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A potential candidate for the sustainable and reliable domestic energy generation–Thermoelectric cogeneration system

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A B S T R A C T

Due to being solid-state, noiseless and maintenance free, thermoelectric devices have found wide applications in different areas since they were discovered over 180 years ago. The applications are concerned with environment-friendly refrigeration and power generation in transportation tools, industrial utilities, military devices, medical services and space applications. It is utilisation of waste heat in varying applications that make the modules particularly attractive. Nevertheless, despite a few academic papers, there has not been extensive use in the domestic sector. A concept of thermoelectric cogeneration system ('TCS') is proposed to highlight the direction for enhancing the sustainability by improving the energy efficiency in domestic sector. Compared to the thermoelectric systems used in other areas which only uses the part of converted energy but wastes the unconverted part by dissipating it into the environment, the system presented here maximally recover the available heat by generating electrical power and producing hot water simultaneously. The viability of this system concept is evaluated on a bench-scale experimental prototype. The outputs of electrical power and hot water have been investigated at different temperature difference. The cost saving potential and cost recovery period have been estimated using the available heat sources in domestic sector. The results intend to provide reference for developing the real-scale domestic thermoelectric cogeneration system and show the potential benefits.

1. Introduction

Power generation using thermoelectric generators have been utilised in the areas like aerospace facilities, transport tools and industry utilities, in which a considerable amount of waste heat offers a great opportunity for making direct use. Fig. 1 shows the energy consumption in four major sectors [1], where a considerable amount of energy has been exhausted into environment without being used.

In vehicles, over 50% of the total fuel energy escapes to the ambient environment as heat loss through the exhaust system and radiator. The possibility of recovering it with thermoelectric module was explored as early as in 1914 [2]. Joint efforts by academia and industry used the most advanced available thermoelectric materials of the time to achieve an overall efficiency of 5–10% [3]. Due to the different temperature levels across the section between engine and exhaust, the optimum performance could be obtained by adapting specific modules for individual temperature level and applying segmented materials or multistage designs. Meanwhile, thermoelectric devices are also used to control temperature and produce cooling and heating from electrical power input in automobiles. This type of application avoids the use of environmentally harmful refrigerants.

Explorations in hostile and inaccessible locations, advances in medical physics, deployment of marine and terrestrial surveillance systems and earth resources require autonomous long-life sources of electrical power. Thermoelectric generators have more than 100,000-h steady-state operation and precise temperature control [4]. Their developments were used by NASA to provide electrical power for spacecraft since 1961. The reliability of thermoelectric technology has been demonstrated in the Voyager spacecraft with Voyager 1 passing into the Heliosheath about 8.3 billion miles from Earth on May 24th 2006. The application normally involves using radioisotopes as the heat sources which are restricted in specialised applications where the advanced properties outweigh the low conversion efficiency. Early successful space applications of thermoelectric power generation were achieved by the development of systems for Nuclear Auxiliary Power in America in 1955 [5]. Similar

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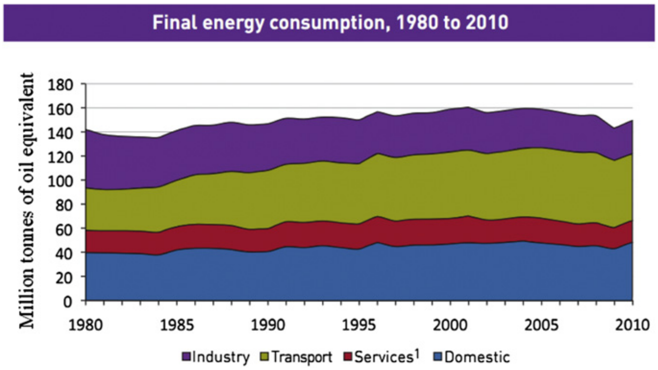

Fig. 1. Energy consumption of different sectors in the UK (1980–2010).

applications on artificial satellites Cosmos-84 and Cosmos-90 in USSR were also recorded [6]. For the aircraft industry (both commercial and military), thermoelectric devices can capture waste heat from the engine and operate over the entire aircraft flight envelope without affecting engine's performance.

The process industries include food, beverages, chemicals, pharmaceuticals, petroleum, ceramics, base metals, coal, plastics, rubber, textiles, tobacco, wood and wood products, paper and paper products. Industrial energy consumption represents a large contingent of energy consumption. For example, it accounted for more than a fifth of all UK energy consumption in 2001 consuming 35,152 thousand tonnes of oil equivalent [7], as shown in Fig. 1. Due to the large scale in most cases, industries involve with a huge amount of energy consumption, in which a considerable amount escapes to the environment in the form of exhausting, radiation and cooling. Fig. 2 compares the energy use and loss in energy systems across sixteen industrial sectors. Five industrial sectors, which include petroleum refining, chemicals, forest products, iron and steel, and food and beverage, account for over 80% of all the energy inputs to energy systems. They are large users of steam systems and fired systems such as furnaces and dryers. In total, energy losses associated with energy systems in these five industries totals represents over 15% of the energy consumed by U.S. industry.

This energy loss or waste heat, produced in the processes of fuel combustions and chemical reactions, is wasted by ending up in the environment rather in the product due to unnecessary processes, intensive drying, inefficient boilers and steam systems. The possibility of employing thermoelectric technology to generate electrical power from low temperature (80–100 K) heat source on off-shore oil platforms was discussed in 1992 [9]. Applications in both small scale and large scale for recovering heat from combustible solid waste have been developed in Japan [10]. An estimated conversion efficiency of 4.36% was achieved in a small scale onsite experiment

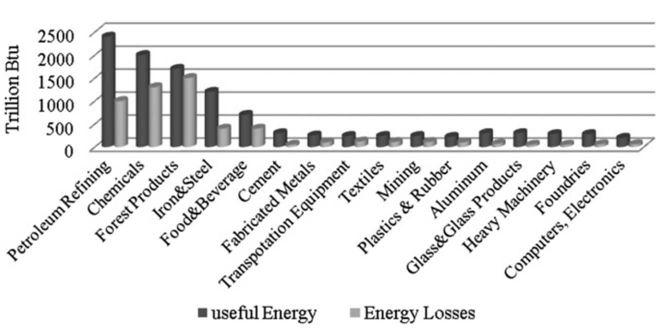

Fig. 2. Energy consumption chart in different industrial sectors [8].

using a 60 W thermoelectric module installed near the boiler section of an incinerator plant [11].

Nowadays, the use of PV (photovoltaic) technology takes over the major role of domestic power generation in many countries and regions. It has to be mentioned that PV delivers higher conversion efficiency compared to the thermoelectric generator. However, it has a small capacity factor due to its dependence on solar radiation. The disadvantage of PV is obvious especially in the regions that show a lack of solar radiation. Due to multi-heat-sourcing, quiet, long period reliable and maintenance free operation, thermoelectric generators have become an environmentally friendly and energy saving star despite lower efficiency compared to solar PV power generation. Efforts have been continuously made to adopt thermoelectric technologies in many different areas. Relevant investigations have been carried out in the pursuit of optimum and sustainable ways of using them.

The domestic power generation using thermoelectric technology has been mentioned in previous studies [12–15]. However, the common disadvantage shown by these stove application designs lies in the use of a cooling fan which consumes electricity and has moving parts. Most of heat output is exhausted to the environment in an unorganised way except for [15] which uses the heat for space/water heating; only a small part of the absorbed heat is converted into electricity. This disadvantage is enlarged further when the conversion efficiency is low. This paper introduces a concept of domestic TCS on a bench-scale experimental prototype which overcomes low system efficiency of current domestic application designs and is oriented to be integrated to existing domestic boiler systems. The power output and heat output have been investigated under different temperature differentials. The viability of the real-scale domestic TCS has been analyzed and prospected based on the experimental results. The annual cost saving and cost recovery period has been estimated on the basis of available heat sources in domestic environment. One of the intentions is to provide information to decision makers, technical managers and house owners for assessing the possible impact of integrating this technology to the domestic sector in future.

2. Design for domestic application

2.1. Background

Thermoelectric materials can be used for either cooling or power generation. Its construction consists of arrays of N & P type semiconductors in which, by applying a heat source on one side and a cooling heat sink to the other side, electric power is produced and vice versa. As shown in Fig. 3, when a temperature difference is established between two ends of semiconductor element, a voltage is generated. This effect, discovered by Thomas J. Seebeck, is called Seebeck effect.

The thermoelectric properties of thermoelectric materials, which form the semiconductor element, are characterized by the dimensionless figure of merit ZT, which is defined in terms of intrinsic material properties of both the N-and P- type materials and determined by three physical properties—Seebeck coefficient (S), electrical conductivity (σ), and thermal conductivity (λ). It can be related to the physical properties by Eq. (1):

$$ZT = \sigma S^2 T/\lambda \tag{1}$$

The larger the value of ZT, the better thermoelectric performance the material has. The materials with higher σ and lower λ have larger value of Z, which contributes more to the enhancement of η. It characterizes the capability of thermoelectric generator in converting heat into electricity and is given by Eq. (2):