PERFORMANCE AND REGRESSION ANALYSIS OF THERMOELECTRIC GENERATOR FOR POWER GENERATION

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Abstract*— In recent years, an increasing concern of environmental issues of emission, in particular global warming and the limitation of energy resources has resulted in extensive research into novel technologies of generating electrical power. The thermoelectric generator is a promising device which converts waste heat into electricity. The experimentation is carried out to examine the effect of the various operating conditions such as the hot plate and cold fluid temperature, cold fluid (water) flow rates, on the output power. In this work, measured open circuit voltage, current and power output at various mass flow rate of water and temperature difference. The thermoelectric generator efficiency will be asses and construct such systems which recover maximum heat recovery by comparing TEG. Bismuth telluride has maximum figure of merit and best selection for maximum thermal power generation in case of higher temperature. Heat sink experimentation will be carried out in order to increase the power density of TEG by maintaining its inlet temperature constant. The output power is linearly depends on temperature difference. Regression analysis is used for optimization and best fit data will be obtained for regression model. Regression analysis is used for maintaining the relationship between the variable.

***Index Terms*— TEG, Regression analysis, TEG Module**

I. INTRODUCTION

The threats of global warming cause by maximum energy released into atmosphere make the development of energy recovery in the nature of an extent imperative. Thermoelectric Module (TEM) offers thermoelectric energy conversion in a simple and suitable path along with advantages of not involving moving or complex parts, silent in operation, maintenance free and environmental friendly [1]. Over the last 30 years, there has been growing interest in applying this thermoelectric technology to enhance the efficiency of waste heat recovery concerning no. of heat sources such as geothermal energy, power plants, and other industrial heat-generating process[1,2].The relatively low conversion efficiency of thermoelectric modules 5%.has been a main important factor in limiting their applications in power generation and has restricted their use to specialized situations where reliability is a major consideration. [3].

John Fairbanks (2008) tested over 100 couples which are made up of oxides, metals, minerals and several other compounds. He conclude that thermoelectric generators and HVAC significantly improve fuel economy also the role of thermoelectric devices in reducing greenhouse gases would be very important in the global climate scheme of things [4]. Xing Niu et al. (2009) carried out the experiments to observe the influences of the main operating conditions such as the hot and cold fluid inlet temperatures, flow rates on the power output and conversion efficiency. The two operation parameters like this hot fluid inlet temperature and flow rate are found to significantly alter the maximum power output and conversion efficiency [5].Cheng-Ting Hsu et al. (2011) constructed a system to recover waste heat by comparing 24 thermoelectric generators (TEG) to convert heat from the exhaust pipe of an automobile to electrical energy. They observed that the open circuit voltage (Voc) is raised linearly with DT and power output is increased instantaneously with increasing the temperature difference. [6]. M.A. Karri et al.(2011) examined the potential benefits of the application of QW and Bi2 Te3 based thermoelectric power generation from the SUV and CNG engine power generator. The increase in power between the QW- and Bi2Te3- based generators was about three times for the SUV and seven times for the CNG generator beneath the same simulation conditions.. For the CNG case the fuel savings was around 0.4% using Bi2Te3 and around 3% using QW generators [7].

Ching-Chang Wang et al. (2011) investigated the performance of a TEG combined with an air-cooling system designed by using two-stage optimization. They used an analytical method to model the heat transfer of the heat sink and a numerical method in the company of a limited element scheme is employed to predict the performance of the TEG. Heat sink efficiency is reduced by 20.93% compared to that without the ideal design; the TEG output power density is increased by 88.70%. It is therefore recommended for the design of the heat sink. Moreover, the TEG power density can be further improved by scaling-down the TEG when the heat sink length is beneath 14.5 mm [8]. John Aldrich (2005) introduced the modern regression model, synthesizing the regression theory of Pearson and Yule and the least squares theory of Gauss. Regression was used for investigating causal relationships but in the statistics tradition the causal interest was not intrinsic to the statistical analysis but something apart [9]. Chris Tofallis (2009) present the method of least squares regression based on percentage errors. Precise expressions are derived for the coefficients. When the relative defect is normally distributed, least squares percentage regression is shown to make possible maximum likelihood estimates [10].

II. EXPERIMENTAL SET UP

TEG is the sandwich between heat source and heat sink. In between heat source and heat sink the TEG module is installed by filling the remaining gap with the help of thermal grease. Thermal grease is provide in order to avoid the temperature loss when heat source is maximum. The modules will generate electricity only if there is a temperature difference cross the modules. So, it is necessary to attach one side of the modules to a heat source and the other side to a cool source like heat sink to dissipate the heat coming from heat source through the modules. Our module is unique and different to others.

The modules have cold and hot sides. You should fasten the cold side to heat sink and hot side to heat source. Then the positive output is shown by red wire in the assembly, if reversed, then in black colour wire. The temperature on the hot side of the module can work continuously at as high as 120 °C. But the temperature at cold side of the module cannot work properly above 200 °C. So, if the mounting is reversed, and the cold side of module is attached to heat source above 200 °C (392 °F), the module will degrade quickly or fail immediately. So, please ensure hot side attached to heat source is very important.

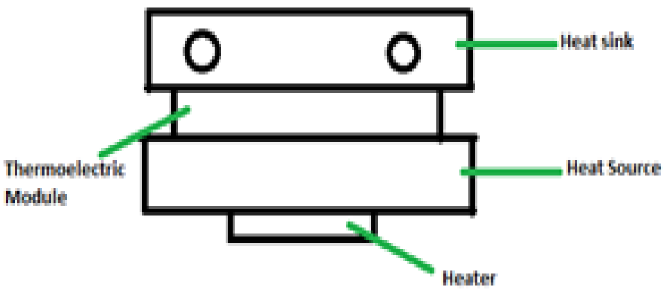

Fig 1. TEG experimental set up

III. SELECTION OF MATERIALS

Thermoelectric device is made up of commonly based alloys but the alloy which shows highest figure of merit at lower temperature range is preferable. Thermoelectric materials commonly classified into three groups based on the temperature range of operation, as shown in Figure 2. Alloys based on Bismuth (Bi) in combinations with Antimony (An), Tellurium (Te) or Selenium (Se) are considered to as low Temperature materials and can be used at temperatures range up to around 450K. The intermediate temperature range- up to around 850K is the regime of materials which is based on alloys of Lead (Pb) while thermoelectric elements employed at the highest temperatures are fabricated from SiGe alloys and operate up to 1300K.

Many of significant advances have been made in synthesizing new materials and fabricating material structures with improved and valuable thermoelectric performance. Main observations have been focused on primarily improving the material's figure-of-merit which probably improve the conversion efficiency, by reducing the lattice thermal conductivity.

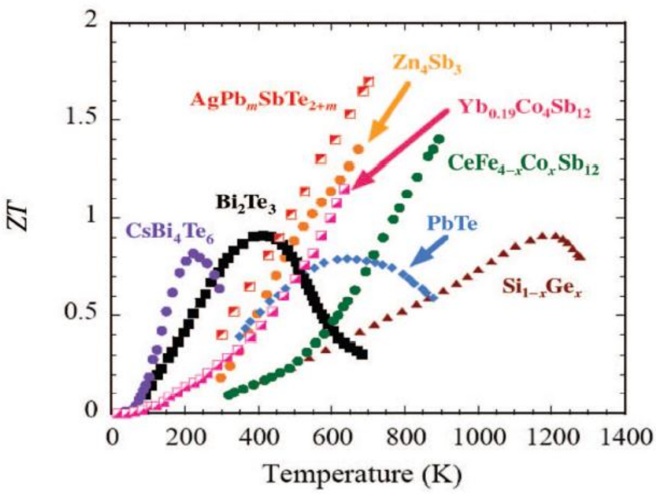

Fig 2. Dimensionless Figure of Merit of Common Thermoelectric Materials [11]

IV. RESULT AND DISCUSSION

Figure 3 shows power changes with Temperature difference at various mass flow of water at cold side of thermoelectric generator. Power increases with increasing temperature difference at all mass flow rate of water. At 0.048 kg/sec mass flow rate shows more power as compared to other mass flow rate.

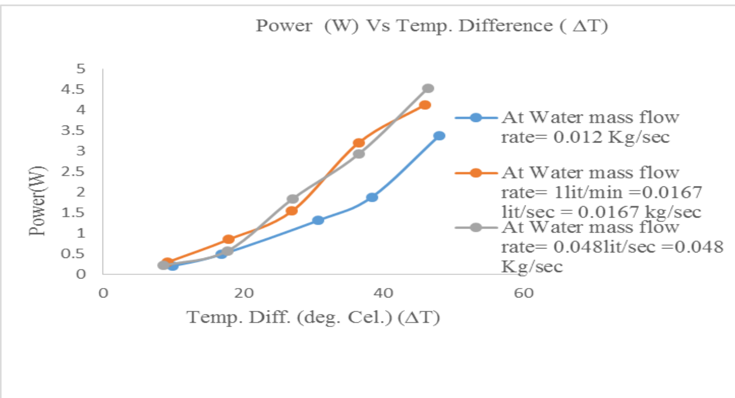

Fig 3. Power vs Temp. Difference

Figure 4 shows power varies with voltage at various mass flow of water at cold side of thermoelectric generator. Power increase with increasing voltage at all mass flow rate of water. At 0.048 kg/sec mass flow rate shows more power as compared to other mass flow rate.

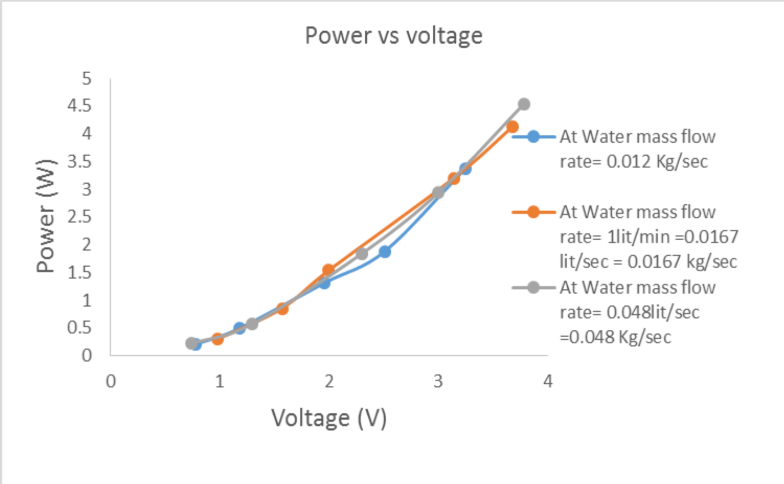

Fig 4. Power vs voltage

Figure 5 shows power varies with current at various mass flow of water at cold side of thermoelectric generator. Power increase with increasing in current at all mass flow rate of water. At 0.048 kg/sec mass flow rate shows more power as compared to other mass flow rate.

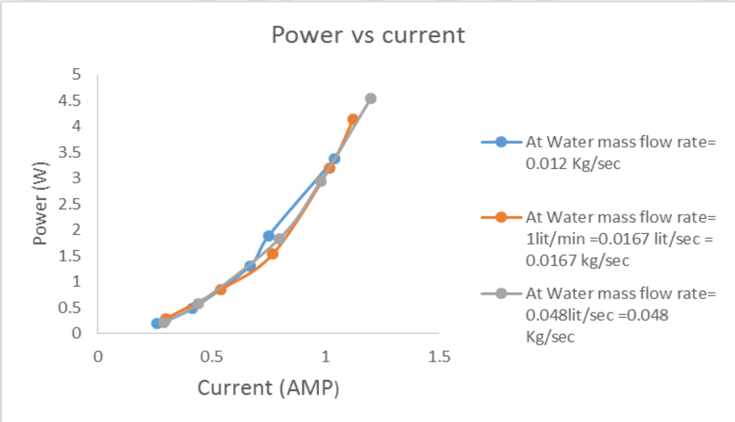

Fig 5. Power vs current

V. REGRESSION ANALYSIS OF TEG

Regression analysis is a process for estimating the relationships among the dependent and independent variables. In this the variables are made relationship with adjacent variable which finally optimize the best value of variable with the help of value plotting on graph. It consists of many techniques for the purpose of modeling and analyzing dependent and independent variables, when the focus is on the relationship between a dependent variable and one or more independent variables. Regression analysis is commonly used for prediction and forecasting, Regression analysis is also used to understand which among the independent variables are related to the dependent variable and from the valuable relationship in between them. At the some stages of restriction these analysis shows infer causal relationship between Independent and dependent variables regression analysis the variable is represented by C1, C2, C3 and C4. Here,

C1 =Temperature diff.
C2 = Open circuit voltage
C3 = Current
C4 = Power
4.1 Regression Analysis: C4 versus C1, C2, C3

I] At Water mass flow rate= 0.012 Kg/sec

The regression equation is

C4 = - 1.31 - 0.201 C1 + 3.53 C2 + 2.74 C3

The line intersect Y axis at 1.31 with negative slope of C1 and positive slope of C2 and C3. For C4, it is increase due to C2 and C3 and decrease due to slope C1 and 1.31.

predictor	Coef	SE Coef	T	P	VF
Constant	-1.3089	0.1559	-8.40	0.075	
C1	-0.20090	0.0511	-3.93	0.159	194.12
C2	3.5343	0.8906	3.97	0.157	244.09
C3	2.736	1.653	1.66	0.346	77.615

The sample estimate of alpha and beta are -1.3089 and values of C1, C2 and C3 for Coef. The corresponding test statistics are - 8.40 and corresponding values of C 1, C2 and C3 for T. Thus first Two large value lies on the extreme end of t- curve. Thus we reject the null hypothesis of alpha=0 and beta=0 and conclude that the beta and alpha play a significant role in regression model.

S = 0.113492	**R-Sq** = 99.8%	**R-Sq(adj)** = 99.2%

The standard deviation of the error terms is 0.113492. A 99.2% R-Sq (adj) indicates that whenever we observe a variation in the value of y 99.8% of it is due to the model that is this data fits well to the linear model.

Analysis of Variance

Source	DF	SS	MS	F	P
Regression	3	6.3794	2.126	165.09	0.057
Residual Error	1	0.0129	0.012		
Total	4	6.3923			

II] At Water mass flow rate = 0.0167 kg/sec

The regression equation is

C4 = - 1.08 + 0.0277 C1 + 1.66 C2 - 1.94 C3

The line intersect Y axis at 1.08 with negative slope of C3 and positive slope of C1 and C2. For C4, it is increase due to C1 and C2 and decrease due to slope C3 and 1.08.

Predictor	Coef	SE Coef	T	P	VIF
Constant	-1.0821	0.2764	-3.91	0.159	
C1	0.2771	0.0535	0.52	0.696	99.787
C2	1.6650	0.4994	3.33	0.186	50.946
C3	-1.942	1.689	-1.15	0.456	53.808

The sample estimate of alpha and beta are -1.0821and values of C1, C2 and C3 for Coef. The corresponding test statistics are – 3.91 and corresponding values of C1, C2 and C3 for T. Thus first Two large value lies on the extreme end of t - curve. Thus we reject the null hypothesis of alpha=0 and beta=0 and conclude that the beta and alpha play a significant role in regression model.

S = 0.156022	**R-Sq** = 99.8%	**R-Sq(adj)**= 99.1%

The standard deviation of the error terms is 0.156022. A 99.1% R-Sq (adj) indicates that whenever we observe a variation in the value of y 99.8% of it is due to the model that is this data fits well to the linear model.

Analysis of Variance

Source	DF	SS	MS	F	P
Regression	3	10.40	3.4686	142.49	0.061
Residual Error	1	0.024	0.0243		
Total	4	10.43			

III] At Water mass flow rate = 0.048 Kg/sec

The regression equation is

C4 = 0.541 - 0.387 C1 + 12.9 C2 - 22.5 C3

The line intersect Y axis at 0.541 with negative slope of C1, C3 and positive slope of C2. For C4, it is increase due to C2. 0.541 and decrease due to slope C1, C3.

Predictor	Coef	SE Coef	T	P	VIF
Constant	0.5410	0.6581	0.82	0.562	
C1	-0.3869	0.1715	-2.26	0.266	668.74
C2	12.935	4.440	2.91	0.211	3074.74
C3	-22.531	8.408	-2.68	0.227	1024.36

The sample estimate of alpha and beta are 0.5410 and values of C1, C2 and C3 for Coef. The corresponding test statistics are – 0.82 and corresponding values of C1, C2 and C3 for T. Thus first Two large value lies on the extreme end of t- curve. Thus we reject the null hypothesis of alpha=0 and beta=0 and conclude that the beta and alpha play a significant role in regression model.

S = 0.197524	**R-Sq** = 99.7%	**R-Sq(adj)**= 98.8%

The standard deviation of the error terms is 0.197524. A 98.8% R-Sq (adj) indicates that whenever we observe a variation in the value of y 99.7% of it is due to the model that is this data fits well to the linear model.

Analysis of Variance

Source	DF	SS	MS	F	P
Regression	3	12.52	4.176	107.04	0.071
Residual error	1	0.039	0.039		
Total	4	12.56			

I] At Water mass flow rate= 0.012 Kg/sec

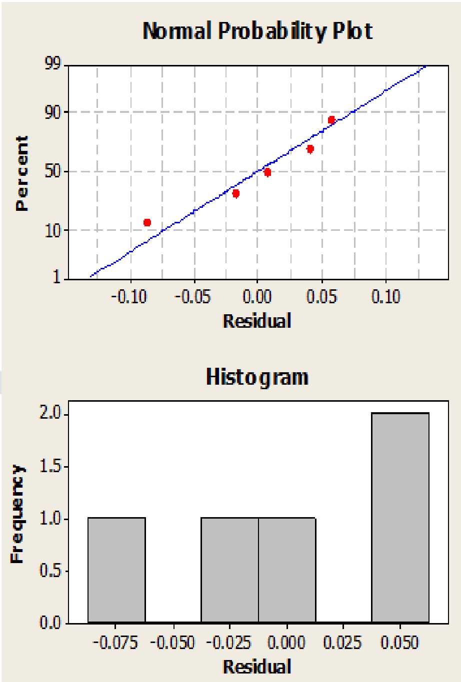

Fig 6. Normal probability plot of Water mass flow rate= 0.012 Kg/sec

1. The graph on the top left checks the assumptions of normality of error terms. In this case we see that most of the point clustered around blue line that error terms are approximately normal. Thus our assumptions of normality is valid.
2. The bottom left graph again re-emphasizes the normality assumption. Thus our sample size is 1

II] At Water mass flow rate = 0.0167 kg/sec

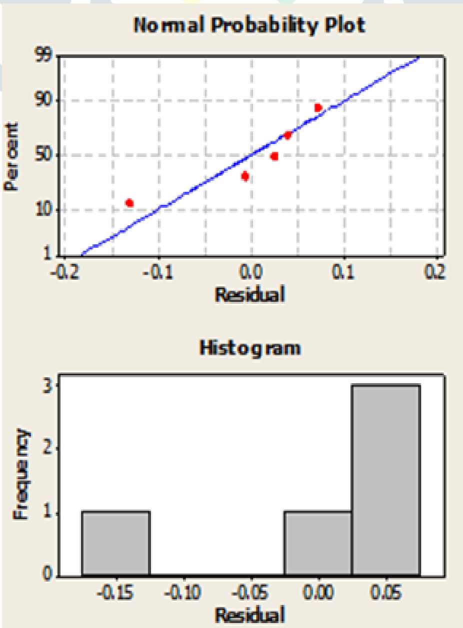

Fig 7. Normal probability plot of Water mass flow rate= 0.0167 Kg/sec

1. The graph on the top left checks the assumptions of normality of error terms. In this case we see that most of the point clustered around blue line that error terms are approximately normal. Thus our assumptions of normality is valid.
2. The bottom left graph again re-emphasizes the normality assumption. Thus our sample size is 1.

III] At Water mass flow rate =0.048 Kg/sec

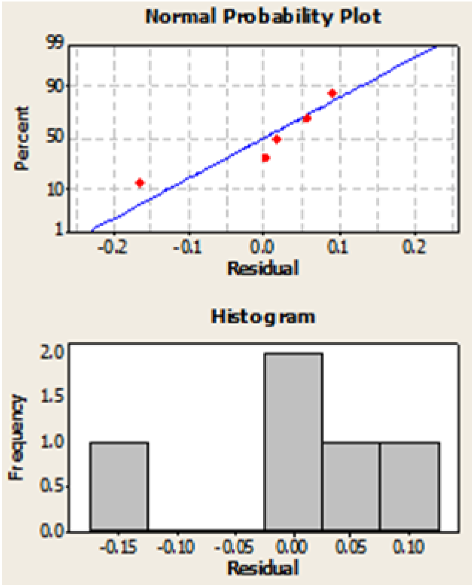

Fig 8. Normal probability plot of Water mass flow rate= 0.048 Kg/sec

1. The graph on the top left checks the assumptions of normality of error terms. In this case we see that most of the point clustered around blue line that error terms are approximately normal. Thus our assumption of normality is valid.
2. The bottom left graph again re-emphasizes the normality assumption. Thus our sample size is 1.

VI. CONCLUSIONS

The thermoelectric generator is a promising device which convert waste heat into electricity. It is observed that the electric power generation of thermoelectric generator be a strong function of flow rate and inlet exhaust temperature. The hot and cold side of TEG module plays an important role in performance of thermoelectric generator. The output power is linearly depends on temperature difference. As per residual plot, normal probability graph shows accuracy of the data. The data for mass flow rate 0.012 kg/ sec are closed to the average line. Power increase with increasing temperature difference at all mass flow rate of water. Power increase with increasing voltage at all mass flow rate of water. Power increase with increasing in current at all mass flow rate of water. At 0.048 kg/sec mass flow rate shows more power as compare to other mass flow rate. We see that most of the point clustered around blue line that error terms are approximately normal. Thus our assumptions of normality is valid.

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