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Review on Heat Recovery Unit with Thermoelectric Generators

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Abstract*— This paper focuses on the use of heat exchanger with thermoelectric generators for waste heat recovery in power and energy sectors with their advantages, limitations and further scope. TE devices are solid state head engine and do not require any working fluid for their working, some tens of thermoelectric device can produce 1 to 2 watt of power, for production of 1Kw of power several thousand of these TE are required in parallel to form a module known as thermoelectric generator. This TEG when incorporated in conventional heat exchanger (as in parallel plate type or plate fin type heat exchanger) can produce energy. Results conclude that with the research of better thermoelectric materials, heat recovery units can be successfully implanted with efficiencies greater than 15%. With optimized control and bypass system to prevent excessive heating, TE device can be efficiently used to recover exhaust heat in I.C engines especially in generator sets. Geothermal and solar energy sources are currently in the phase of transformation of using thermoelectric generator while one promising application is found in concentrated solar TE device. Schematic models of such units are presented in this paper.

Index Terms—**heat exchanger, heat recovery, thermoelectric generator.**

I. INTRODUCTION

Waste recovery units such as recuperators and regenerators are one of the most widely used heat recovery units but for low temperature working fluids these heat exchangers become ineffective. Thus there is a need of a heat recovery unit which can work at relatively lower temperatures. Many different methods such as Organic Rankine cycle which converts low grade heat source to electricity and piezoelectric generators which directly converts deformations produced in piezoelectric materials into electricity are proposed for secondary heat recovery but limitation being their high investment cost or high equipment weight and increased complexity. TE devices on the other hand are light weight and do not require any moving parts. Performance of TE devices is represented by a dimensionless quantity known as "figure-of-merit" and denoted by "ZT". It's defined as:

$$ZT = \alpha^2 \sigma T/\lambda$$

Where'σ' is electrical conductivity of material
'α' is seebeck coefficient of the material
'λ' is thermal conductivity of the material

For a thermoelectric device working between two temperature limits, the lower limit being ' T_L ' and higher limit being ' T_H ', the maximum efficiency is given by

$$\eta = \frac{\Delta T}{T_h} \cdot \frac{\sqrt{1+ZT}-1}{\sqrt{1+ZT}+\frac{T_c}{T_h}}$$

Where $\Delta T = T_H - T_L$ (i.e., temperature difference)

Thus from the above expression we can relate that for better thermal efficiency of TE devices a higher ZT value will be required. The commonly used thermoelectric materials have this value between 1and 2.In 2002, Harman of Lincoln Laboratory [22] published results claiming ZT = 3.2 at 300^0C for a thermoelectric material. Further in 2003 Kanatzidis [3] published results claiming to achieve a minimum ZT = 1.4. Thus it's evident that with future research of better thermoelectric materials heat recovery units with TE devices can be economical and productive. This paper reviews the existing applications of thermoelectric generators in heat recovery units with their advantages along with limitations and proposes various new areas for its implementation.

II. ANALYSIS

A. Heat recovery from geothermal sources

In current scenario energy from geothermal sources are harnessed by the use of binary Rankine cycle but it suffers from serious drawbacks one of them being high maintenance and minimum temperature above 450K. Thermoelectric generators coupled with heat exchangers can produce electricity even at temperature as low as 350K with low maintenance. There are two types of thermoelectric modules, one used for high power application known as large bulk TEM and other for low power production known as thin film TEM or micro TEM (μTEM). For high temperature μTEM are used and they also help in low weight of heat exchanger. Some of the limitations in the application of TE devices for geothermal energy are:

- Difficult heat exchanger design, since the surface temperature of hot and cold surface of TE device would be unlike working fluid.
- Fouling in heat exchanger, if hot water is used as hot side fluid it may lead to excessive increase of fouling resistance.

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- High surface area for heat exchanger, for doubling the power production capacity of the plant, size of heat exchanger must also be doubled which subsequently leads to the increase in investment cost.

Some of these limitations can be avoided by using better and optimized heat exchange mechanism. Fouling in heat exchanger can be reduced by water treatment and regular maintenance of it also; surface temperature of conversion devices can be kept as close as possible to that of working fluid.

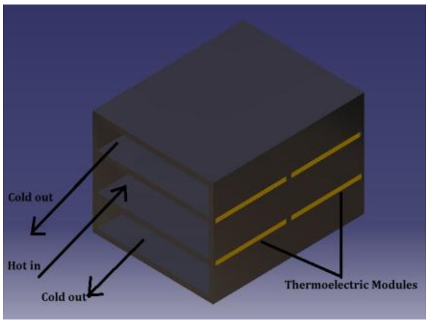

Fig 1. Simple parallel plate Heat exchanger with TE modules.

B. Heat recovery from I.C engine

In internal combustion engines out of the total heat supplied, about 30% to 35% of the heat is rejected in the exhaust. Turbo charging and supercharging are the current methods employed to increase fuel efficiency and power of the engines. The further heat recovery of heat from the exhaust is difficult or infeasible but with the advancement in thermoelectric materials, thermoelectric power generation is possible under reasonable costs. The preliminary model of automotive TEG uses exhaust gas as heat source while coolant through radiator acts as heat sink. Performance of this TEG greatly depends upon the exhaust temperature, the exhaust mass flow rate, and the type of thermoelectric material used and the design of heat exchanger used along with control system.

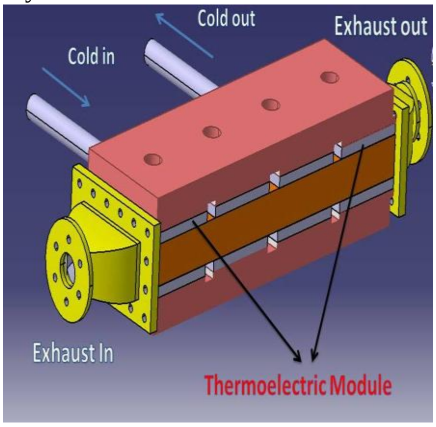

Fig 2. Model of Automotive TEG

Some of the problems that would be encountered during its operation would be:

Design Considerations and requirements	Possible solution
Short term high exhaust temperature(damage to TE device)	Bypass system activated by temperature sensors
Increased backpressure in exhaust(Reduced power and fuel efficiency)	Pressure and temperature sensors connected to bypass system
Maintain constant power output from TE device	Variable electric pump for coolant

Another point of consideration is the increased weight of the vehicle due to the presence of extra heat exchanger of TEG. The heat exchanger used should be of compact heat exchanger type such as the cross counter flow and two stream heat exchanger. Another possibility is the direct installment of TE modules to the exhaust which is very less in weight but suffers from reduced convective heat transfer coefficient.

III. ADVANTAGES

- Improvement in Brake specific fuel consumption (BSFC).
- Reduction in NO_x emission.
- TE module has long life thus it can be easily recycled
- Increased fuel saving in case of commercial vehicles.
- When compared to automotive TEG heat exchanger, onsite I.C engine like generator sets have the advantage of using larger heat exchanger.

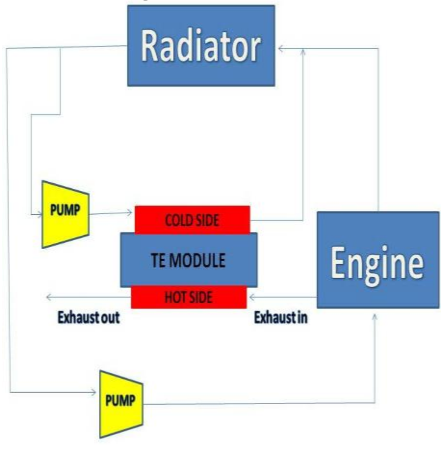

Fig 3. Design example for TEG on I.C engine

C. Industrial waste heat recovery

Recent advances in modern thin layer and nano-scale manufacturing technologies have enabled to achieve

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efficiencies greater than 15% for thermoelectric materials. This means conventional power producing techniques could be replaced with more efficient, reliable and economical TE power generators. Another benefit of using TEG for power production is that they leave no carbon footprint therefore production of greenhouse gases can be lowered. Unlike solar cells, they can produce electricity even at night. For industrial waste heat recovery, high temperature discharges (in the form of flue gases) above 500^0F are used to run steam turbines. The final discharge temperature is around 300^0F to 350^0F which is not suitable for TEG application. TEG of discharge temperature above 500^0F is indeed suitable and gives 10 to 15% efficiency. While in most of the industries TEG may not find good application but aluminum, glass and metal casting industries have greater potential for TEG heat recovery units. The reason is comparatively high discharge temperature (above 750^0C). Moreover the power so generated can be consumed on site for various needs. The opportunity of recovering waste heat is more with metal industries where large numbers of heat treatment process are involved. Some engineering problems that were encountered are:

- Manufacturing challenges: The engineering of these TE modules should be low cost and high production. Moreover it should be fully functional with the high performance heat exchange mechanisms. The design of heat exchanger would also be a critical point since fouling in heat exchanger would result in lowered convective heat transfer coefficient which would indirectly affect the performance of TEG.
- Thermoelectric material selection: TE materials with ZT~2 or above will be required with better thermal and chemical stability. Also the material should have long term service. Low performance TE module (ZT~1) may not fulfil the energy requirements and thus will be cost ineffective.

Another matter of concern is the availability of semiconductors used for manufacturing of TE modules. Increased demand of these materials for TE modules may cause market disruption and sudden rise in their prices.

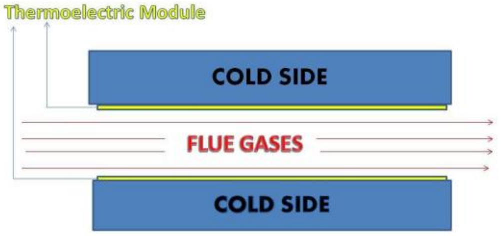

Fig 4. Conceptual TEG design. A heat exchanger may further be used on the cold side.

D. Heat recovery from solar energy sources (Alternative to photovoltaic cells)

Solar thermoelectric generators (STEG) are new promising alternatives to largely used photovoltaic solar cells. Solar cell can only absorb the high frequency part of the radiations, while the low frequency part remains unutilized. Unlike Solar cells, thermoelectric cells use both parts of radiations and can be easily installed in remote places. They can be employed in both concentrated and non-concentrated systems. They are more efficient than photovoltaic cells and in recent applications new hybrid models incorporating both types of cells are being developed. The basic model of STEG combines a solar thermal collector with a thermoelectric generator. STEG is more beneficial when used with concentrated solar intensity; it is 50 times more efficient than non concentrated type and helps in shrinking the size of cell reducing external heat losses. Dent and cobble [20] built a prototype STEG comprising a sun tracking heliostat which directs the incident sunlight to a parabolic mirror which indeed finally concentrates it on STEG, while using PbTe as thermoelectric material they were able to achieve an efficiency of 0.63% at one sun and 3.35% at 50 suns. STEG can be optimized for both optimum power and efficiency but for high energy production, power optimization would be required. The major problem with concentrated STEG is excessive heating of thermoelectric material and high surface temperatures for which a high performance heat exchanging unit must be installed but difficulty lies with its design since the size of STEG is small and less surface area of STEG results in lower convective heat transfer coefficient. The heat losses in STEG are avoided by creating vacuum around the thermoelectric device. The radiation losses on the back side of STEG definitely limit the maximum efficiency of device but they can be overcome by using spectral solar absorber. Some of the ways of increasing the viability of STEG in solar power harnessing is through use of better thermoelectric materials, increasing absorbance of absorber and reducing its IR emittance, increasing optical concentration and changing geometry of STEG.

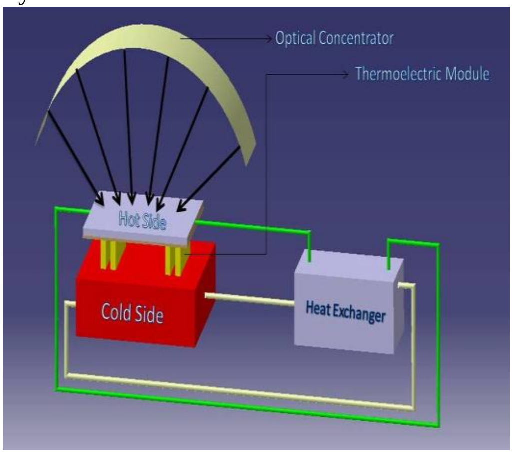

Fig. 3. Model of concentrated STEG with a heat exchanger to avoid excessive heating

IV. CONCLUSION

It has been identified that using TEG with a proper heat exchanging mechanisms will surely replace the conventional methods of waste heat recovery and will open new fields for

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its exploration. History of thermoelectric materials reveals that there is a large possibility of manufacturing thermoelectric devices having ZT value greater than 2. With the advancement in manufacturing technologies we will be able to produce large quantities of these TE devices at low cost and thus harnessing of geothermal energy would be easier. Application of automotive TEG not only enhances the performance and fuel efficiency of vehicle but will also help in reduction of NO_x emission. World's maximum power consumption is found in industrial applications; long service life of TEG and its simple mechanism of working will definitely help in saving a fraction of the waste energy. A great amount of work is still in progress for obtaining better efficiency for STEG, one day we may see STEG cells replacing our conventional photovoltaic solar cells. Thus its evident that in the near future heat recovery through thermoelectric has enormous potential though its optimization and research is required before thermoelectric generation becomes economically viable.

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