Recent Patents on Electrical Engineering **2009, *2*, 27-39**

Thermoelectric Power Generation Using Waste-Heat Energy as an Alternative Green Technology

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Received: August 1, 2008; Accepted: November 20, 2008; Revised: November 24, 2008

Abstract: In recent years, an increasing concern of environmental issues of emissions, in particular global warming and the limitations of energy resources has resulted in extensive research into novel technologies of generating electrical power. Thermoelectric power generators have emerged as a promising alternative green technology due to their distinct advantages. Thermoelectric power generation offer a potential application in the direct conversion of waste-heat energy into electrical power where it is unnecessary to consider the cost of the thermal energy input. The application of this alternative green technology in converting waste-heat energy directly into electrical power can also improve the overall efficiencies of energy conversion systems. In this paper, a background on the basic concepts of thermoelectric power generation is presented and recent patents of thermoelectric power generation with their important and relevant applications to waste-heat energy are reviewed and discussed.

Keywords: Thermoelectric power generation, waste-heat recovery, alternative green technology, direct energy conversion, electrical power, thermoelectric materials.

1. INTRODUCTION

A thermoelectric power generator is a solid state device that provides direct energy conversion from thermal energy (heat) due to a temperature gradient into electrical energy based on “Seebeck effect”. The thermoelectric power cycle, with charge carriers (electrons) serving as the working fluid, follows the fundamental laws of thermodynamics and intimately resembles the power cycle of a conventional heat engine. Thermoelectric power generators offer several distinct advantages over other technologies [1-4]:

- they are extremely reliable (typically exceed 100,000 hours of steady-state operation) and 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% [5]). This has been a major cause in restricting their use in electrical power generation to specialized fields with extensive applications where reliability is a major consideration and cost is not. Applications over the past decade included industrial instruments, military, medical and aerospace [1, 5], and applications for portable or remote power generation [6]. However, in recent years, an increasing concern of environmental issues of emissions, in particular global warming has resulted in extensive research into nonconventional technologies of generating electrical power and thermoelectric 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 [7]. Probably the earliest application is the utilization of waste heat from a kerosene lamp to provide thermoelectric power to power a wireless set. Thermoelectric generators have also been used to provide small amounts electrical power to remote regions for example Northern Sweden, as an alternative to costly gasoline powered motor generators [8]. In this 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 [1,8]. In fact, more recently, they can be used in many cases, such as those used in cogeneration systems [9], to improve overall efficiencies of energy conversion systems by converting waste-heat energy into electrical power [3].

In general, the cost of a thermoelectric power generator essentially consists of the device cost and operating cost. The operating cost is governed d by the generator’s conversion efficiency, while the device cost is determined by the cost of its construction to produce the desired electrical power output [1]. Since the conversion efficiency of a module is comparatively low, thermoelectric generation using waste

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heat energy is an ideal application. In this case, the operating cost is negligible compared to the module cost because the energy input (fuel) cost is cheap or free. Therefore, an important objective in thermoelectric power generation using waste heat energy is to reduce the cost-per-watt of the devices. Moreover, cost-per-watt can be reduced by optimising the device geometry, improving the manufacture quality and simply by operating the device at a larger temperature difference [1]. In addition, in designing high-performance thermoelectric power generators, the improvement of thermoelectric properties of materials and system optimization have attracted the attention of many research activities [10]. Their performance and economic competiveness appear to depend on successful development of more advanced thermoelectric materials and thermoelectric power module designs.

In this paper, a background on the basic concepts of the thermoelectric power generation is presented through the applications implemented in the recent patents of thermoelectric power generation relevant to waste-heat energy.

2. BASIC THEORY OF A THERMOELECTRIC POWER GENERATOR

The basic theory and operation of thermoelectric based systems have been developed for many years. Thermoelectric power generation is based on a phenomenon called “Seebeck effect” discovered by Thomas Seebeck in 1821 [1]. When a temperature difference is established between the hot and cold junctions of two dissimilar materials (metals or semiconductors) a voltage is generated, i.e., Seebeck voltage. In fact, this phenomenon is applied to thermocouples that are extensively used for temperature measurements. Based on this Seebeck effect, thermoelectric devices can act as electrical power generators. A schematic diagram of a simple thermoelectric power generator operating based on Seebeck effect is shown in Fig. (**1**). As shown in Fig. (**1**), heat is transferred at a rate of $\dot{Q}_H$ from a high-temperature heat source maintained at T_H to the hot junction, and it is rejected at a rate of $\dot{Q}_L$ to a low-temperature sink maintained at T_L 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 is produced. Using the first-law of thermodynamics (energy conservation principle) the difference between $\dot{Q}_H$ and $\dot{Q}_L$ is the electrical power output $\dot{W}_e$. It should be noted that this power cycle intimately resembles the power cycle of a heat engine (Carnot engine), thus in this respect a thermoelectric power generator can be considered as a unique heat engine [11].

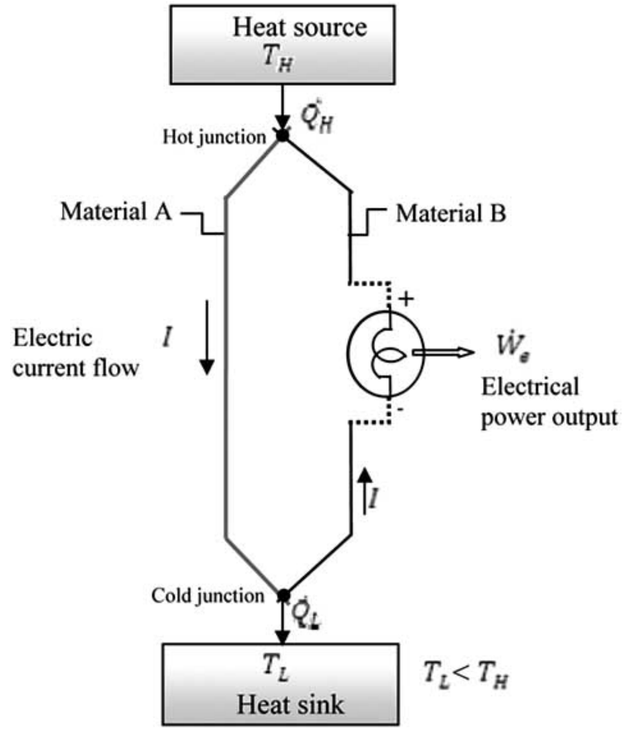


Fig. (1). Schematic diagram showing the basic concept of a simple thermoelectric power generator operating based on Seebeck effect.

3. COMPOSITION AND SPECIFICATIONS OF A THERMOELECTRIC POWER GENERATOR

Figure **2** shows a schematic diagram illustrating components and arrangement of a conventional single-stage thermoelectric power generator. As shown in Fig. (**2**), it is composed of two ceramic plates (substrates) 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. The ceramic plates are commonly made from alumina (Al_2O_3), but when large lateral heat transfer is required, materials with higher thermal conductivity (e.g. beryllia and aluminum nitride) are desired. The semiconductor thermoelements (e.g. silicon-germanium SiGe, lead-telluride PbTe 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 are normally assembled together to form a thermoelectric module and within the module a pair of thermoelements is called a thermocouple [1]. The junctions connecting the thermoelements between the hot and cold plates are interconnected using highly conducting metal (e.g. copper) strips as shown in Fig. (**2**).

The sizes of conventional thermoelectric devices vary from 3 mm^2 by 4 mm thick to 75 mm^2 by 5 mm thick. Most of thermoelectric modules are not larger than 50 mm in length due to mechanical consideration. The height of single-stage thermoelectric modules ranges from 1 to 5 mm. The modules contain from 3 to 127 thermocouples [1]. There are multistage thermoelectric devices designed to meet requirements for large temperature differentials. Multi-stage thermoelectric modules can be up to 20 mm in height, depending on the number of stages. Photographs of single-

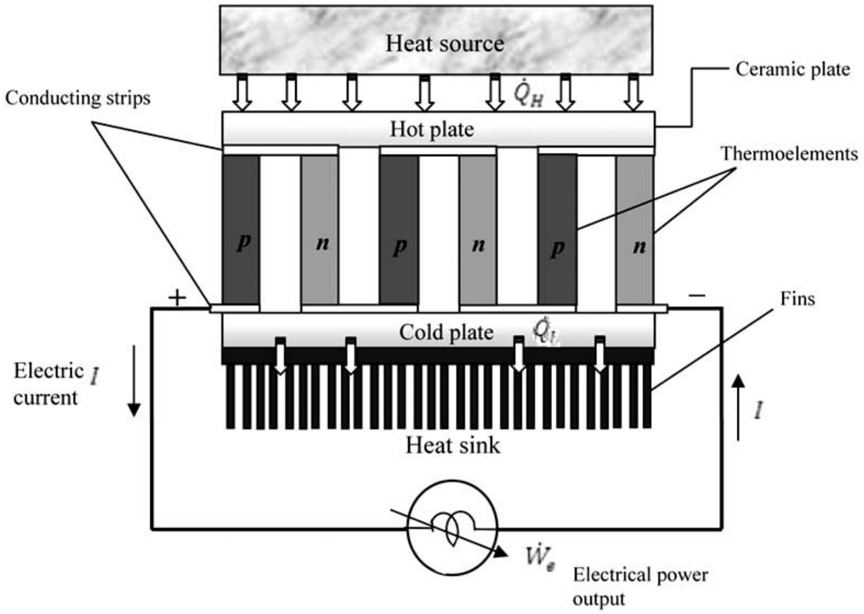
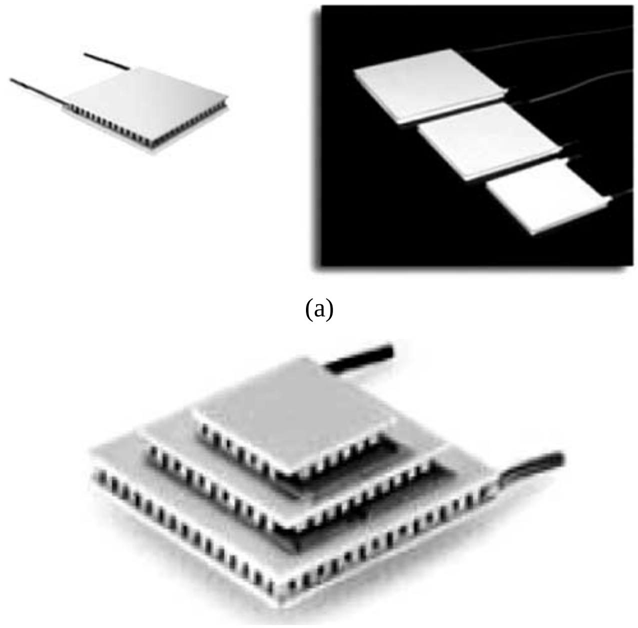


Fig. (2). Schematic diagram showing components and arrangement of a typical single-stage thermoelectric power generator.

and multi-stage thermoelectric modules are shown in Fig. (**3**) [12,13].



(a)

(b)

Fig. (3). Photographs of (a) single-stage, and (b) three-stage thermoelectric modules (typical pyramid shape) [12, 13].

The power output for most of the commercially-available thermoelectric power generators ranges from microwatts to multi-kilowatts [1, 8]. For example, a standard thermoelectric device consists of 71 thermocouples with the size of 75 mm^2 can deliver electrical power of approximately 19 W [1]. The maximum output power from a thermoelectric power generator typically varies depending on temperature difference between hot and cold plates and module specifications, such as module geometry (i.e. cross-sectional area and thermoelement length), thermoelectric materials and contact properties. For example, Figs. (**4a & b**) show the maximum power output as a function of temperature difference for modules which possess different geometry as listed in Table **1** [5]. It can be seen from Figs. (**4a & b**) that the maximum power output increases parabolically with an increase in temperature difference. For a given temperature difference, there is a significant variation in maximum power output for different modules due to variation in thermoelectric materials, module geometry and contact properties. However, as shown in Fig. (**3a**), the maximum power output follows a clear trend and increases with a decrease in thermoelement length for a given module cross-sectional area.

4. PERFROMANCE OF THERMOELECTRIC POWER GENERATORS

The performance of thermoelectric materials can be expressed as [7]

$$Z = \alpha^2 / kR , \tag{1}$$

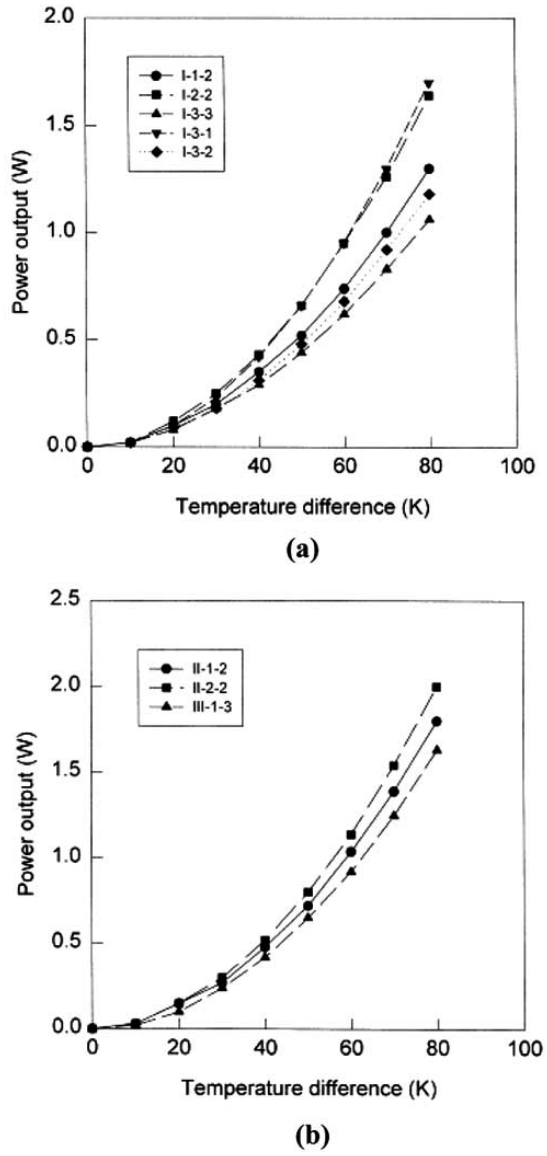
where Z is the thermoelectric material figure-of-merit , α is the Seebeck coefficient given by

$$\alpha = -\frac{\Delta V}{\Delta T} , \tag{2}$$

R is the electric resistivity (inverse of electric conductivity) and k is the total thermal conductivity. This figure-of-merit may be made dimensionless by multiplying by $\overline{T}$ (average absolute temperature of hot and cold plates of the thermoelectric module, K), i.e.,

$$Z\overline{T} = \alpha^2 \overline{T} / kR \tag{3}$$

and



(a)

(b)

Fig. (4). Maximum power output as a function of temperature differences. (a) Modules denoted I possess 127 thermocouples; (b) Modules denoted II possess 31 thermocouples and modules denoted III possess 50 thermocouples (more specifications are given in Table **1**) [5].

$$\overline{T} = \frac{T_H + T_L}{2}. \tag{4}$$

The term α^2 / R is referred to as the electrical power factor. In general, a thermoelectric power generator exhibits low efficiency due to the relatively small dimensionless figure-of-merit ($Z\overline{T} \leq 1$) of currently available thermoelectric materials. The conversion efficiency of a thermoelectric power generator defined as the ratio of power delivered to the heat input at the hot junction of the thermoelectric device, is given by [7]

Table 1. Thermocouple Number (*N*), Cross-Sectional Area (*A*) and Thermoelement Length (*l*) of Several Commercially Available Modules [5]

Modules	N	A (mm^2)	l (mm)	A/l (mm)
I-1-2	127	1.35×1.35	1.53	1.19
I-2-2	127	1.47×1.47	1.47	1.47
I-3-1	127	1.40×1.40	1.14	1.72
I-3-2	127	1.40×1.40	*2.03*	*0.96*
I-3-3	127	1.40×1.40	2.54	0.77
II-1-2	31	4.30×4.30	1.52	12.16
II-2-2	31	4.50×4.50	1.67	12.12
III-1-3	50	5.00×5.00	3.00	8.33

$$\eta = \frac{\dot{W}_e}{\dot{Q}_H} \tag{5}$$

Limited by the second-law of thermodynamics, the ideal (absolute maximum) efficiency of a thermoelectric power generator operating as a reversible heat engine is Carnot efficiency, given by [11]

$$\eta_{Carnot} = 1 - \frac{T_L}{T_H} \tag{6}$$

The maximum conversion efficiency of an irreversible thermoelectric power generator can be estimated using [14]

$$\eta = \eta_{Carnot}\left[\frac{\sqrt{1+Z\overline{T}} - 1}{\sqrt{1+Z\overline{T}} + T_L / T_H}\right] \tag{7}$$

The value of the figure-of-merit is usually proportional to the conversion efficiency. The dimensionless term $Z\overline{T}$ is therefore a very convenient figure for comparing the potential conversion efficiency of modules using different thermoelectric materials. The conversion efficiency as a function of operating temperature difference and for a range of values of the thermoelectric material's figure-of-merit is shown in Fig. (**5**). It is evident that an increase in ΔT provides a corresponding increase in available heat for conversion as dictated by the Carnot efficiency, so large ΔT's are advantageous [7]. For example, a thermoelectric material with an average figure-of-merit of 3×10^{-3} K^{-1} would have a conversion efficiency of approximately 23% when operated over a temperature difference of 600K.

5. THERMOELECTRCI MATERIALS FOR POWER GENERATORS

Among the vast number of materials known to date, only a relatively few are identified as thermoelectric materials. As reported by Rowe [7], thermoelectric materials can be categorized into established (conventional) and new (novel) materials, which will be discussed in the next sections. Today's most thermoelectric materials, such as Bismuth Telluride (Bi_2Te_3)-based alloys and PbTe-based alloys, have a $Z\overline{T}$ value of around unity (at room temperature for Bi_2Te_3 and 500-700K for PbTe). However, at a $Z\overline{T}$ of 2-3 range, thermoelectric power generators would become competitive with other power generation systems [1,15]. The figure-of-merit Z of a number of thermoelectric materials together

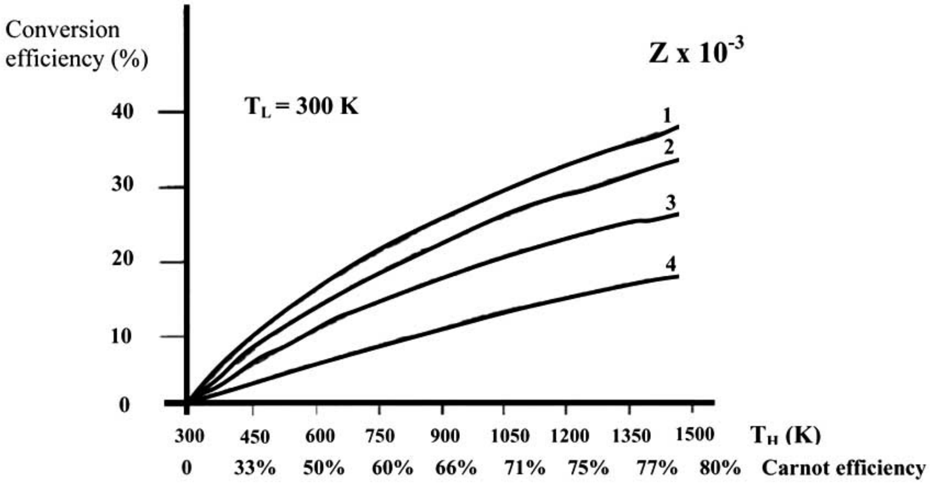


Fig. (5). Conversion efficiency as a function of temperature and module material figure-of-merit [7].

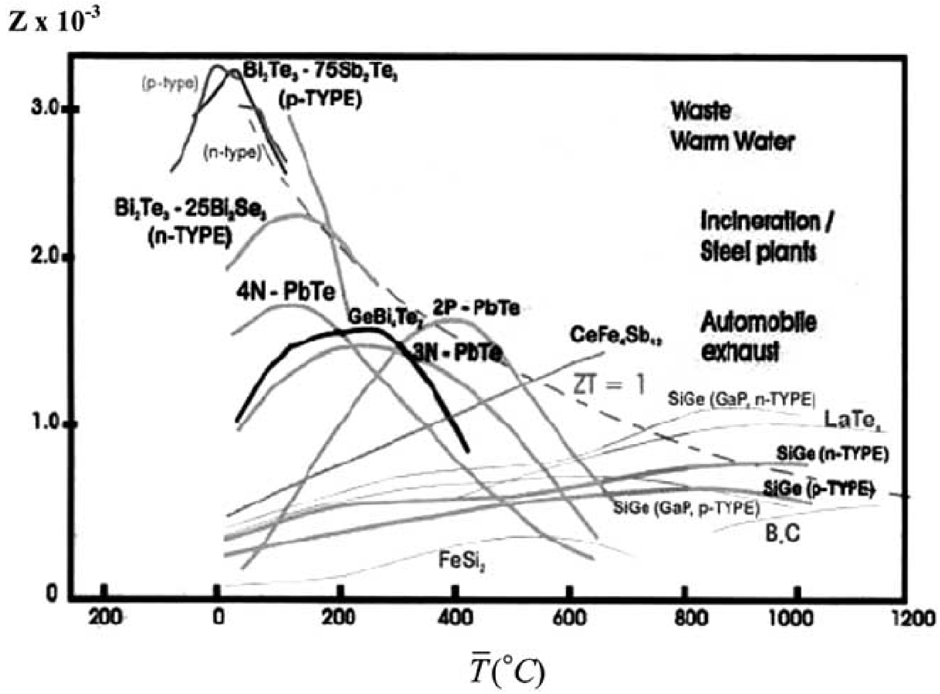


Fig. (6). Figure-of-merit of a number of thermoelectric materials and their potential applications [7].

with potential power generating applications relevant to waste heat energy is shown in Fig. (**6**) [7]. Effective thermoelectric materials should have a low thermal conductivity but a high electrical conductivity. A large amount of research in thermoelectric materials has focused on increasing the Seebeck coefficient and reducing the thermal conductivity, especially by manipulating the nanostructure of the thermoelectric materials. Because the thermal and electrical conductivity correlate with the charge carriers, new means must be introduced in order to conciliate the contradiction between high electrical conductivity and low thermal conductivity as indicated by Weiling and Shantung [15].

5.1. Conventional Thermoelectric Materials

Rowe [7] reported that established thermoelectric materials (those which are employed in commercial applications) can be conveniently divided into three groupings based on the temperature range of operation, as shown in Fig. (**6**). Alloys based on Bismuth (Bi) in combinations with Antimony (An), Tellurium (Te) or Selenium (Se) are referred to as low temperature materials and can be used at temperatures up to around 450K. The intermediate temperature range - up to around 850K is the regime of materials based on alloys of Lead (Pb) while thermoelements employed at the highest temperatures are fabricated from SiGe alloys and operate up to 1300K. Although the above mentioned materials still remain the cornerstone for commercial and practical applications in thermoelectric power generation, significant advances have been made in synthesising new materials and fabricating material structures with improved thermoelectric performance. Efforts have focused primarily on improving the material's figure-of-merit, and hence the conversion efficiency, by reducing the lattice thermal conductivity [7].

5.2. Novel Thermoelectric Materials And Module Configurations

It was recently reported in [5] that a material which is a promising candidate to fill the temperature range in the *ZT* pectrum between those based on Bi_2Te_3 and PbTe is the semiconductor compound ß-Zn_4Sb_3. This material possesses an exceptionally low thermal conductivity and exhibits a maximum *ZT* of 1.3 at a temperature of 670K. This material is also relatively inexpensive and stable up to this temperature in a vacuum [5].

Attempts are also being made to improve the competitiveness of thermoelectrics in directions other than by improving the figure-of-merit. In particular, efforts have focused on increasing the electrical power factor, decreasing cost and developing environmentally friendly materials. In addition, when the fuel cost is low or essentially free, as in waste heat recovery, then the cost per watt is mainly determined by the power per unit area and the operating period [5]. For example, considering the electrical power factor as the dominant parameter, it has initiated a search for materials with high power factors rather than conversion efficiency. Considerable success has been enjoyed in synthesising materials, particularly attractive for waste heat recovery. For example, it is reported in [16] that the rare earth compounds $YbAl_3$, although possessing a relatively low figure-of-merit, has a power factor at least double that of any other reported in the literature, which operates over the temperature range of a waste heat source. When compared to $YbAl_3$, MgSn has almost the same performance but costs less than 25% [7].

Another recent direction to improve the competitiveness of thermoelectric materials, other than by improving the figure-of-merit, is by developing novel thermoelectric module shapes. As discussed previously, thermoelectric modules have typically plate-like shapes Fig. (**3**) and fabricated from bulk semiconductors such as Bi_2Te_3 and PbTe, making them rigid and unsuitable for covering relatively large surfaces that are curved or non-flat (e.g. circular tubes) used in waste heat recovery applications. Also, this conventional configuration is suitable for applications where the flow of heat is perpendicular to the ceramic plates. However, when heat flows in radial directions, the attachment of plate-shape modules around a cylindrical heat source is often complicated. It becomes increasingly difficult, if not impossible, when the diameter of the cylindrical heat source decreases to less than 1 cm [17]. In addition, in order to improve thermal contact to heat sources of arbitrary geometry, it is desirable to fabricate thermoelectric modules which can conform easily to a surface.

Therefore, recent research has been focused on developing novel flexible- and cylindrical-based shapes of thermoelectric power generators. For example, very recently, Yadav *et al*. [3] proposed and demonstrated the use of flexible and cost-effective thermoelectric power generator based on thin film thermoelectric on flexible fiber substrates as shown in Fig. (**7**). They concluded that their innovation can be effectively applied in making flexible thermoelectric power generators for waste heat recovery applications. In [3] it was also suggested that utilizing thicker semiconductor films evaporated onto hollow, low thermal conductivity substrates represents an opportunity to further increase power extraction efficiency from heat sources having a variety of shapes.

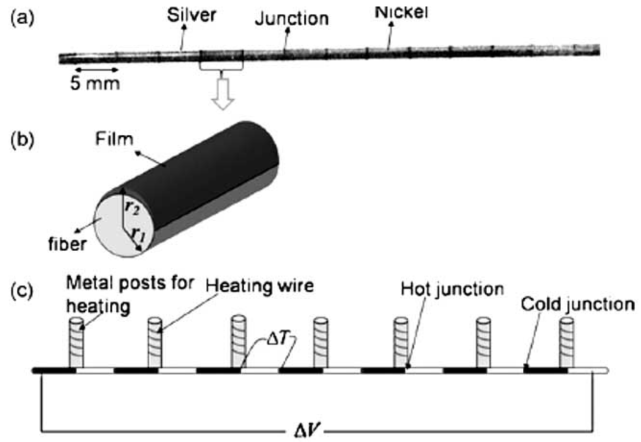


Fig. (7). (a) Schematic diagram of a striped thin film thermoelectric fiber made with thermal evaporation of nickel and silver; (b) schematic of fiber with thin film deposited on one side; and (c) schematic of experimental setup for applying a temperature difference and measuring the induced open circuit voltage [3].

Min and Rowe [17] have also recently developed a novel tube-shape thermoelectric module for power generation. It is fabricated from four ring-shaped thermoelements and its performance in electrical power generation is evaluated by measuring the power output as a function of temperature gradient across the device. Fig. (**8**) shows a schematic of the novel thermoelectric module developed by [17]. It consists of two coaxial tubes: the inner tube is a thermoelectric assembly with heat source flowing in the center and the outer tube is an ordinary tube to hold the cooling fluid flowing between the inner and outer tubes. It was concluded by [17] that a tube-shape thermoelectric module could achieve similar performance to that of a conventional plate-like module, and has an advantage in waste heat recovery applications where heat flows in a radial direction.

6. RECENT DEVELOPMENTS & NOVEL APPLICATIONS

Enormous quantities of waste heat generated from various sources are continuously 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, which presents itself as a promising alternative green technology, has been successfully used to produce electrical power in a range of scales directly from various sources of waste-heat energy. This will be discussed in the next sections.

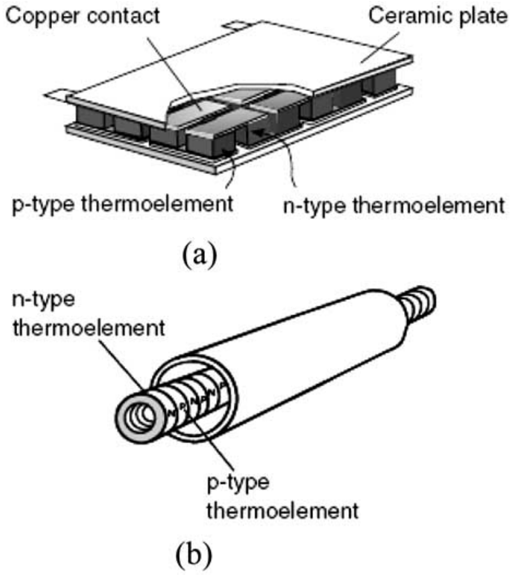


Fig. (8). Schematic diagram of thermoelectric modules. (a) Conventional thermoelectric module with a plate-like configuration. (b) A novel thermoelectric module consisting of two coaxial tubes [17].

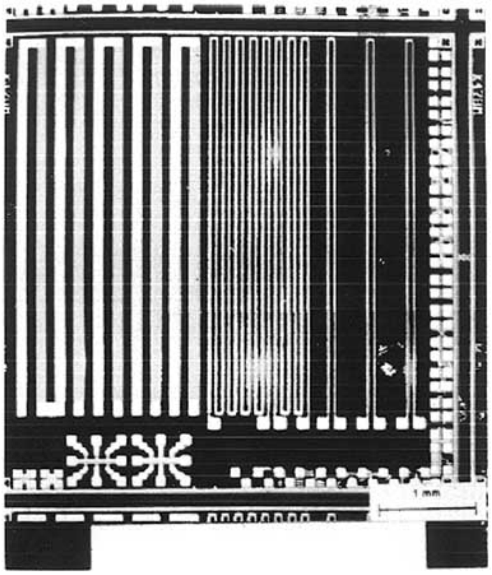


Fig. (9). Photograph of the miniature thermoelectric generator [18].

6.1. Micro-Scale Waste Heat Applications

Growing applications like autonomous micro-systems or wearable electronics urgently look for micro-scale power generators. One possibility is to convert waste heat into electrical power with a micro thermoelectric power generator. Micro thermoelectric power generators can be fabricated using integrated circuit technology [8]. For example, in [18], alternate n- and p-type thermoelements are ion implanted into an undoped silicon substrate. A photograph of the miniature thermoelectric generator developed by [18] is shown in Fig. (**9**) [18]. Metalisation of thermoelement connecting strips and output contacts enables several hundred thermocouples to be connected electrically in series and occupy an area approximately 25 mm^2. The miniature generator in [18] was designed specifically to provide sufficient electrical power to operate an electronic chip in a domestic gas-monitoring system. In excess of 1.5 volts could be produced when a temperature difference of a few tens of degrees was established across the module. In this case, any available waste heat source, such as the surface of a hot water pipe would provide sufficient heat flux to thermoelectrically generate the required chip-voltage [8]. In [19], waste human body heat is used to power a thermoelectric 'watch battery'. In this application, thermocouples were prepared by depositing germanium and indium antimonide on either side of a 1 mm thick insulator which served as a simulated watch strap. It was estimated that 2875 thermoelements connected in series would be required to obtain the 2V required to operate the watch.

Recently, a patent of a micro-scale thermoelectric device for generating power from waste heat to operate an electronic component is presented in [20]. The device includes a heat-conducting substrate (composed, e.g., of diamond or another high thermal conductivity material) disposed in thermal contact with a high temperature region. During operation of this device, heat flows from the high region into the heat-conducting substrate, from which the heat flows into the electrical power generator. In this patent, a Bi_2Te_3 alloy-based film thermoelectric material is placed in thermal contact with the heat-conducting substrate. The low temperature region is located on the other side of the thermoelectric module opposite that of the high temperature region. In this innovation, the thermal gradient across the device generates electrical power and drives an electrical component. A schematic diagram illustrating the concept of this patent is shown in Fig. (**10**) [20].

More recently, Glatz *et al.* [21] presented a novel polymer based wafer level fabrication process for micro thermoelectric power generators for the application on non-planar surfaces. The power generators are fabricated by subsequent electrochemical deposition of Cu and Ni in a 190-μm thick flexible polymer mold formed by photolithographic patterning of SU-8. In this invention, the generators were first tested and characterized and the thermoelectric module generated an electrical power of 12.0 $\pm$ 1.1 nW/cm^2 for a ΔT of 0.12K at the micro thermoelectric generator interface. This is equivalent to a thermoelectric efficiency factor of 0.83 μW K^{-2} cm^{-2}. It was concluded by [21] that the thermocouple length should be in the range of 80-150μm when the best thermoelectric bulk material (Bi_2Te_3) is used and realistic interface condition are assumed. A schematic diagram of this invention is shown in Fig. (**11**) [21].

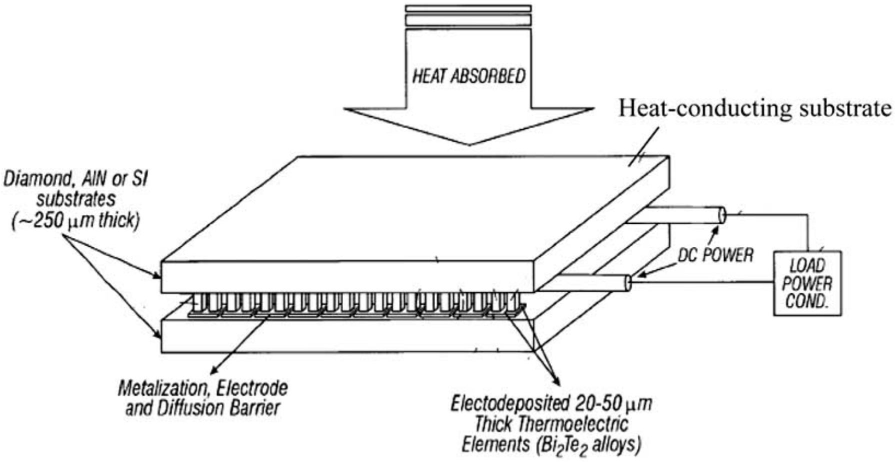


Fig. (10). Schematic diagram illustrating the patent of micro thermoelectric power generator that can be used to convert waste heat into electrical power to drive an electronic chip [20].

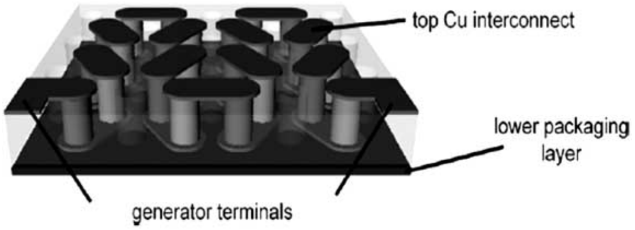


Fig. (11). Schematic diagram illustrating the patent of micro thermoelectric power generator that can be used to convert waste heat into electrical power to drive an electronic chip [21].

6.2. Macro-Scale Waste Heat Applications

6.2.1 Domestic Waste Heat Applications

Rowe [7] reported that a waste heat-based thermoelectric power generator is used in a domestic central heating system with the modules located between the heat source and the water jacket. In this application, the heat output provided by the gas/oil burner passes through the generator before reaching the central heating hot-water exchanger. The generator converts about 5% of the input heat to electrical power, the remainder of 95% transfers to the hot water heat exchanger for its intended use in heating the radiator system. It was concluded that two modules based on PbTe technology when operated at hot and cold side temperatures of 550^{o}C and 50^{o}C, respectively, would generate the 50W required to power the circulating pump [7].

Waste heat energy can also be utilized proportionally from 20-50 kW wood- or diesel-heated stoves [22], especially, during the winter months in rural regions where electric power supply is unreliable or intermittent, to power thermoelectric generators. For example, in [22], a thermoelectric power generator to produce electricity from stove-top surface temperatures of 100-300^{o}C was designed and evaluated. In this application, two commercially available thermoelectric modules were considered and 100W of electrical power output was targeted for a minimum domestic use. In this invention, the following general criteria for selecting thermoelectric modules for domestic waste heat application were considered: a high Z value; stability, and resistance to oxidation, sublimation, and evaporation; effective contact properties; non-toxicity; low component cost; and simplicity of design. When considering a waste-heat ‘Parasitic’ application, the primary criterion is a high power factor. Optimization requires a high power factor even at the expense of somewhat reducing Z. In this case, and given that the maximum temperature available on the stove surface is approximately 550 K, the modules options reported by [22] for their design of the waste heat powered thermoelectric generator, include:

- $FeSi_2$. This has excellent stability at high temperatures and may be used in open flames. The power output is, however, too low to make this an interesting preposition.
- PbTe. But this offers no advantage in this temperature-limited regime. In fact, in this range Bi_2Te_3 has an advantage in both power factor and Z as well.
- Use densely packed large area modules based on Bi_2Te_3. These may suffer somewhat from contact inadequacy leading to some power loss and could use some re-design for more power. They are limited to a maximum temperature of approximately 500-530K leading to a loss of some available heat. They appear costly per module at first.
- Use so-called high-temperature Bi_2Te_3 Peltier modules in power generation mode. These suffer from optimization inappropriate for power generation. Additionally, being limited to a maximum hot temperature of approximately 450K requires significant attenuation and heat availability loss. While here the advantage in power factor over PbTe material is reduced (due to attenuation), it still exists.

In their [22] invention, a simplified model of the generator was modeled using a 2-dimensional heat transfer program. Fig. (**12**) [22] shows a half-section of the generator model. The program assigns appropriate thermal conductivities to each material section as well as a convective heat transfer boundary condition to the top side. In their [22]

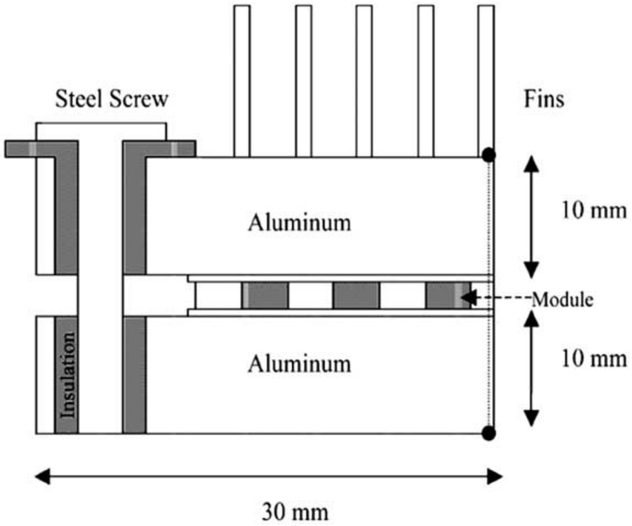


Fig. (12). Model of single module generator test rig. Half the generator is seen and the view is at slice through the edge of the rig through the fixing screws. Dark parts represent insulation [22].

model, typical thermal conductivity values were used for the materials such as aluminum, insulator, steel screws, Bi_2Te_3, and Al_2O_3. Furthermore, the conductive coefficient used was typical of forced air convection. Fig. (**13**) [22] shows the temperature profile through a section of the generator from the hot plate to the fin base. As shown in Fig. (**12**) [22], the fixing screws present a significant heat leak path thus causing cold side temperatures to be high (and a resultant low ΔT). It was concluded in [22] that in practise, the situation is not as bad as presented in Fig. (**13**) [22], since the model is only two-dimensional and it does not show the situation deeper within the generator.

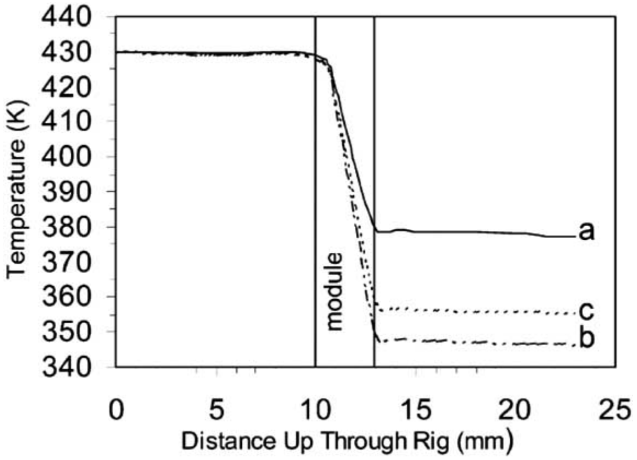


Fig. (13). Temperature profile through center of single module generator from hot side via module to fin base. Convective coefficient h =100 W/m^2K. (a) Aluminum screws and nuts with no insulating gasket above it. (b) Steel screws and nuts with an insulating gasket above it. (c) As in (b), but convective coefficient is 75 W/m^2K [22].

A similar application is reported in [7]. In this application, thermoelectric power generators were used to generate small amounts of electrical power to remote regions for example Northern Sweden, as an alternative to costly gasoline powered engine generators. The generator uses heat from a wood burning stove with the cold side cooled with a 12 volt, 2.2W fan. The generator produces around 10 watts.

6.2.2. Waste Heat From Exhaust Gases Generated From Automobiles Applications

The utilization of waste heat energy from exhaust gases in reciprocating internal combustion engines (e.g. automobiles) is another novel application of electricity generation using thermoelectric power generators. Although a reciprocating piston engine converts the chemical energy available in fossil fuels efficiently into mechanical work a substantial amount of thermal energy is dissipated to the environment through exhaust gas, radiation, cooling water and lubricating oils. For example, in a gasoline powered engine, approximately 30% of the primary gasoline fuel energy is dissipated as waste heat energy in the exhaust gases; waste heat energy discharged in the exhaust gases from a typical passenger car travelling at a regular speed is 20-30 kW [1]. A comprehensive theoretical study concluded that a thermoelectric generator powered by exhaust heat could meet the electrical requirements of a medium sized automobile [8]. It was reported in [8] that among the established thermoelectric materials, those modules based on PbTe technology were the most suitable for converting waste heat energy from automobiles into electrical power. Wide-scale applications of thermoelectrics in the automobile industry would lead to some reductions in fuel consumption, and thus environmental global warming, but this technology is not yet proven [1].

Since 1914 the possibility of using thermoelectric power generation to recover some of waste heat energy from reciprocating engines has been explored and patented [23]. A schematic diagram showing this patent of converting waste heat into electrical power applied to an internal combustion engine using a thermoelectric power generator is shown in Fig. (**14**) [23]. In this invention, the exhaust gases in the pipe provide the heat source to the thermoelectric power generator, whereas the heat sink (cold side) is suggested to be provided by circulation of cooling water.

More recently, Taguchi [24] invented an exhaust gas-based thermoelectric power generator for an automobile application. A schematic diagram showing this recent patent applied to an automobile for converting waste heat available in exhaust gases directly into electrical power using a thermoelectric power generator is shown in Fig. (**15**) [24]. In this patent, a pump supplies cooling water through each of cooling water circulation paths. The cooling water circulation path includes a cooling water pipe arranged along the exhaust pipe to pass the cooling water. At stacks a plurality of thermoelectric generation elements are attached to the exhaust pipe and the cooling water pipe successively in a direction from the upstream toward downstream of the exhaust gas. The cooling water pipe and the exhaust pipe pass the cooling water and the exhaust gas, respectively, in opposite directions so that the downstream stack has an

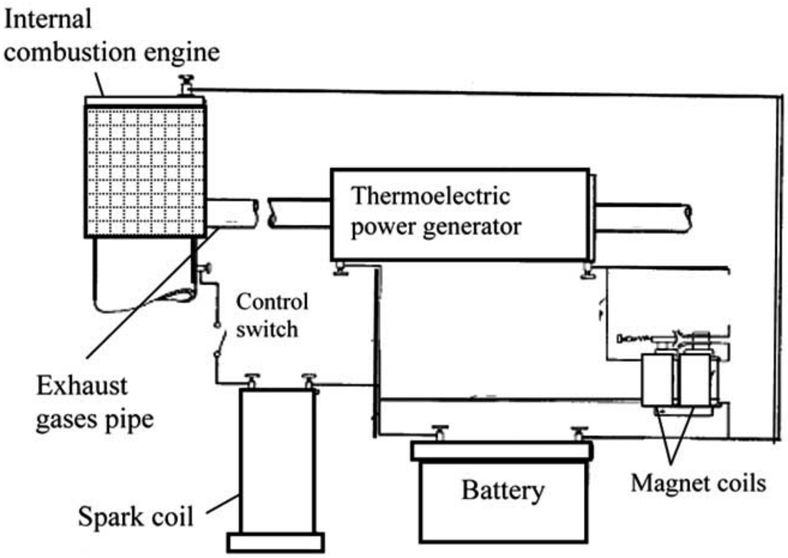


Fig. (14). Schematic diagram showing early invention of converting waste heat into electrical power applied to an internal combustion engine using a thermoelectric power generator [23].

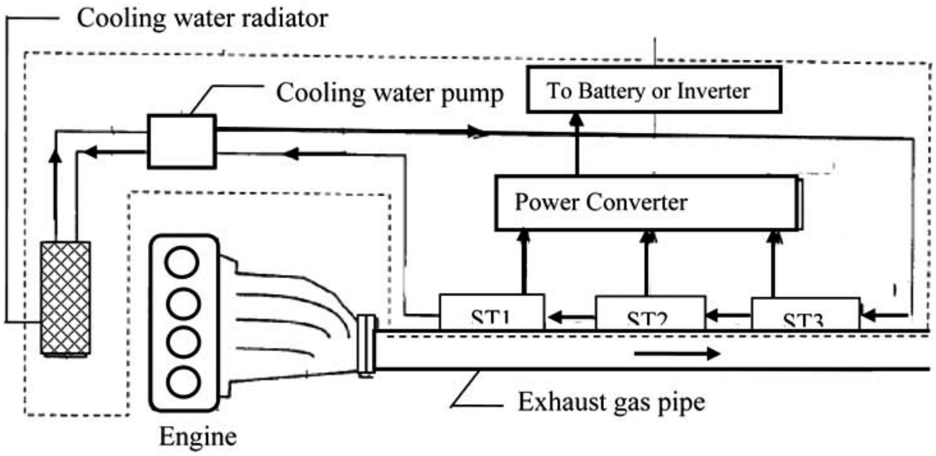


Fig. (15). Schematic diagram showing a recent patent applied to an automobile for converting waste heat directly into electrical power using a thermoelectric power generator [24].

increased difference in temperature between the exhaust pipe and the cooling water pipe, and the stacks provide power outputs having a reduced difference, and hence an increased total power output. This invention is proposed to provide increased thermoelectric conversion efficiency without complicated piping [24].

6.2.3. Industrial Waste Heat Applications

Most of the recent research activities on applications of thermoelectric power generation have been directed towards utilisation of industrial waste heat [1]. Vast amounts of heat are rejected from industry, manufacturing plants and power utilities as gases or liquids at temperature which are too low to be used in conventional generating units (<450 K). In this large-scale application, thermoelectric power generators offer a potential alternative of electricity generation powered by waste heat energy that would contribute to solving the worldwide energy crisis, and the same time help reduce environmental global warming. In particular, the replacement of by-heat boiler and gas turbine by thermoelectric power generators makes it capable of largely reducing capital cost, increasing stability, saving energy source, and protecting environment. A photograph of a thermoelectric power generator used in natural gas field to directly produce power for cathodic protection of the well and gas line is shown in Fig. (**16**) [15]. In this application, the thermoelectric device used the temperature difference between hot and cold legs of a glycol natural gas dehydrator cycle [15].

Recently, Min and Rowe [7] reported that in 1994 a £1.8M research project sponsored by the Japanese New Energy and Technology Development Organization (NEDO) commenced in the School of Engineering at Cardiff University, UK with the objective to convert low temperature waste heat into electrical power. A series of WATT (Waste heat Alternative Thermoelectric Technology) prototype genera-

Fig. (16). Photograph of a thermoelectric power generator produced power for cathodic protection of the well and gas line, which used the temperature difference between hot and cold legs of glycol natural gas dehydrator cycle [15].

tors have been constructed and identified as WATT-X where X denoted the power output in watts. Basically the generator consists of an array of modules sandwiched between hot and cold water-carrying channels. Some of the heat flux which is established by the hot and cold temperature difference between the hot and cold water flows is directly converted into electrical power. When operated using hot water at a temperature of approximately 90^{o}C and cold flow at ambient Watt-100 generates 100 watts at a power density approaching 80 kW/m^3. In this application, the system was scalable enabling 1.5 kW of electrical power to be generated [7].

Thermoelectric power generators have also been successfully applied in recovering waste heat from steel manufacturing plants. In this application, large amounts of cooling water are typically discharged at constant temperatures of around 90^{o}C when used for cooling ingots in steel plants. When operating in its continuous steel casting mode, the furnace provides a steady-state source of convenient piped water which can be readily converted by thermoelectric power generators into electricity. It was reported by [7] that total electrical power of around 8 MW would be produced employing currently available modules fabricated using Bi_2Te_3 thermoelectric modules technology.

Another application where thermoelectric power generators using waste heat energy have potential use is in industrial cogeneration systems [1,9,25]. For example, Yodovard *et al*. [9] assessed the potential of waste heat thermoelectric power generation for diesel cycle and gas turbine cogeneration in the manufacturing industrial sector in Thailand. The data from more than 27,000 factories from different sectors, namely, chemical product, food processing, oil refining, palm oil mills petrochemical, pulp and paper rice mills, sugar mills, and textiles, were used. It is reported that gas turbine and diesel cycle cogeneration systems produced electricity estimated at 33% and 40% of fuel input, respectively. The useful waste heat from stack exhaust of cogeneration systems was estimated at approximately 20% for a gas turbine and 10% for the diesel cycle. The corresponding net power generation is about 100 MW.

Very recently, an invention [26] which related to a thermoelectric-based power generation system designed to be clamped onto the outer wall of a steam pipe is presented. This patent can include a number of assemblies mounted on the sides of a pipe. Each assemble can include a hot block, an array of thermoelectric modules, and a cold block system. In this invention, the hot block can create a thermal channel to the hot plates of the modules. The cold block can include a heat pipe onto which fins are attached [26].

6.2.4. Waste Heat from Incineration of Solid Waste Applications

Recently, the possibility of utilizing the heat from incinerated municipal solid waste has also been considered. For example, in Japan the solid waste per capita is around 1 kg per day and the amount of energy in equivalent oil is estimated at 18 million kJ by the end of the 21st century. It was reported by [7] that an on-site experiment using a 60W thermoelectric module installed near the boiler section of an incinerator plant, achieved an estimated conversion efficiency of approximately 4.4%. The incinerator waste gas temperature varied between 823K and 973K and with forced air-cooling on the cold side an estimated conversion efficiency of approximately 4.5% was achieved. An analysis of a conceptual large scale system burning 100 ton of solid waste during a 16 hour day indicated that around 426 kW could be delivered [7]. In the waste heat from incineration applications, the thermoelectric modules are typically placed on walls of the furnace's funnels. This construction can eliminate the by-heat furnace, gas turbine and other appending parts of steam recycle [15]. Figure **17** [15] shows a photograph of a thermoelectric power generator produced by the Japanese Energy Conservation Center, which used waste heat as energy source to generate an electric power density of 100 kW/m^3.

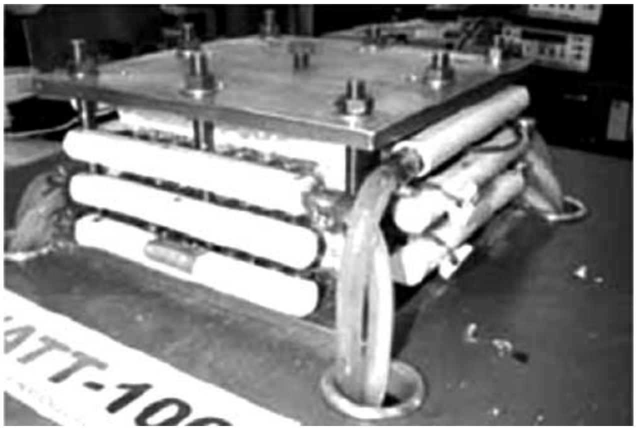


Fig. (17). Photograph of a thermoelectric power generator produced by the Japanese Energy Conservation Center, which used waste heat as energy source to generate an electric power density of 100 kW/m^3 [15].

7. CURRENT & FUTURE DEVELOPMENTS

Recently, an increasing concern of environmental issues of emissions, in particular global warming and the constraints on energy sources has resulted in extensive research into innovative technologies of generating electrical power and thermoelectric power generation has emerged as a promising alternative green technology. In addition, vast quantities of waste heat are discharged into the earth's environment much of it at temperatures which are too low (i.e. low-grade thermal energy) to recover using conventional electrical power generators. Thermoelectric power generation offers a promising technology in the direct conversion of waste-heat energy, into electrical power. In this paper, a background on the basic concepts of thermoelectric power generation is presented and recent patents of thermoelectric power generation with their important and relevant applications to waste-heat energy are reviewed and discussed. Currently, waste heat powered thermoelectric generators are utilized in a number of useful applications due to their distinct advantages. These applications can be categorized as micro- and macro-scale applications depending on the potential amount of heat-waste energy available for direct conversion into electrical power using thermoelectric generators. Micro-scale applications included those involved in powering electronic devices, such as microchips. Since the scale at which these devices can be fabricated from thermoelectric materials and applied depends on the scale of the miniature technology available. Therefore, it is expected that future developments of these applications tend to move towards nano technology. The macro-scale waste heat applications included: domestic, automobiles, industrial and solid waste. Currently, enormous amounts of waste heat are discharged from industry, such as manufacturing plants and power utilities. Therefore, most of the recent research activities on applications of thermoelectric power generation have been directed towards utilisation of industrial waste heat. Future developments in this area might focus onto finding more suitable thermoelectric materials that could handle higher temperatures from various industrial heat sources at a feasible cost with acceptable performance. Another future direction is to develop more novel thermoelectric module geometries and configurations. The developments of more thermoelectric module configurations by developing novel flexible thermoelectric materials will make them more effective and attractive in applications where sources of waste heat have arbitrary shapes.

ACKNOWLEDGEMENT

Not applicable in this article.

CONFLICT OF INTEREST

Not applicable in this article.

TERMINOLOGY

A = Cross-sectional area (mm^2)

I = Electric current (Amp)

k = Thermal conductivity (W/m.K)

l = Thermoelement length (mm)

N = Number of thermocouples

$\dot{Q}_H$ = Heat transfer rate from high-temperature source (W)

$\dot{Q}_L$ = Heat transfer rate from low-temperature sink (W)

R = Electric resistivity (Ω)

T_H = Temperature of heat source (K)

T_L = Temperature of heat sink (K)a

$\overline{T}$ = Average temperature between hot and cold plates (K)

ΔT = $T_H - T_L$

V = Voltage (Volt)

$\dot{W}_e$ = Electrical power (W)

Z = Thermoelectric material figure-of-merit (goodness factor) (K^{-1})

α = Seebeck coefficient

η = Thermoelectric module conversion efficiency

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