Research article

MAXIMIZING THE PONTENTIAL OF WASTE HEAT FOR GENERATION OF ENVIRONMENTAL FRIENDLY ENERGY

[1]Olukayode Lawrence Ayodele, [2] Kazeem Oladele Sanusi and [1] MTE Kahn

[1] Faculty of Engineering, Department of Mechanical Engineering, Cape Peninsula University of Technology, Cape Town, 1906, South Africa

[2] Faculty of Engineering and the Built Environment, Department of Mechanical Engineering Science, University of Johannesburg, Auckland Park Kingsway Campus, Johannesburg 2028, South Africa

Olukayode Lawrence Ayodele, (corresponding author) E-mail: AyodeleO@cput.ac.za

Phone: +27820925793

Abstract

Autonomous systems source energy from waste heat which are generated by home appliances and industrial machineries and mitigate the effect of global warming which threatens the environment as a result of fossil fuel energy based sources that release undesirable carbon-monoxide into the atmosphere. This paper described current waste heat recovery practices in different applications, and an innovative approach to convert heat energy into usable forms. This can significantly contribute towards sustainable energy development and meet the growing need for power in small scale applications due to its relative advantages over other sources of energy generation. It will help in optimizing existing waste recovery technologies and developing new heat recovery technologies and gives an insight into various ways by which waste heat can be exploited to meet the growing energy demand and increasing interest in space exploration, satellite activities, structural health monitoring and terrestrial monitoring in harsh and inaccessible environments place a high demand for energy sources for autonomous systems.

Keywords: autonomous systems; energy; thermoelectric; Seebeck effect; waste heat

1. Introduction

Waste heat losses arise both from equipment inefficiencies and from thermodynamic limitations on equipment and processes. For example, consider reverberatory furnaces frequently used in aluminum smelting operations (Das,2007). Heat recovery technologies frequently reduce the operating costs for facilities by increasing their energy productivity. Many recovery technologies are already well developed and technically proven; however, there are numerous applications where heat is not recovered due to a combination of market and technical barriers (Johnson and Choate, 2008). Numerous technologies are available for transferring waste heat to a productive end use. The increasing interest in space exploration, satellite activities, terrestrial monitoring in remote areas and hermetic environments place a high demand for energy sources for autonomous systems. Availability of autonomous energy sources for home appliances and industrial machineries will also mitigate the effect of global warming which threatens the environment as a result of fossil fuel energy based sources that release undesirable carbon-monoxide into the atmosphere. Captured and reused waste heat is an emission free substitute for costly purchased fuels or electricity.

Examples of Waste Heat Sources and End Uses are Combustion Exhausts from Glass melting furnace, Cement kiln Fume incinerator , Aluminium reverberatory furnace Boiler, Process off gases from Steel electric arc furnace and Aluminium reverberatory furnace , and Cooling water from Furnaces Air compressors , Internal combustion engines and Conductive, convective, and radiative losses from heated products from Hot cokes Blast furnace slags. This can be used for Combustion air preheating , Boiler feedwater preheating , Load preheating , Power generation, Steam generation for use in power generation mechanical power process steam , Space heating , Water preheating and transfer to liquid or gaseous process streams barriers (Johnson and Choate, 2008).

Advancement in manufacturing technology in the past 20 years has resulted in the development of various types of micro-scale devices in the range of millimeter to nanometer. However, it has been challenging to make the same progress in developing miniaturized or micro power source (Guo et al. 2008). The conventional batteries still being used for most of the micro-scale and nano-scale devices bring about bulky systems and frequent recharging or replacement of batteries in addition to low energy density and limited life span by Duggirala et al, (2004), A critical requirement for the success of autonomous systems in applications such as environmental monitoring and civil infrastructure health monitoring, is the realization of miniaturized power sources with long life span, especially for sensor networks in harsh and inaccessible environments where battery replacement would be expensive or practically impossible.

An autonomous system is designed to operate or function as long as possible in known or unknown environments providing, elaborating and storing information without being connected to a power grid. The system could operate in external natural or industrial environments. Autonomous systems such as wireless sensor networks, actuators, and ambient intelligence devices have the ability to operate with less than hundreds of micro-watts (μW) of power within less than some cubic centimetre (Catrene, 2005). Energy sources on a macro scale for autonomous operations are batteries, solar panels, fuel cells and radioisotope generators. These power sources have their relative strengths and weaknesses. Solar panels, especially the modern ones have the capacity to provide abundant power however solar panels have their associated drawbacks some which are: very large and fragile constructions that are vulnerable to damage from external factors that include solar flares and meteorites or even just mechanical failures, relatively expensive to build, they need to always be pointed at the sun, which means they are not useful when blocked by planets or other objects, power generated becomes inadequate the farther the satellite is from the sun since the intensity of light from the sun decreases with the square of the distance between the satellite and sun. Fuel cells have a longer lifespan compared to batteries and do not require recharging since it can be refuelled. Theoretically, a fuel cell will produce electricity as long as fuel is being supplied constantly. They are extremely efficient, simple to design, have virtually no emissions, and they run silently since no moving part is involved (Larmimie, and Dicks, 2000). Fuel cells are already in use in the space shuttle and are quite useful in other near-Earth missions. However, despite their merits they are relatively expensive since long flights require considerable amount of fuel. They also run very hot (400–1000 F), and the waste heat is often a huge problem to manage (Coutts et al. 1996). Batteries are reliable and have a well-understood technology, however, batteries have the down side of short life span, and rechargeable batteries being utilized in remote areas need to be recharged by other source of power such as solar panels (Raymen and Sherwin, 2003). Besides the inadequacy of short life span and reliance on other power source for recharging purposes, size is also a drawback. Thermoelectric energy generator which utilizes waste heat offers an alternative source of power generation due to the following merits: extremely reliable, simple, compact, environmentally friendly, not position-dependent, runs silently because of no moving parts (Rowe, 1999).The dependent of human being on energy is synonymous to human existence since energy is required for survival especially during extreme weather conditions; also access to energy is crucial for technological advancement.

Waste heat recovery technologies, although currently employed to varying degrees at many industrial facilities, face technical and economic barriers that impede their wider application. In order to promote waste heat recovery and process integration, efforts must be undertaken to extend the economic feasibility of conventional recovery technologies, as well as promote new technologies that can be applied to waste heat sources not typically exploited for waste heat recovery.

2. Thermoelectric Energy Generators

Thermoelectric Generator (TEG) is a solid state device that converts temperature gradients directly into electricity using the Seebeck effect (Carmo et al. 2011) .TEG components do not require moving parts or any kind of fluids, these attributes make TEG very versatile for stand-alone nodes of wireless sensor networks with harvesting capabilities. TEGs are reliable sources of energy and produce no noise or vibration since there are no mechanical moving parts; they have small size and light in weight (Riffat and Ma, 2003). TEGs run quietly, they are compact, highly reliable and environmentally friendly. Owing to the aforementioned features coupled with relatively low operating and maintenance costs, TEG have found a large range of applications, however despite the high-points of TEG, it is plagued by its relatively low heat to electricity conversion efficiency (Qiu and Hayden, 2008).

A schematic diagram of a simple thermoelectric generator operating on Seebeck effect is shown in figure 1. Heat is transferred at a rate of $\dot{Q}_H$ from high temperature heat source maintained at hot junction temperature T_H. Heat is rejected at a rate of $\dot{Q}_L$ to a low temperature heat sink maintained at cold junction temperature T_L. The heat supplied at the hot junction causes electric current to flow in the circuit and electrical power is produced.

The efficiency of a TEG can be conveniently expressed as function of the temperature over which it is operated and a 'goodness factor' which is also known as thermoelectric figure-of-merit Z which is expressed as (Ismail & Ahmed, 2009):

$$Z = \frac{\alpha^2}{\rho\lambda} \quad \text{or} \quad Z = \frac{\alpha^2\sigma}{\lambda} \tag{1}$$

where α is the Seebeck coefficient, ρ is the electrical resistivity, σ is the electrical conductivity, and λ is the thermal conductivity.

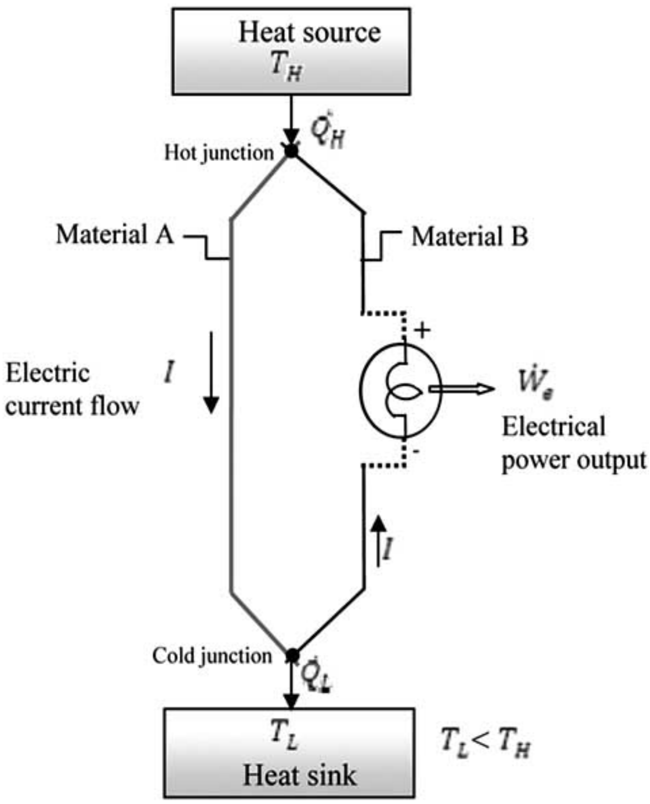

Figure 1: Schematic diagram showing the basic concept of a simple thermoelectric power generator operating on Seebeck effect (Ismail and Ahmed, 2009).

The relationship between the conversion efficiency and operating temperature difference for a range of values of the material's figure-of-merit was investigated (Rowe , 2006) and confirmed that an increase in temperature provides a corresponding increase in conversion efficiency. Also, increase in figure-of-merit yields corresponding increase in conversion efficiency. The figure-of-merit is often expressed in its dimensionless form by multiplying Z by T (the average absolute temperature of the hot and cold junctions of the thermoelectric module), i.e.

$$ZT = \frac{\alpha^2 \sigma T}{\lambda} \quad \text{and} \quad T = \frac{T_H + T_L}{2} \tag{2}$$

The performance parameter ZT is very useful in Seebeck sensing devices, such as infrared thermal detectors (Carmo et al. 2011) . The Seebeck coefficient of metals is usually between 0 and

$50\,\mu\text{mK}^{1}$, whereas the Seebeck coefficient of semiconductors could be over $350\,\mu\text{mK}^{1}$(Qiu and Hayden, 2008). When a temperature difference exists between two thermal surfaces (hot and cold junctions of two dissimilar materials that can either be metals or semiconductors), an open circuit output voltage, V_G, is generated according to the following equation: $V_G = N\alpha\Delta T$ where, N is the number of thermocouples, α is the Seebeck coefficient of the TEG materials and ΔT is the temperature difference applied.

The core element of a TEG is the thermopile (Rowe, 1995). A thermopile which is also known as a module, is a device formed by a large number of thermocouples placed between a hot plate and a cold plate and connected thermally in parallel and electrically in series as shown in figure 2.

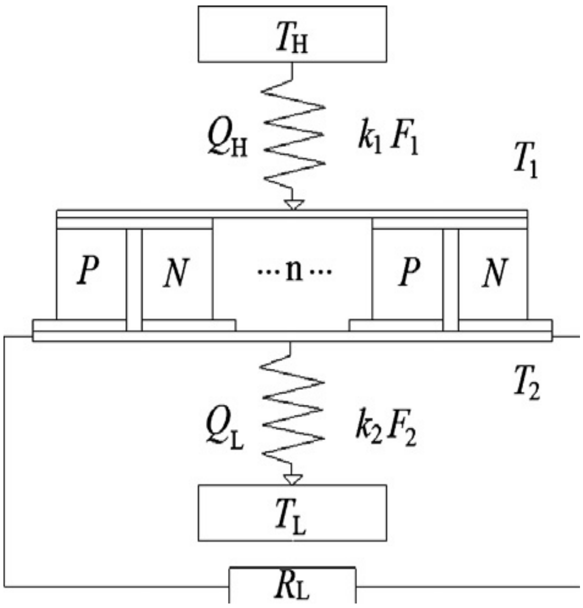

Figure 2: Schematic diagram showing the basic concept of a simple thermoelectric power generator operating on Seebeck effect (Xiaolong et al. 2010).

The significance of the series and parallel arrangement of the thermocouples is to enhance reliability by minimizing the effect on total power due to an open circuit or short circuit failure in a single thermocouple (Schmidt et al,2011) .The most widely used thermocouples are bismuth telluride (BiTe), lead telluride (PbTe), lead tin telluride (PbSnTe), silicon germanium (SiGe) and tellurides of antimony, germanium, and silver (TAGS), however, many more other materials have been used while some are still being investigated with the hope of finding ideal thermocouples that have the capability of higher efficiency, lower mass, and more stable performance over longer operating lifetimes (Lange and Carroll, 2008). Another performance factor of a TEG known as the electrical power factor is defined as the electric power per unit area through which the heat flows per unit temperature gradient between the hot and cold junctions and it is expressed as: The power output for most of the commercially available TEGs range from microwatts to multi-kilowatts (Rowe, 1999). Generally, TEGs exhibit low efficiency due to the relatively small dimensionless ZT of currently available thermoelectric materials . The efficiency of a TEG which is defined as the ratio of the energy delivered to the load to the heat energy absorbed at the hot junction (Rowe, 2006) which can be expressed as (Ismail and Ahmed, 2009) :.

$$\eta = \frac{\dot{Q}_H - \dot{Q}_L}{\dot{Q}_H} = \frac{\dot{W}e}{\dot{Q}_H} \qquad (3)$$

where $\dot{W}e$ is the electrical power output.

3. Applications of Thermoelectric Generators

Utilization of power generated from heat conversion is not new. Conversion of heat into energy was first discovered in 1822 by Thomas Seebeck. The first TEG was built in the former USSR (Soviet Union) in 1942 with efficiency of approximately 2%. However the discovery of semiconductors, the increasing the demand for energy and the threat to environment by other sources of energy generation is for the use of TEGs, there is growing interest in the utilization of TEGs. Vast quantities of waste heat are discharged into the environment with great part of it at temperatures which are too low to recover using conventional electrical power generators. Waste heat are generated by kerosene lamps, exhaust pipes from automobiles, human body, cooling towers, incinerated municipal solid waste and radioactive wastes.

3.1 Electrification of isolated rural homes

Exploitation of residual heat thrown away by firewood home stoves to generate electricity was studied experimentally (Rinalde, 2010).TEGs capable of being operated by non-technicians users for electrification of rural homes was developed. The simplicity of the prototype developed confirms the potentiality of local development of this technology. The developed TEG constitute an option of sustainable electricity generation (its operation being based on residual heat which otherwise would have been wasted) which could be developed in rural economies. The simplicity of its design and low operating cost makes the developed TEG an attractive option for low-income rural homes.

3.2 Self-powered residential heating system

A thermoelectric self-powered residential heating system was developed and a good applicability of thermoelectric generation to the heating equipment was demonstrated (Qiu and Hayden, 2008).The developed TEG has a capacity of 550 W. The TEG takes advantage of heat generated by a gas burner. The temperature gradient between the hot junction (heat from burners) and the cold junction (room environment) was approximately 535 ^{o}C. It was found that an increase in the temperature gradient bring out an increase in the power output. The TEG output was adequate to power all electrical components for the residential heating system, thus achieving self-powering. Excess power can be used to charge batteries or provide electricity for other electrical loads. It was asserted since for certain applications, electrical efficiency is not always the most important criterion, that the electricity generation is essentially 100% efficient since in this case for a thermoelectric self-powered heating system, the dissipated heat is recovered for . Consequently, thermoelectric self-powered heating systems could be economically competitive and provide a means of reducing greenhouse gas emissions.

3.3 Space exploration

TEG has safely and reliably provided continuous power over the past three decade in regions of space where the use of solar power is not practically feasible. Heat generated from the spontaneous decay of radioactive materials into nonradioactive ones has been exploited via radioisotope thermoelectric generators (RTGs) to generate hundreds of watts of electrical power through either a static or a dynamic energy conversion system using the Seebeck effect (Cataldo and Bennett, 2011).

A typical RTG consists of three basic elements: the radioisotope heat source that provides the thermal power, the converter (thermocouples) that transforms part of the thermal power into electricity, and the radiator which rejects most of the remaining amount of untransformed thermal power to space (Cataldo and Bennett, 2011). The first RTG which generated 1.8 mWe electrical power was conceived and built in 1954 by two researchers, K.C. Jordan and J.H Birden, working at what was then known as the US Atomic Energy Commission's (AEC's) Mound Laboratory (Bennett and Skrabek, 1996). Since then RTGs have been enhancing and/or enabling challenging space missions. The United State department of energy has used RTGs for for space in the last three decades. The Apollo to the Moon, Viking to Mars), Pioneer, Voyager, Ulysses, Galileo and Cassini (to outer Solar System). The National Aeronautics and Space Administration (NASA) missions that have utilized RTGs are documented by (Schmidt et al, 2011). Although not properly documented, the former USSR has also utilized RTGs for her space missions.

3.4 Heat-powered wristwatch

The temperature gradient (1 to 3 ^{o}C) between ambient and body temperatures was exploited by Seiko Instruments Inc. of Japan to develop and commercialize heat-powered wristwatch SEIKO THERMIC in 1998 (Kish et al,1999). The wristwatch utilized micro-thermoelectric device based on Bismuth Telluride materials. The user's arm serves as the hot end and dissipates heat to the back lid of the watch, while the wristwatch case which efficiently emits heat from the back lid serves as the cold end

3.5 Other applications

TEGs have also found applications in the Military (Chou et al. 2011), sensors (gas and heat) Gulian et al. 2000), and remote telecommunication, navigation and instrument protection (Ghamaty et al. 2003).

Piezoelectric Power Generation

Piezoelectric Power Generation (PEPG) is an option for converting low temperature waste heat to electrical energy. Piezoelectric devices convert mechanical energy in the form of ambient vibrations to electrical energy (Nechibvute et al. 2012). A piezoelectric thin film membrane can take advantage of oscillatory gas expansion to create a voltage output. While the conversion efficiency of PEPG technology is currently very low (1%), there may be opportunities to use PEPG cascading, in which case efficiencies could reach about 10% . Other key issues are the costs of manufacturing piezoelectric devices, as well as the design of heat exchangers to facilitate sufficient heat transfer rates across a relatively low temperature difference (Johnson and Choate, 2008).

Based on estimates of waste heat losses in selected applications, several trends were identified regarding opportunity areas and RD&D needs for waste heat recovery

4 The Prospects of Applications of Underutilise Waste Heat

The demand for energy sources that are compact, lightweight, high energy density and long-life on a smaller scale for micro-scale devices in autonomous systems application such as sensors for toxic gas and sensors in inaccessible remote areas for environmental monitoring or in hermetic environments such as extreme heat, cold, or corrosive conditions has significantly increased in recent years. Energy scavenging means of harvesting ambient energy such as wind and solar are being exploited in order to reduce this current effect of global warming to the environment. However, the availability of these means of energy scavenging at micro level is posing a great challenge in addition to their inherent drawbacks. The conventional electrochemical batteries cannot meet the requirements due to their limited energy density and adverse effects on the environment upon disposal (Nuwayhid et al. 2003). The innovative approaches to convert available energy into usable forms on micro-scale can significantly contribute towards sustainable energy development and meet the growing need for power in small scale applications. Operation of a micro-system in which the power supply does not dominate the volume requires compact power sources with long life span and high power density.

5 Waste Heat Recovery Opportunity Areas

Due to the increase in high of waste heat losses, several key opportunities areas of needs for waste heat recovery are:

- High temperature systems where heat recovery is less common There are market segments where waste heat recovery is less common; this is due to barriers such as chemical constituents in exhaust gases that interfere with heat exchange, as well as limitations on economies of scale for smaller waste heat streams.
- Systems already including waste heat recovery that can be further optimized to reduce heat losses. The extent of heat recovery from existing systems is often constrained by costs and temperature limits for the heat recovery system. In many cases, such as cement preheater kilns and recuperative glass furnaces, exhaust gases exiting the recovery device are still in the mediumto high temperature range. This represents an opportunity for additional waste heat recovery. Opportunities are also available to maximize the quality of heat recovered, since facilities often use dilution air to lower the temperature of waste heat streams.

6 Area of Research and Development Opportunities for Waste Heat Recovery

Several efforts could be made to reduce system costs, optimize heat exchange materials, heat transfer rates, low temperature recovery, and available end uses for waste heat. Opportunities for RD&D that address technology and cost barriers are listed below.

- Low cost, novel materials – Develop low cost, novel materials for resistance to corrosive contaminants and to high temperatures.

- Reduce overall costs – Economically scale down heat recovery equipment and reduce relative costs for small scale operations.

- Easier maintenance – Develop economic recovery systems that can be easily cleaned after exposure to gases with high chemical activity.
- Process improvements – Develop alternative manufacturing processes that generate less waste heat. Or, develop processes that avoid introducing contaminants into process offgases, thereby enabling easier heat transfer from exhaust gases. Of course, both must retain acceptable product quality and financial returns.
- Develop low cost methods for cleaning exhaust gases.

- Develop and demonstrate low temperature heat recovery technologies, including heat pumps and low temperature electricity generation. Develop new working fluids that can efficiently recover low temperature heat.
- Alternate end uses – Develop alternative end uses for waste heat. In addition to new technologies for power generation, options could include converting waste heat into other transportable forms.
- Development and improve novel heat exchanger designs with increased heat transfer coefficients, especially in gas to gas and gas liquid heat exchangers.
- Reducing the cost, technical, and product control challenges of process specific feed preheating systems like batch/cullet preheating in the glass industry.
- Development of new heat recovery technologies such as solid state generation.
- Low cost manufacturing of recovery technologies and promoting low cost manufacturing techniques for the technologies.

6 Conclusions

Vast amounts of underutilise heat which is discharged to the environment can be exploited to generate electric power. Thermoelectric energy generation is an environmentally friendly technology which can convert this unused heat, and in particular low temperature heat, into electricity. Although TEGs are plagued by conversion of efficiency of approximately 6%, however the trade-off between conversion efficiency and power output in order to minimise cost is reflected in turn by a trade-off between the construction and running costs.

Conflict of interests

The authors declare that there is no conflict of interests regarding publication of this paper

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