less bulky equipment, and fewer moving parts.

There have been many studies related to pyroelectric-based energy harvesting mostly involving the Olsen cycle [1], which is based on the thermodynamic Ericsson cycle, with two isothermal and two isoelectric field processes. This cycle has been realized for different materials like polymers, single crystals, and relaxor ferroelectrics and for different electrical fields and temperature ranges.

Navid et al. performed the Olsen cycle by alternatively dipping purified and porous 60/40 poly(vinylidene fluoride-tri fluoro ethylene) [P(VDF-TrFE)] in hot and cold silicone oil baths in the presence of electric fields and harvested maximum energy density up to 426 J/L/cycle[2]. Kandilian et al. performed the dipping experiment on 68PbMg Nb O - 32PbTiO (PMN-32PT) single crystal and obtained energy density of 100 mJ/cm /cycle corresponding to the power density of 4.92 mW/cm [3]

Recently, Lee et al. harvested a maximum energy density of 888 J/L/cycle from oil bath experiments on 290- m-thick lanthanum-doped lead zirconate titanate (8/65/35 PLZT) ferroelectric relaxor crystal [4]. The other well-known method to perform an Olsen cycle is to force a working fluid, usually silicone oil, back and forth across a stack of pyroelectric material between heating and cooling heat exchangers.

Navid et al. achieved a power density of 38.4 W/L at 0.5-Hz frequency with lead zirconate stannate titanate (PZST) as the pyroelectric material [5]. Similar experiments were carried out by Nguyen et al. on 60/40 P(VDF-TrFE) and a maximum energy density of 130 J/L at 0.061-Hz frequency was obtained [6]. Alternatively, Lee et al. generated the thermal oscillations to carry out the Olsen cycle by alternatively placing 60/40 P(VDF-TrFE) on a hot and cold source instead of convective mode of heat transfer. The authors reported an energy density of 155 J/L/cycle at 0.066 Hz for temperatures between 25 C and 110 C [7].

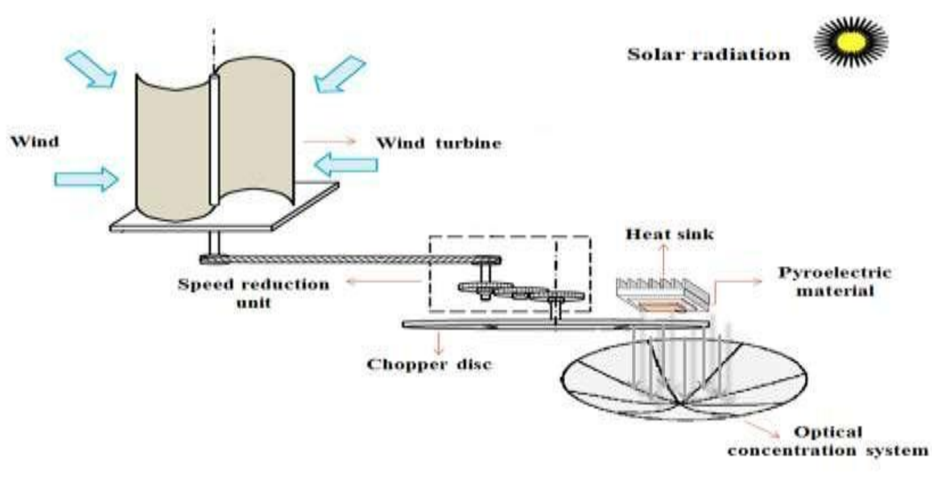

Fig. 1.Schematic diagram of the pyroelectric energy harvesting system

However, there were attempts to extract energy from pyroelectric material in non-Olsen-cycle ways. Xie et al. used a resistance heater to create the temperature changes on a lead zirconate titanate (PZT-5A) ceramic and measured a peak power density of 0.23 W/cm, for a rate of change of temperature of 15 Cs [8].Mane et al. used a heat lamp as a radiation source and a rotating disc with an aperture as a radiation chopper to periodically heat three different materials such as PZT, a prestressed PZT composite, and single crystal PMN-30PT. Among the three, a maximum power density of 8.64 W/cm was generated by PMN-30PT for a temperature rate of 8.5 Cs because of its high pyroelectric coefficient [9]. The possibilities of directly taping ambient thermal sources through pyroelectricity, instead of pumping working fluid or using heat lamp are seriously hampered by the lack of thermal sources with a large time varying temperature. Recently, Zhang et al. demonstrated that the pyroelectric material PZT when placed in solar radiation can produce energy by exploiting the natural fluctuations in solar radiation intensity and the fluctuations created by the wind [10]. The authors conducted a laboratory experimental procedure which modeled the actual situation and achieved a power density of 4.2 W/cm for a rate of change of temperature of 0.53 Cs for a wind speed of 2 ms. Similarly, Sebald et al. observed natural temperature variations on a coat and applied the temperature profile on a 0.75 Pb(Mg Nb)O -0.25PbTiO (PMN-0.25PT) ceramic and estimated a mean power density of 1 W/cm from the material [11]. The harvested energy by these principles is very low because the natural fluctuations of solar radiation are too slow and very small to produce rapid changes in temperature.

II. DESIGN OF THE PROPOSED ENERGY HARVESTING SYSTEM

A. *Operating Principle*

The principle of the anticipated energy harvesting system relies on the increased intensity of solar radiation on the pyroelectric material by means of an optical concentration system and is shown in Fig.1. By concentrating solar radiation, higher temperature can be achieved which may not be possible by normal exposure to solar radiation. And this incident concentrated radiation on the pyroelectric material has to be modulated in order that the pyroelectric material heating is periodic.

Modulation can be achieved by means of a rotating mechanical chopper disc which is placed in between the reflector and the pyroelectric material. The energy required to rotate the chopper can be derived from the kinetic energy of the wind by means of a wind turbine attached to the optical concentration system. The mechanical energy input from the wind turbine is transmitted to the chopper disc using a belt drive mechanism via a speed reduction unit. The speed reduction unit is necessary to reduce speed of rotation of the chopper disc, so that the active material will have a longer period of heating and cooling phase.

B. Selection of Components

Optical concentrators can be either the reflective type, like those which use parabolic trough, or the refractive type, like those which employ Fresnel lens [12], [4], [13]. However, these concentrating devices require tracking systems in order to follow the sun precisely and they are able to concentrate only the beam or direct radiation from the sun. An imaging type Fresnel lens actually transfers the image of the sun onto the receiver but falls short of the maximum concentration limit due to the chromatic aberrations [14], [15]. Also the cost of Fresnel lens is higher compared to parabolic reflectors in which trackers are available. Hence parabolic reflectors are used for the energy harvesting system.

The wind turbine, which provides the mechanical input to the chopper disc, has to be attached to the optical concentration unit which in turn will be aligned into the direction of the sun. So it would be reasonable to use a vertical axis wind turbine (VAWT) which can capture wind from any direction regardless of its orientation [2].

Among the two common types of vertical axis wind turbines, Savonius and Darrieus wind turbines, the former is selected because of its simple design and good starting torque when compared to Darrieus turbine which is not self-starting and often requires an induction motor or a Savonius rotor, as a starter [16]. But it should be note that the Savonius turbine is less efficient in extracting power from the wind producing peak power coefficient when the tip speed ratio is less than one [17]. Hence, it is more suitable for low rotations per minute (rpm) applications, which is the present situation. Fig. 2 shows the schematic diagram of the fully assembled pyroelectric energy harvesting system.

C. Experimental Setup

The performance potential of the above described energy harvesting technique has been investigated by an experimental setup shown in Fig.2. Lead zirconate titanate (PZT), whose dimensions and properties are given in Table 1, is used as the pyroelectric material.

Fig.2.Experimental setup of the pyroelectric energy harvesting system

As given in Table 1, the Curie temperature of thePZT-5H is 195ºC and hence, the crystal's temperature can be raised safely up to 115ºC without causing damage to the pyroelectric property of the crystal. The materials are placed in on the wooden plate which acts as a heat sink.

Table 1: Dimensions and Properties of PZT pyroelectric material

Properties	**Value**
Area (Apyro)	$5\times10^{-4}m^2$
Thickness (tpyro)	$5\times10^{-4}m^2$
Density (ρ)	7500 kg/m^3
Curie temperature (Tc)	195ºc
Specific heat (c)	440 J/kg ºc
Pyroelectric coefficient (p)	452$\mu C/m^2K$

A steel pipe of diameter 10.16 cm and length of 30 cm is cut vertically into exactly two halves and they are on a stand as shown in Fig.3, in order to get the required

"S" shape of the savonius wind turbine with bucket gap width of 3 cm and diameter of 17 cm.

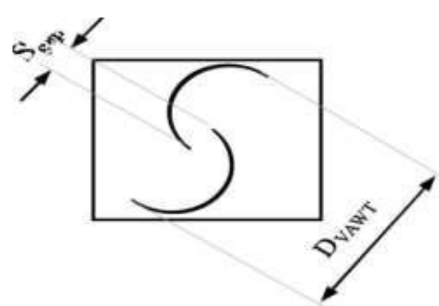

Fig.3.Dimension of the Savonius Vertical Axis Wind Turbine

A point focusing parabolic reflector made up of aluminium sheets as shown in fig.4 and is held firmly to a stand facing the sun. Above the reflector, the pyroelectric material fitted onto the wooden plate is placed exactly focusing the lens. And the heat sink is kept at 15cm from the reflector so that the concentrated spot size of the reflector is almost the size of the pyroelectric material. This ensures uniform surface heating of the pyroelectric material and prevents secondary pyroelectric effect which may rise due to spot heating [18].The PZT-5H is placed on the heat sink and standard insulation tapes are used to hold the crystal at outer edges ensuring good thermal contact with the heat sink.

Fig.4.Experimental Setup of the Parabolic Reflector

A hollow rectangular aluminium frame with proper bearing setup to hold the savonius wind turbine is attached to one of the side supports of the steel frame. The rotations of the Savonius wind turbine is transferred to a two-stage gear speed reduction unit using belt drive mechanism attached to the bottom tip of the wind turbine shaft. The chopper disc is made from steel sheet with the shape of two "T"s placed opposite to each other. And this disc is attached to the shaft of the final stage of the speed reduction unit. The thin steel chopper disc is placed between the parabolic reflector and the ferroelectric ceramic so that when it rotates, it chops the concentrated irradiation from the reflector onto the active material. The orientation of the whole steel frame setup along with the wind turbine is manually adjusted in order to align the reflector towards the direction of the sun throughout the day.

III. EVALUATION THROUGH EXPERIMENTAL PROTOTYPE

The fully assembled prototype along is tested on 5.11.2014 on a cool day in actual operating conditions. During testing, the ambient temperature was around 29ºC. Fig.5 shows a graph of output voltage from with respect to time using a multimeter connected to its electrode terminals. The temperature of PZT-5H reached a maximum of 33.45ºC and the output voltage reached a maximum and minimum of 2.17 and -3.19 V, respectively. The maximum change in the temperature is 3.25 ºC.

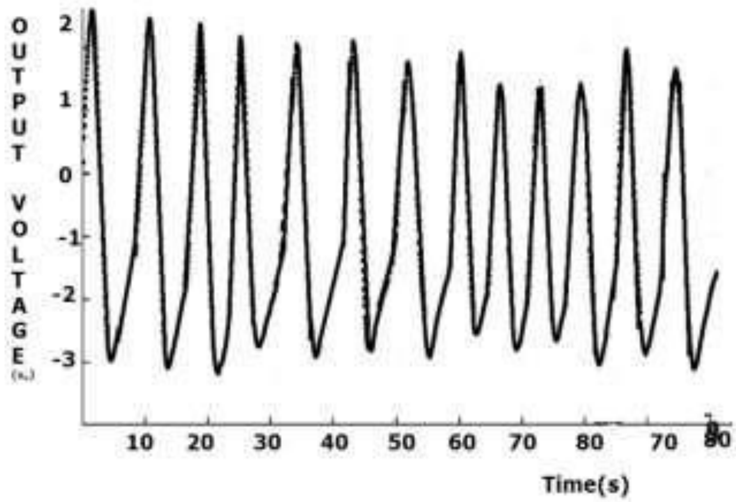

Fig.5. Output Voltage Vs. Time Waveform of Pyroelectric Material

Table 2.Tabulation of the Output Voltage Value for Different Temperature During Heating And Cooling Phase

S. NO.	TEMPERATURE(°c)		VOLTAGE (V_0)	
	HEATING PHASE	COOLING PHASE	HEATING PHASE	COOLING PHASE
1	33	31	-2.9	2.51
2	33.45	30.2	-3.1	2.3
3	32.6	31.1	-3.19	2
4	31	30	-2.8	1.97
5	30.7	29	-2.91	1.7

The Table 2 shows the tabulation of the output voltage of the pyroelectric material for different temperature during heating and cooling phase. From the table it is clear that when the temperature of the pyroelectric material rises from the ambient temperature, the voltage produced by the material increases in the negative direction and when the rotating chopper disc blocks the input concentrated radiation, the temperature drops and the output voltage of the pyroelectric material Vo responds by increasing to reach positive maximum.

It is understandable that very large temperature rates could have been obtained if the ambient temperature is high i.e., during summer season. As the pyroelectric material generates a temporary voltage for normal room temperature, if the solar intensity is more than the reflected solar light intensity will be too high from the parabolic reflector then the material will generate even more voltage as the rate of change of temperature will be more. The rate of cooling is rapid at the beginning and it slows down as the temperature of the ceramic reaches the ambient temperature which explains the low slope region of the output voltage. The power density produced by the ceramic will be relatively low for the cases where the irradiation intensity is low and the radiation chopping frequency is high due to high wind speed.

IV. CONCLUSION

The solar energy is a free form of source for the pyroelectric materials and it has large temperature potential. A large rate of change of temperatures can be created by utilizing the ambient solar and wind energies which results in higher output voltage. Also the results demonstrate a significant fact that, with the help of concentrating optics and a proper cooling mechanism, a temperature profile oscillating between large temperature gradient can be obtained, which is, in general, rather difficult to find in nature. In this thesis, a pyroelectric-based energy harvesting system which converts the radiant energy from the Sun into useful power is designed and tested.

The principle aim of the present work is to maximize the rate of change of temperature of the pyroelectric material, as it directly influences the power output from the pyroelectric material using the freely available solar and wind energies. A well-known technique to increase solar intensity by means of concentrating solar collector based on parabolic reflectors and the mechanical input from the Savonius wind turbine are combined to produce the desired large rate of change of temperature on the pyroelectric material PZT-5H. It is also observed that the variations in the generated power density depend on the intensity of the solar radiation and the wind speed.

REFERENCES

[1] Hadni A.(1981), Applications of the pyroelectric effect, J. Phys. E: Sci. Instrum., 14 Pg.No:1233-1240.

[2] Harihara Krishnan S., Ezhilarasi D., Uma G., and Umapathy M.(2014), 'Pyroelectric-Based Solar and Wind Energy Harvesting System',IEEE transactions on sustainable energy, vol.5.no.:1.

[3] Hemami .A, (2012) 'Wind Turbine Basic Types: Analysis and

Characteristics inWind Turbine Technology', 1st ed. NewYork, NY,USA:Cengage Learning, ch.4, pp. 47–61

[4] Hiroshi Maiwa, Yasuhisa Ishizone, And Wataru Sakamoto(2012), 'Thermal And Vibrational Energy Harvesting Using PZT- And BT-Based Ceramics'

[5] A. Navid, D. Vanderpool, A. Bah, and L. Pilon, "Towards optimization of a pyroelectric energy converter for harvesting waste heat," Int. J. Heat Mass Transfer, vol. 53, pp. 4060–4070, Jun. 2010.

[6] [H. Nguyen, A. Navid, and L. Pilon, "Pyroelectric energy converter using co-polymer P(VDF-TrFE) and Olsen cycle for waste heat energy harvesting," Appl. Thermal Eng., vol. 30, pp. 2127– 2137, May 2010.

[7] F. Y. Lee, A. Navid, and L. Pilon, "Pyroelectric waste heat energy harvesting using heat conduction," Appl. Thermal Eng., vol. 37, pp. 30–37, Dec. 2011.

[8] J. Xie, P. P. Mane, C. W. Green, K. M. Moss, and K. K. Leang,"Energy harvesting by pyroelectric effect using PZT," in Proc. ASME Conf. Smart Materials, Adaptive Structures and Intelligent Systems (SMASIS08), Maryland, USA, 2008, pp. 1–5.

[9] P.Mane, J. Xie, K.K. Leang, and K.Mossi, "Cyclic energy harvesting from pyroelectric materials," IEEE Trans. Ultrason., Ferroelectr., Freq. Control, vol. 58, no. 1, pp. 10–17, Jan. 2011.

[10] Q. Zhang, A. Agbossou, Z. Feng, and M. Cosnier, "Solar micro-energy harvesting with pyroelectric effect and wind flow," Sens. Actuators A,Phys., vol. 168, pp. 335–342, May 2011.

[11] G. Sebald, D. Guyomar, and A. Agbossou, "On thermoelectric and pyroelectric energy harvesting," Smart Mater. Structures, vol. 18, no. 125006, p. 7, Sep. 2009.

[12] Krikke J.(2005), 'Sunrise for energy harvesting products',IEEE Pervasive Comput. vol.4, pp. 4-35.

[13] Smestad G.,Ries H., Winston R., and Yablonovitch E.,(1990) 'The thermodynamic limits of light concentrators,' Solar Energy Mater., vol. 21, pp. 99–111.

[14] Paradiso J.A. and Starner T. (2005), 'Energy scavenging for mobile and wireless electronics' ,IEEE Pervasive Computing , vol. 4, pp. 18 27.

[15] Satillwell P. F. T. C.(1981), Thermal imaging, J. Phys. E: Sci. Instrum., 14,pg. no.: 1113-1138.

[16] Nye J.F., (1985)'Thermodynamics of equilibrium properties of crystals,'in Physical Properties of Crystals: Their Representation by Tensorsand Matrices. London, U.K.: Oxford Univ. Press, ch. 10, pp.188–190.

[17] Mane P., Xie J., Leang K.K., and Mossi K. (2011), 'Cyclic energy harvestingfrom pyroelectric materials', IEEE Trans. Ultrason., Ferroelectr., Freq.Control, vol. 58, no. 1, pp. 10–17.

[18] Navid A. and Pilon L.(2011), 'Pyroelectric energy harvesting using Olsencycles in purified and porous poly(vinylidene fluoride-trifluoroethylene)[P(VDF-TrFE)] thin films', Smart Mater. Structures,vol. 20, no.025012, p.9.