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Waste Heat Energy Recovery Using Thermoelectric Generator

Rajat Murdia[1]
[1](*Mechanical Engineering, National Institute of Technology, Raipur, India)*

Abstract: *Present day modern industries are very energy intensive one. In various manufacturing and process plants large amount of residual heat is being wasted. For example in a steel plant cooling of newly casted or rolled bars is involved, in a cement process plant cooling of clinker evolve large amount of residual heat etc. Although the heat available from these sources is of low grade quality and conventional energy conversion process proves to be insufficient, however by the application of thermoelectric generator this low grade energy can be converted into high grade electrical energy. Through analysis of an arbitrary thermoelectric generator using ANSYS feasibility of thermoelectric generation is been shown in the following paper. Along with that selection criteria and design considerations are also been discussed.*

Keywords: *Thermoelectric, Seebeck effect, figure of merit, thermocouple, high grade energy, thermoelectric module*

I. Introduction

Conversion of heat energy into electrical energy can be accounted by the Seebeck effect according to which if a steady state temperature gradient is maintained along the finite conductor, the free carrier at the hot end will have greater kinetic energy and tends to diffuse to cold end and it would lead to development of electric potential. The accumulation of charge results in a back e.m.f which opposes the further flow of charges. The Seebeck voltage is open circuit voltage when no current flows. If the junction of two dissimilar conductor 'a' and 'b' are maintained at two different temperature T_h and T_c, where $T_h > T_c$, than open circuit potential difference is developed will be given by(1):

$$V = \alpha_{ab}(\mathrm{Th} - \mathrm{Tc})$$

Where ($\alpha_{ab} = \alpha_a - \alpha_b$)

Most of the metals possess Seebeck coefficient of $10\mu V^{-1}$ or less, **but semiconductors are promising in construction of thermocouple because they have Seebeck coefficient in excess of $100\mu V^{-1}$.**

A good thermoelectric material must have large Seebeck coefficient, high electrical conductivities and low thermal conductivities to retain heat at the junction and to reduce the heat transfer losses. The above requirements are summarized in form of figure of merit (Z) (1)

$$Z = \frac{\alpha^2 \sigma}{\gamma}$$

II. Material for Thermoelectric Generator

Only few material to date are identified as thermoelectric materials. Most thermoelectric materials today have ZT value around unity, such as bismuth telluride at room temperature and lead telluride at 500-700K. While selecting material for thermoelectric generation number of factors needs to be considered, as during operation thermoelectric generator has large temperature gradient across it. Thermal expansion will then introduce stress in device which may cause facture of TE legs, or separation from coupling material. The mechanical properties of material must be considered and coefficient of thermal expansion of the n-type and p-type must be matched reasonable well.

As in manufacturing plants the operation range is somewhat between 200°C to 600°C, so PbTe is most suitable because in this range its ZT value is significantly high(1). Beside this PbTe have a high melting point, good chemical stability, low vapor pressure and good chemical strength.

Lead telluride, has rock salt structure (face center cubic (FCC)). PbTe can be n- or p-type material as a result of departure from stoichiometry. To produce the Seebeck coefficient of+200μVk^{-1}, doping is necessary (2).

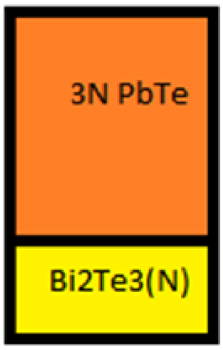
III. Design of thermoelectric generator

Here the intended application of thermoelectric generator is in manufacturing industries like steel, cement etc. where the average temperature of operation is in range of 200°C to 600°C. From the study of various research papers it was concluded that in this range 3N-PbTe and 2P-PbTe shows highest figure of merit(1).

As figure of merit and performance of TE material strongly depends on temperature and the temperature varies along the semiconductor length of semiconductor leg so their also lies a scope of using more than one type of semiconductor which shows highest figure of merit in a particular range along this length. And the size of different semiconductors material legs can be optimized by using temperature distribution contours from analysis of TE module. Such an arrangement may help in increasing the efficiency as well as power output.

A thermocouple produces low voltage and high current. Thus to obtain high voltages, a number of thermocouple can be connected electrically in series and thermally in parallel to form a TE module. At device level, the conflicting parameter becomes thermal conductance and electrical resistance which includes physical geometry of material in addition to intrinsic material properties. There is a trade-off between the total thermal conductance and electrical resistance of TE material at module level.

There are challenging material requirement for module substrate. The substrate must be electrically insulating but thermally conducting. The TE legs are attached to substrate, so substrate must have sufficient mechanical strength to support legs and interconnects. After an intensified study it was found that AlN(Aluminum Nitride) is most suitable material for substrate as it has high thermal conductivity and possess great insulating properties along with this AlN have thermal expansion coefficient. Some of its important properties are tabulated:



Properties of Aluminium Nitride	
Coeff. of thermal expansion(RT 1000°C) x10^{-6} K^{-1}	5.6
Thermal conductivity (watt/mK)	140-177
Dielectric constant	8.6

TE leg with two different materials

Now since the voltage developed is directly proportional to the temperature difference between the two junctions hence there is a strong need for removing heat from colder side, in order to achieve this fins can be extruded from the colder junction as by doing this area for heat transfer is greatly increased along with this coefficient for convective heat transfer can also be increased by using fans at cold junction.

IV. Analysis of performance of thermoelectric couple using ANSYS

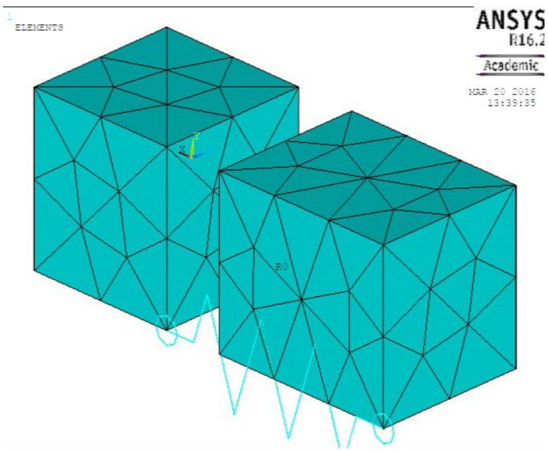
A model of thermoelectric couple was prepared using the ANSYS® MECHCNICAL APDL and this was than analysed using thermoelectric capabilities of ANSYS®. Here the main purpose of analysis is to show the feasibility of real life application of Seebeck effect in thermoelectric generator. Thermocouple was designed with assumption of average material properties, details of properties, load data, design data are tabulated below:

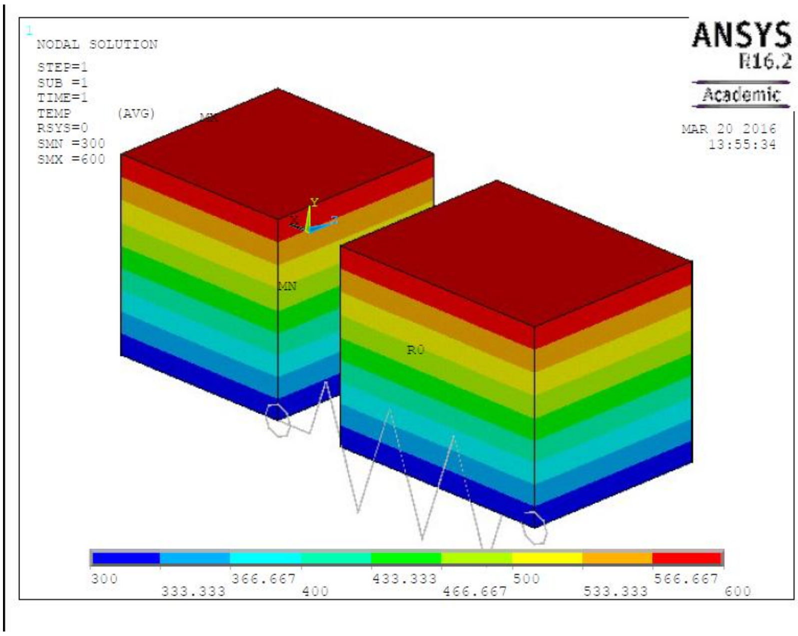
Dimension	n-type material	p-type material
Length	10mm	10mm
Width	10mm	12.4mm
Thickness	10mm	1mm

Load data	
Cold junction temperature	300°C
Hot junction temperature	600°C
External Load resistance	3.92e-03 ohms
Element for p & n material	SOLID226
Element for Resistance	CIRCU124

Component	Resistivity (ohm*cm)	Thermal Conductivity (watt/cm°C)	Seebeck coefficient (µvolts/°c)
n-type material	$\rho_n = 1.35 \times 10^{-3}$	0.014	$\alpha_n = -195$
p-type material	$\rho_p = 1.75 \times 10^{-3}$	0.012	$\alpha_p = 230$

Results (analysis was performed on ANSYS Student V16.2)	
VOLTAGE	0.074806 VOLTS
CURRENT	19.083 AMPERE
POWER	1.4275 TS





V. Conclusion

Above results is very encouraging and it shows the huge potential of thermoelectric generation to recover the low grade thermal energy and convert it high grade electrical energy. The above result is an output of single thermocouple, if hundreds of similar thermocouples are arranged electrically in series than several hundreds of watts of useful energy can be recovered at desired potential difference.

With the help of thermoelectric analysis, the design of thermocouple can be further optimized by changing the dimensions and shape of TE legs. Along with this the scope of using two different materials in single leg can also be verified as the analysis provide us with counters of temperature distribution, by doing this the efficiency of TE module can be improved. Analysis performed here was intended just to show the feasibility of thermoelectric generators and the material properties were taken as average for more accurate details the actual non-linear variation in properties can be incorporated. Furthermore to make model more realistic convective heat transfer at colder junction can be put as boundary condition it will provide more accurate results

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