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THERMOELECTRIC ELEMENT ASSIGNED AS ELECTRICGENERATOR FROM WASTE HEAT

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Abstract- The thermoelectric effect is the direct conversion of temperature differences to electric voltage and vice-versa. A thermoelectric device creates a voltage when temperature differ on side respect to next side. At the atomic scale, the temperature gradient causes charge carriers in the material to diffuse from the hot side to the cold side. In this case, electricity generated as a measure or change of the temperature difference of hot and cold sides of the thermoelement. The investigation involved using waste heat as input source. For this purpose, 72 bismuth telluride thermoelectric modules were used for energy conversion. The number of modules and their arrangement were delicate to select, where the power generated at the expense of temperature differences appeared between two sides of thermoelement. The 100 W generator was tested on chimneys, which outlet the hot gases to the atmosphere. Many of the design features, e.g. heat sink and fin designs were changed during this development as more information was obtained. The involved parameters of the generator are considered.

Keywords: Thermoelectric, Electric Generator, Waste Heat, Thermoelement.

I. INTRODUCTION

Most of the energy we use today comes from coal, oil, and natural gas. They are fossil fuels. They take millions of years to form. We can't make more quickly. They are nonrenewable. A good way to save energy is by not wasting it. Broad societal needs have focused attention on technologies that can reduce ozone depletion, greenhouse gas emissions, and fossil fuel usage. Electrical power, are increasingly being seen as having the potential to make important contributions to reducing CO_2 and greenhouse gas emissions and providing cleaner forms of energy. Solid-state systems with more familiar mechanical are the providers of electrical power generation, such as air conditioners, refrigerators and turbine engines. These classes have complementary regimes in which they can provide clean energy performance [1-2].

Conventional metallic thermocouples are made from metal or metal alloys. They generate small voltages, typically tens of microvolts per degree temperature difference by the Seebeck effect. Thermoelectric power generator offers several distinct advantages over other technologies [3-5]:

- ✓They are extremely reliable (typically exceed 100,000 Hours of steady-state operation).
- ✓Silent in operation since they have no mechanical moving parts and require.
- ✓Considerably less maintenance;
- ✓They are simple, compact and safe;
- ✓They have very small size and virtually weightless;
- ✓They are capable of operating at elevated temperatures;
- ✓They are suited for small-scale and remote applications
- ✓Typical of rural power supply, where there is limited or no electricity;
- ✓They are environmentally friendly;
- ✓They are not position-dependent; and
- ✓They are flexible power sources.

The major drawback of thermoelectric power generator is their relatively low conversion efficiency (typically ~5% [6]). This has been a major cause in restricting their use in electrical power generation of specialized fields with extensive applications where reliability is a priority and cost is not considered. Applications over the past decade included industrial instruments, military, medical and aerospace [3, 6], and for portable or remote power generation [7]. However, in recent years, an increasing concern of environmental issues of emissions, in particular global warming has resulted in extensive research into unconventional technologies of generating electrical power and thermo-electric power generation has emerged as a promising alternative green technology. Vast quantities of waste heat are discharged into the earth's environment much of it at temperatures which are too low to recover using conventional electrical power generators. Thermoelectric power generation (also known as thermoelectricity) offers a promising technology in the direct conversion of low-grade thermal energy, such as waste-heat energy, into electrical power [8].

With the waste heat powered thermoelectric technology, it is unnecessary to consider the cost of the thermal energy input, and consequently thermoelectric power generators' low conversion efficiency is not a critical drawback [3, 9]. In bulk devices for power generation or cooling applications, thermoelectric legs have a typical geometry and consist of two ingot shaped pellets of semi conducting material having dimensions of the order of millimeters connected at one end with an electrically conducting metal strap to form the junction.

II. MEASURING AND POWER OF WASTE HEAT

A. Waste Heat Measurement

In any heat recovery situation it is essential to know the amount of heat recoverable and also its usage. The total heat that could potentially be recovered can be calculated using this formula:

$$Q = V \times \rho \times C_p \times \Delta T \quad (1)$$

where, Q is the heat content in kcal; V is the flow rate of the substance in m^3/hr; ρ is the density of the flue gas in kg/m^3; C_p is the specific heat of the substance in kCal/kg°C; and ΔT is the temperature difference in °C.

A thermoelectric converter is a heat engine and like all heat engines, it obeys the laws of thermodynamics. If we first consider the converter operating as an ideal generator in which there are no heat losses, the efficiency is defined as the ratio of the electrical power delivered to the load to the heat absorbed at the hot junction. Expressions for the important parameters in the thermoelectric electric generator can readily be derived by considering the simplest generator consisting of a single thermocouple with legs or thermo elements fabricated from n-type and p-type semiconductors. The efficiency of the generator is given by:

$$\eta = \frac{\text{energy delivered to the load}}{\text{heat energy absorbed at hot junction}} = \frac{\overset{\circ}{W}_e}{\overset{\circ}{Q}_h} \quad (2)$$

The efficiency of a thermoelectric converter depends heavily on the temperature difference $\Delta T = T_h - T_c$ across the device. This is because the thermoelectric generator, like all heat engines, cannot have the efficiency greater than that of a Carnot cycle ($\Delta T/T_h$). The efficiency of a thermoelectric generator is typically defined [10].

$$\eta = \frac{\Delta T}{T_h}\left[\frac{\sqrt{1+ZT}-1}{\sqrt{1+ZT}+T_c/T_h}\right] \quad (3)$$

where the first term is the Carnot efficiency and ZT is the figure of merit for the device. While the calculation of a thermoelectric generator efficiency can be complex, the average material figure of merit, ZT, can provide an approximate value. The Z is the so called 'goodness factor' or thermoelectric figure-of-merit of the thermocouple material.

$$\mathrm{Z} = \frac{\alpha^2 \sigma}{\kappa} \quad (4)$$

where $\alpha^2\sigma$ is referred as the electrical power factor, α is the Seebeck coefficient, σ is the electrical conductivity and κ is the total thermal conductivity. The total thermal conductivity is the sum of electrical and lattice conductivities.

$$\kappa_{total} = \kappa_e + \kappa_L \quad (5)$$

Evidently an increase in temperature difference provides a corresponding increase in available heat for conversion as dictated by the Carnot efficiency, so large temperature differences are desirable. A thermocouple fabricated from thermoelement materials with an estimated figure of merit of 3×10^{-3} K^{-1} would have an efficiency of around 20% when operated over a temperature difference of 500K.

Table 3 gives temperatures of waste gases from process equipment in the medium temperature range, [11]. Most of the waste heat in this temperature range comes from the exhaust of directly fired process units.

Table 3. Typical waste heat temperature at medium temperature range from various sources [11]

Types of Devices	Temperature (°C)
Steam boiler exhaust	230-480
Gas turbine exhaust	370-540
Reciprocating engine exhaust	315-600
Reciprocating engine exhaust (turbo charged)	230-370
Heat treatment furnace	425-650
Drying & baking ovens	230-600
Catalytic crackers	425-650

B. Power from Waste Heat

R&D demonstrated waste heat recovery in automobiles [12]. In this system ~1 kW range, even relatively inefficient thermoelectric elements can be competitive for use with such waste heat sources (e.g. automobile exhaust) when design, fabrication, and maintenance cost are factored in. The thermoelectric generator will extract waste heat from the exhaust that will deliver DC electrical power to recharge the battery. By reducing or even eliminating the need for the alternator, the load on the engine is reduced thereby improving fuel efficiency by as much as 10%. Instead of recovering waste heat, cogeneration recovers some of the useful work wasted on heat.

Often a high energy content fuel with a high flame temperature (such as natural gas) is used for low generation recovers some of the useful work wasted on heat. Often a high energy content fuel with a high flame temperature (such as natural gas) is used for low ΔT heating (e.g. home heating or hot water). In electricity-heat cogeneration, electricity is produced with nearly 100% efficiency (as opposed to ~40% for power plants) because the remaining energy is used for heating instead of being wasted. In applications such as home co-generation, the desire for silence, low vibration frequency, and maintenance free operation will favor thermoelectrics. Residential co-generation and automotive waste heat recovery are two examples where "small" systems could have an impact on the global energy consumption if implemented on a large scale.

III. COMPOSITION AND SPECIFICATIONS OF A THERMOELECTRIC POWER GENERATOR

Figure 1 shows a schematic diagram illustrating components and arrangement of a conventional single-stage thermoelectric power generator. As shown in the figure, it is composed of two ceramic plates that serve as a foundation, providing mechanical integrity, and electrical insulation for n-type (heavily doped to create excess electrons) and p-type (heavily doped to create excess holes) semiconductor thermoelements. In thermoelectric materials, electrons and holes operate as both charge carriers and energy carriers. There are very few modules without ceramic plates, which could eliminate the thermal resistance associated with the ceramic plates, but might lead to mechanical fragility of the module.

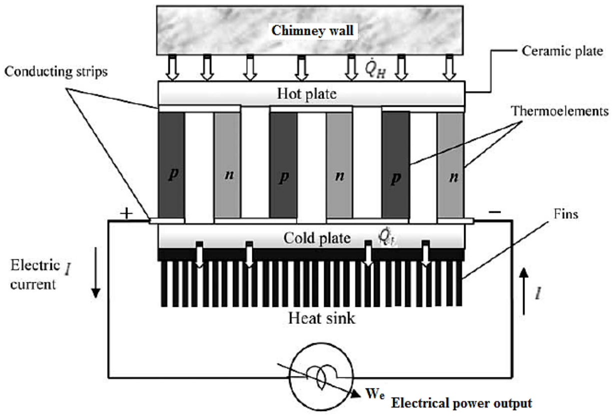

Figure 1. Thermoelectric modules and heat sink assembly

The ceramic plates are commonly made from alumina (Al_2O_3), but when a large lateral heat transfer is required, materials with higher thermal conductivity (e.g. beryllia and aluminum nitride) are desired. The semiconductor thermoelements (e.g. Bismuth tellutide, Bi_2Te_3, lead-telluride PbTe, silicon-germanium SiGe, based alloys) that are sandwiched between the ceramic plates are connected thermally in parallel and electrically in series to form a thermoelectric device (module). More than one pair of semiconductors is normally assembled together to form a thermoelectric module and within the module a pair of thermoelements is called a thermocouple [9]. The junctions connecting the thermoelements between the hot and cold plates are interconnected using highly conducting metal (e.g. copper) strips as shown in Figure 1.

Waste heat is generated in a process of fuel combustion or chemical reaction, which is then "dumped" into the environment and not reused for useful and economic purposes. The mechanism to recover unused heat depends on the temperature of waste heat gases and the economics involved. Large quantities of hot gas flux are generated from boilers, furnace and gas turbine. If some of the waste heat could be recovered, then a considerable amount of primary fuel could be saved. The energy lost in waste gases cannot be fully saved. However, much of the waste heat could be reused and can minimize losses [13].

The designed generator contains 72 (TEC1-12706, TEC1-12706S ΔT_{max} = 67 °C, P_{max} (ΔT = 0) 57.0 W), [14] Bismuth-Telluride modules to convert the energy in the chimney directly to electricity. The modules and heat sink are shown in Figure 2, with the size of 40mm square by 3 mm thick each. The pellets are vacuum hot pressed materials are used to make the thermoelements as a module. The modules are arranged in four groups of 18 modules, (72 modules). Each group of modules is mounted on a single water cooled heat sink. The module and heat sink assemblies are then positioned on the outer surface of a 170×170×250 mm square section chimney. This chimney is a tube with square cross section 130×130 mm^2, 2 mm wall thick and 250 mm height.

The heat source forces the exhaust gas flow close to the surface of the chimney. Hollow displacement body (chimney) provides a better gas flow distribution within the source and can be easily changed in size to match the exhaust gas flow rate of various displacements. The source is coupled directly to the exhaust gas outlet such as outlet chimney of a gas turbine in the petroleum industry.

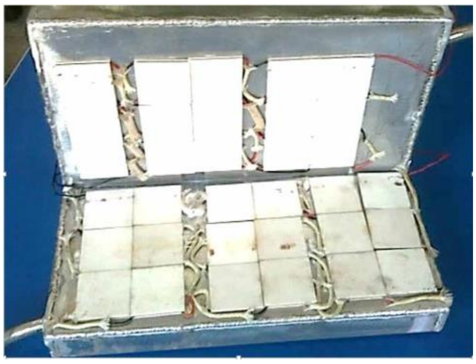

Figure 2. A thermoelectric module
(TEC1-12706S ΔT_{max} = 67 °C, P_{max} (ΔT = 0) 57.0 W)

IV. GENERATOR TESTING AND MODIFICATION

Initial generator testing started with a simulated system a domestic gas cooker. These tests were conducted using the assembly on big flare. The initial results were quite poor since we were able to achieve a maximum of about 65 watts of output. It was suspected that there was a boundary layer problem with the heat transfer from the exhaust gas to the support structure. The original heat transfer fin design used 90 fins about 6mm high, which were continuous from the inlet to the outlet. A more detailed picture of the differential temperature distribution than could be obtained from the several thermocouples that were installed along the support structure was required. A good indication of the heat transfer profile was obtained as shown in Figure 3 by wiring the thermoelectric modules on one heat sink assembly, so that the open circuit voltage of each module could be obtained individually. The profile, which is an analog of the local heat transfer rate, confirmed that the laminar boundary layer was the source of the heat transfer problem.

The design of the assembly was modified by reducing the number of fins to 30 and lengthening then to maintain the required heat transfer area. The fins were also made to be discontinuous by placing 9 mm gaps at about 40mm intervals to aid in breaking the laminar boundary layer. Testing the modified generator resulted in a marked improvement of power output. The generator output improved over 70 Watts and the power curves were less erratic than in the previous test (Figure 3). Two water reservoirs with L cross section are used as a heat sink to obtain high efficiency shown in Figure 4. The chimney also appears in this figure.

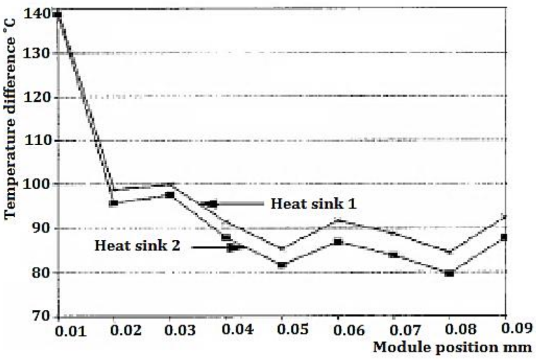

Figure 3. Differential temperature profiles from early test

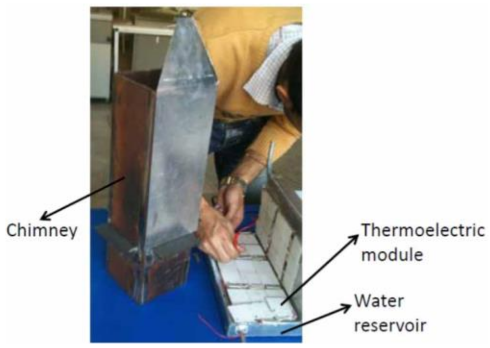

Figure 4. A prototype thermoelectric generator, water reservoir with L cross section, thermoelectric module and chimney

A schematic diagram of a simple thermoelectric power generator operating based on Seebeck effect is shown in Figure 5. As shown in Figure 5, heat is transferred at a rate of Q_h from a high-temperature heat source maintained at T_h to the hot junction, and it is rejected at a rate of Q_c to a low-temperature sink maintained at T_c from the cold junction. Based on Seebeck effect, the heat supplied at the hot junction causes an electric current to flow in the Circuit and electrical power are produced. Using the first law of thermodynamics (energy conservation principle) the difference between Q_h and Q_c is the electrical power output W_e.

The open circuit voltage temperature profile showed some improvement from the first test series, however, it still indicated that there was a problem with the gas boundary layer and it was suspected that the heat transfer problem was associated with lack of turbulence in the exhaust gas as it exited the turbocharger drive turbines. The heat transfer fins had been made discontinuous, they were placed in line because of both the time required and the cost of changing was high [15, 16].

The generator with the modified displacement body was tested on domestic gas cooker. The results of the final test on the cooker increase neatly linear against the temperature gradient. A maximum generator output of 100 Watts was obtained at 100 °C. One will note that after the high initial temperature at the generator inlet, the remainder of the temperature points is quite flat compared to the early profiles [7].

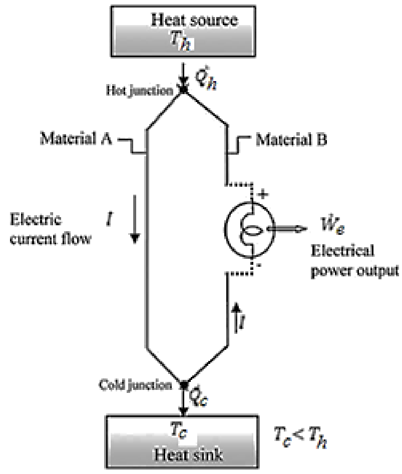

Figure 5. Schematic diagram showing the basic concept of a simple thermoelectric power generator operating based on Seebeck effect

V. CONCLUSIONS

A high power generator to provide electric power from dumping waste heat is feasible. Thermoelectric electric generator has been designed and tested for optimum. The design of this generator could be further refined, however, the current design has now met the original design goal for the program of producing 1 kW of electricity directly from the exhaust hot gases. The information presented here shows how important the details of the heat transfer design can be. It is necessary to pay attention to such details is even more important in thermoelectric systems because of the increased sensitivity of such systems to both temperature difference across the elements and average temperature of the elements.

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BIOGRAPHIES

Ghassem Kavei received his B.Sc. in Applied Physics from University of Tabriz, Tabriz, Iran, the M.Sc. degree in Atomic Physics from the Southampton University, UK and his Ph.D. in Surface Physics from Keele University, UK. He is a member of the Iranian Crystallography Association (ICA) and Iranian Physics Society (IPS). He has co-authored approximately 11 books, and has published over 65 publications on various aspects of atomic physics, thermoelectric, TiO_2 thin film, SPM application, ITO thin film and nano-science and technology. He was also a lecturer at several universities in Iran teaching different subject in electron physics. Currently, he is a Research Professor at the Material and Energy Research Centre, Tehran, Iran and applied for a permission to publish a periodical scientific International Journal "International Materials Physics Journal".

Ali Asghar Khakpour received his B.Sc. degree in Applied Physics and the M.Sc. degree in Solid State Physics from Isfahan University, Isfahan, Iran. He is currently a Ph.D. student in Nano Physics in Material and Energy Research Center, Tehran, Iran. He is also a lecturer at Islamic Azad University, Iran since 1993 and teaching different subject in Physics. He is a member of the Iranian Crystallography Association (ICA) and Iranian Physics Society (IPS). He has a project in TiO_2 thin film as a self-cleaning material.

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