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Experimental Investigation of Heat Sink as a Heat Pipe to Improve Performance of Thermoelectric Generator

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ABSTRACT

Present study focuses on the thermoelectric generator (TEG) using heat pipe as heat sink and Waste heat can be used to generate electricity using thermoelectric generator (TEG). TEG utilizes the thermoelectric effect to generate electric power from a temperature difference across the device. The combined heat pipes thermo-electric generator (CHP-TEG) has been introduced in this study of recovering the free energy from the industrial and automobile waste heat. Two technologies identified to be of use for waste heat recovery are TEGs and heat pipes. Both TEGs and heat pipes are solid state, passive, silent, scalable and durable. The use of heat pipes can potentially reduce the thermal resistance and pressure losses in the system as well as temperature regulation of the TEGs and increased design flexibility. TEGs do have limitations such as low temperature limits and relatively low efficiency. Heat pipes do have limitations such as maximum rates of heat transfer and temperature limits. When used in conjunction, these technologies have the potential to create a completely solid state and passive waste heat recovery system. The conversion efficiency of thermoelectric generator is function of temperature difference (Heat source and heat sink temperature). The thermal performance of thermoelectric generator will be improved or enhanced by using heat pipe as a heat sink on thermoelectric generator.

Keywords: Heat Pipe, Peltier Effect, Seebeck Effect, Thermoelectric Generator, Temperature Difference, Efficiency.

I. INTRODUCTION

During the past few decades, the world population is growing fast along with the progress of new technology for assisting our life quality in a more convenient way. In exchange, the rate of energy consumption also rises significantly, which affects the global natural environment. For example, the emission of carbon monoxide gases from industries waste and transport combustion has destroyed both living thing and ozone layer. [1] In the year 2008, total world requirement for energy was 500 quadrillion BTU, approximately 50% of which was dumped into the environment in the form of waste heat. Waste heat is heat generated in a process by way of fuel combustion or chemical reaction, then “dumped” into the environment even though it could still be reused for some useful and economic purpose. In the industrial sector 20–50% of the energy input is lost as waste heat. The energy lost in waste heat cannot be fully recovered because it is often low-grade heat and dispersed. With the world’s population growing at the rate of 1.1% per year, the energy requirement is expected to double by 2020 [3]. Two promising technologies that are found to be useful for this purpose are thermoelectric generators (TEGs) and heat pipes. Both TEGs and heat pipes are solid state, passive, silent, scalable and durable [2].

A. Principle of Operation of TEG’s

Thermoelectric devices are basically solid state devices that can convert energy from heat to electricity or vice versa. Devices are normally made up of semiconductor materials, the most common being bismuth telluride. A typical configuration of a thermoelectric module consists of many leg pairs made of semiconductor pellets, joined together using contact tabs made of high conductivity materials [3].

1) Seebeck Effect: The principle behind the working of the thermoelectric module is the Seebeck effect. In 1821 Thomas Johann Seebeck observed that when two dissimilar metals with junctions at different temperatures are connected in a circuit, a magnetic needle would be deflected. Seebeck initially attributed this phenomenon to magnetism. However, it was quickly realized that it was an induced electrical current that deflects the magnet. In a thermoelectric module, the two dissimilar conductors are connected electrically in series and thermally in parallel. When the two junctions are maintained at temperatures and respectively, and an open circuit electromotive force is developed between the junctions, as seen in Fig. 1.1.

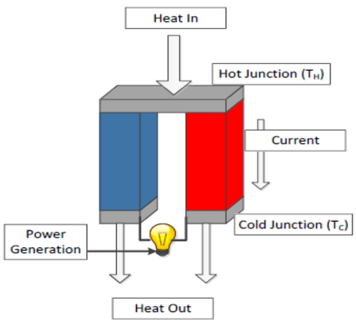


Figure 1: Seebeck Effect

The voltage produced is proportional to the temperature difference between the two junctions. This is given by:

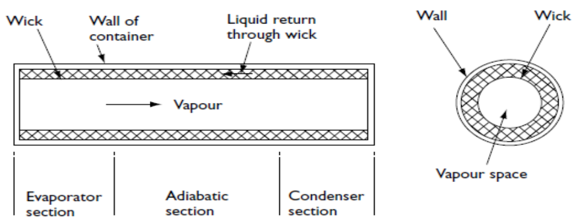
$$V = \propto (Th - Tc) \qquad (1)$$

The proportionality constant, α, is the difference between the Seebeck coefficients of the two materials forming the junction. This is known as the overall Seebeck coefficient, and often referred to as the thermoelectric power or thermo- power. The Seebeck voltage does not depend on the distribution of temperatures along the material between the junctions. This phenomenon is what is used to measure temperatures using thermocouples [4].

B. Heat Pipe

The heat pipe is a vapor and liquid phase change device of very high thermal conductance that transfers heat from a heat source (hot reservoir) to a heat sink (cold reservoir) using capillary forces generated by wick material and the working fluid. It is similar to the thermosyphon in few respects. It combines the principles of both thermal conductivity and phase transition to efficiently manage the transfer of heat between two interfaces. [5] It is referred as superconductor of heat due to their fast heat transfer capability with low heat loss. Heat pipe consists of the evaporators section, adiabatic section, and condenser section. There are three regions separated as vapor region, wick region and the wall region. The working fluid is assumed to be liquid phase in the wick region and vapor phase in the vapor region. Thermal input at the evaporator region vaporizes the working fluid and this vapor travels to the condenser section through the vapor region. At the condenser region, the vapor of the working fluid condenses by rejecting the latent heat. The condensate returns to the evaporator by means of capillary action in the wick. Originally, the heat pipe was first suggested by Gurgler in 1944. But the operational characteristics of heat pipe were not widely publicized until 1963 when Grover and his colleagues at Los Alamos Scientific Laboratory independently reinvented the concept. Since then many types of heat pipes have been developed and used by a wide variety of industries.

The main regions of the standard heat pipe are shown in Fig 2. [7] [8] [9].



(a) Front view (b) Side view

Figure 2: The Main regions of the heat pipe.

Capillary Limit - The capillary limit is the most commonly encountered limitation in the operation of low-temperature heat pipes. It occurs when the pumping rate is not sufficient to provide enough liquid to the evaporator section. This is due to the fact that the sum of the liquid and vapor pressure drops exceeds the maximum capillary pressure that the wick can sustain.

$$\Delta P_c = \Delta P_l + \Delta P_g + \Delta P_v$$

$$r_c = \frac{w + d_w}{2}$$

$$\Delta P_c = \frac{2\sigma\cos\theta}{r_c}$$

$$\varepsilon = 1 - \frac{1.05 \times \pi \times N \times D}{4}$$

$$K = \frac{d_w^2 \times (1-\varepsilon)^2}{66.6 \times \varepsilon^2}$$

$$\Delta P_l = \frac{\mu_l \times Q_c \times L_{eff}}{\rho_l \times L \times A_w \times K}$$

$$\Delta P_g = \rho_l \times g \times l_{eff} \times SIN\emptyset$$

$$\Delta P_v = 0.9^{12} \times k_v \times Q$$

Boiling Limit - If the radial heat flux in the evaporator section becomes too high, the liquid in the evaporator wick boils and the wall temperature becomes excessively high. The vapor bubbles that form in the wick prevent the liquid from wetting the pipe wall, which causes hot spots. If this boiling is severe, it dries out the wick in the evaporator, which is defined as the boiling limit. However, under a low or moderate radial heat flux, low intensity stable boiling is possible without causing dry out. The boiling limit is often associated with heat pipes of on-metallic working fluids. For liquid-metal heat pipes, the boiling limit is rarely seen.

$$l_{eff} = L_a + \frac{L_e + L_c}{2}$$

$$k_{eff} = \frac{k_l[(k_\lambda + k_w) - (1-\varepsilon)(k_l - k_w)]}{(k_\lambda + k_w) + (1-\varepsilon)(k_l - k_w)}$$

$$Q_b = \frac{2\pi l_{eff} \times k_{eff} \times T_v}{A_v \times h_{fg} \times \rho_v \times ln(\frac{r_i}{r_v})}\left[\frac{2\sigma}{r_n} - (\Delta P_c)_{max}\right]$$

Entrainment Limit - A shear force exists at the liquid-vapor interface since the vapor and liquid move in opposite directions. At high relative velocities, droplets of liquid can be torn from the wick surface and entrained into the vapor flowing toward the condenser section. If the entrainment becomes too great, the evaporator will dry out. The heat transfer rate at which this occurs is called the entrainment limit. Entrainment can be detected by the sounds made by droplets striking the condenser end of the heat pipe. The entrainment limit is often associated with low or moderate temperature heat pipes with small diameters, or high temperature heat pipes when the heat input at the evaporator is high[6].

$$Q_e = \pi r_v^2 L \sqrt{\frac{2\pi \rho_v \sigma_l}{z}}$$

Sonic Limit-The evaporator and condenser sections of a heat pipe represent a vapor flow channel with mass addition and extraction due to the evaporation and condensation, respectively. The vapor velocity increases along the evaporator and reaches a maximum at the end of the evaporator section. Therefore, one expects that the vapor velocity at that point cannot exceed the local speed of sound. This choked flow condition is called the sonic limitation. The sonic limit usually occurs either during heat pipe startup or during steady state operation when the heat transfer coefficient at the condenser is high. The sonic limit is usually associated with liquid-metal heat pipes due to high vapor velocities and low densities. Unlike the capillary limit, when the sonic limit is exceeded, it does not represent a serious failure.

$$Q_s = \rho_v L \sqrt{\frac{r R T_v}{2(r-1)}}$$

The Merit number - It will be shown, with reference to the capillary limit, that if vapour pressure loss and gravitational head can be neglected then the properties of the working fluid which determine the maximum heat transport can be combined to form a figure of merit, M [10].

$$M = \frac{\rho_l \times \sigma \times L}{\mu_l}$$

II. EXPERIMENT ANALYSIS

TABLE 1

SPECIFICATION OF HEAT PIPE

Sr. No.	Description	Dimension (mm)
1	Heat pipe total L	140
2	Evaporator sec.L	40
3	Adiabatic sec. L	20
4	Condenser sec. L	70
5	Heat pipe inner dia.	8
6	Heat pipe outer dia.	10
7	Heat pipe wall thic.	0.5
8	Wick area (m^2)	2.3202e-5
9	Water jacket	Circular
10	Number of water j.	One each H.P.
11	Fin outer diameter (	25.4

Figure3: Heat sink (Heat Pipe) with heat spreder

Experimental setup is constructed on the basis of simplicity and practicability. Experiment was conducted. Heat source are manufactured using 10 mm thick commercially available aluminum material and mild steel. Fabrication work was carried out by Ashirwad enterprises, nigadi, Pune. The upper part of heat source is clamped with the help of nut and bolt assembly. In order to avoid the leakage, the nut and bolt are tight very well. On the upper surface of heat source thermoelectric module is place with thermal grease is applied on it in order to avoid the thermal contact resistance.

Figure 4 : Experimental Setup

On the upper surface of TEM the heat sink (Heat Pipe) is placed with properly attachment of surface to the module. In order to avoid the gap in between module, heat source and heat sink the nut & bolts is providing to make proper contact in order to avoid the loss of temperature as shown in fig.5.

Figure5: Heat pipe arrangement as heat sink

III. RESULTS AND DISCUSSION

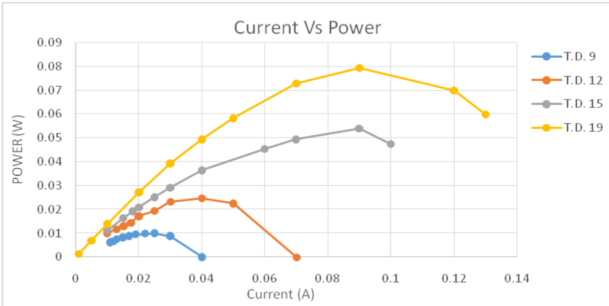


Figure 6: Current vs Power Output at different temp

Figure 6 shows output power varies with current at various temperature differences at cold side of thermoelectric generator. Output power increases initially and gradually decreases when current increases at all temperature difference. At 19°Ctemperature difference more output power as compare to other temperature difference.

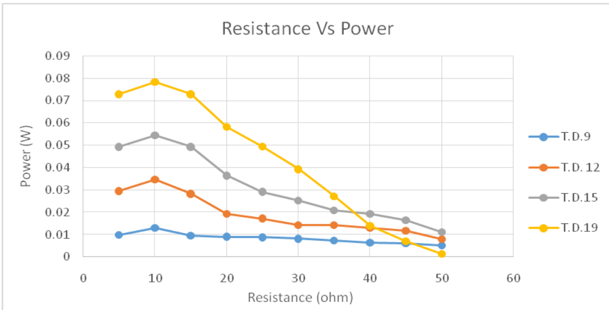


Figure 7 : External Load Resistance Vs.Power O/pat diff,temp diff.

Figure 7 shows output power varies with current at various temperature differences at cold side of thermoelectric generator. Output power increases initially and gradually decreases when current increases at all mass flow rate of water. At 19 ^{0}C mass flow rate shows more output power as compare to other temperature difference.

Figure 8 shows External Load Resistance Vs Current at different temp difference which is varied by rheostat. It is observed that when external resistance increases, initially current increases and reach at maximum value and decreases with increasing external resistance. Maximum current is obtained at temperature difference 19^{o} C and external resistance is 05 ohms.

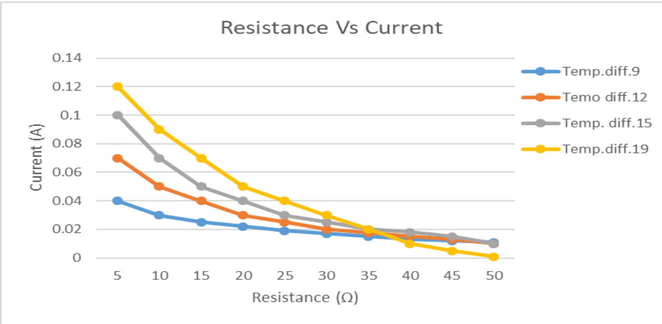


Figure 8: External Load Resistance Vs Current at different temp difference

Figure 9 shows external load resistance Vs voltage which is varied by rheostat. It is observed that when external resistance increases, initially voltage increases and reach at maximum value. Maximum voltage obtained is 1.41 V at temperature difference 19 ^{0}C and external resistance is 05 ohms.

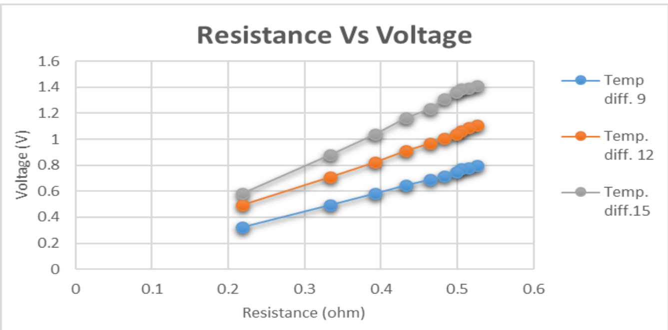


Figure 9: Effect of Ext. Load Resistance Vs Voltage diff. temp. diff.

At Water mass flow rate= 30.00 Kg/sec

Figure 10 shows output power and conversion efficiency vs resistance at constant mass flow rate of water = 30.00 Kg/sec. The output power and conversion efficiency initially increase with increasing resistance. It is observed that at 10 Ω it shows maximum power 0.0145W and at 10 Ω it shows maximum conversion efficiency of 0.09623 ‰ and after that it is decreases with increasing in resistance

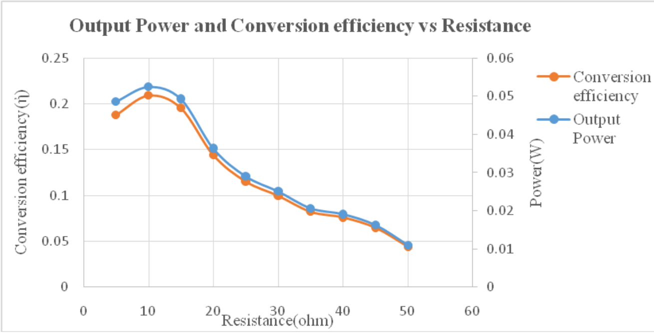


Figure 10 : O/P Power and Conversion Eff. Vs Resistance at constant mass flow rate

At Water mass flow rate= 93.00 Kg/sec

Figure 11 shows output power and conversion efficiency vs resistance at constant mass flow rate of water = 93.00 Kg/sec. The output power and conversion efficiency initially increase with increasing resistance. It is observed that at 10 Ω it shows maximum power 0.07929W and at 10Ω it shows maximum conversion efficiency of 0.234308‰ and after that it is decreases with increasing in resistance.

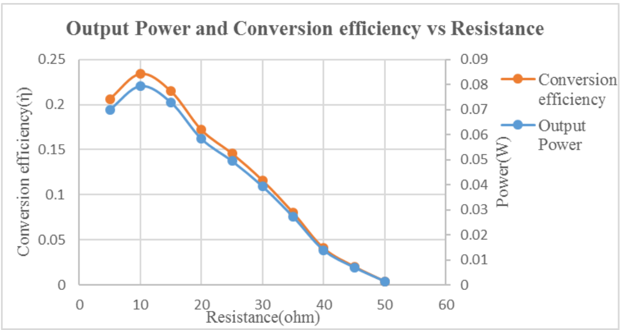


Figure 11: O/P Power and Conversion Efficiency Vs Resistance at const. mass flow rate

Open circuit voltage means, voltage measured without load resistance. When temperature difference increases, open circuit voltage gradually increases. At high temperature difference open circuit voltage is maximum and along with this output power is also increases. At temp difference 19^{o}c open circuit voltage obtained is 1.67 V and P_o is 0.07929 watt. The behaviour of open circuit and output power Vs temperature difference is shown in fig 12.

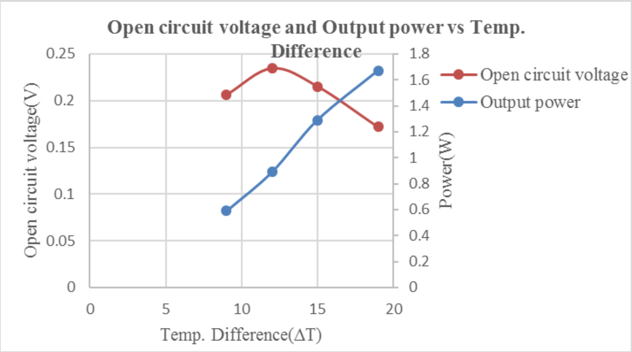


Figure12: Effect of Open circuit voltage and Output Power Vs Temp. Difference without load resistance at various mass flow rate

IV. CONCLUSION

The conversion efficiency of thermoelectric generator is function of temperature difference (Heat source and heat sink temperature). The thermal performance of thermoelectric generator will be improved or enhanced by using heat pipe as a heat sink on thermoelectric generator.Heat pipes do have limitations such as maximum rates of heat transfer and temperature limits. TEGs do have limitations such as low temperature limits and relatively low efficiency. When used in conjunction, these technologies have the potential to create a completely solid state and passive waste heat recovery system. Open circuit voltage, current and output power of thermoelectric generator increase with increasing temperature difference at various mass flow rate of water. At no mass flow rate condition, current and output power decreases with increasing temperature difference, because used thermoelectric module design for 0-300C when temperature of cold side of generator excess or cross this limit, generator gives less output power. The 93.00 kg/sec mass flow rate shows good result than other mass flow rate of water.

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