Energy Conversion and Management 174 (2018) 138–156

Contents lists available at ScienceDirect

Energy Conversion and Management

journal homepage: www.elsevier.com/locate/enconman

Review

A review of thermoelectric power generation systems: Roles of existing test rigs/ prototypes and their associated cooling units on output performance

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ARTICLE INFO

Keywords:
Waste heat recovery
Thermoelectric modules and power generation
Existing test rigs and prototypes
Passive and active cooling
Output performance

ABSTRACT

Thermoelectric technology is a promising solution to recover waste heat from different resources. There are numerous researches in the literature that measure performance of thermoelectric modules (TEMs). A comprehensive review of research studies that classifies and expounds disparities between various thermoelectric power generation (TEPG) systems is still unavailable and therefore, this paper reviews major concerns on their designs and performances. Firstly, various main elements of TEPG systems, which affect the output power of TEMs such as stabilizer or heat exchanger, interface, contact pressure, insulation, cooling system, and integrity are studied. Secondly, performances of test rigs and various prototypes are reviewed in detail based on their cooling methods since cooling is the most prominent factor among other counterparts. In general, the cooling unit is divided into either passive or active cooling system, which is selected based on its well-defined use. A comprehensive study on various test rigs with active cooling systems is given while a broader range in prototypes is covered and classified under detailed surveys. This review is expected to be of value for researchers in the field of thermoelectric. Overall, in order to have a prospective future towards commercialization of TEPG systems, the existing prototypes in the literature are still subjected to many enhancements in their design aspects, while further improvements are needed to be achieved independently in TEMs' development.

1. Introduction

The 18th century refers to a discovery of thermoelectric (TE) phenomenon, which is a generation of small voltage between two disparate metals in the form of thermocouples. The invention of high-efficient semiconductors resulted in a rapid development of TE technologies over the last 60 years [1], and the development of new materials is rapidly progressing. TE technologies use Seebeck effect for power generation [2] and Peltier effect for refrigeration [3,4]. In power generation, various materials such as bismuth telluride (Bi_2Te_3) [5–9], skutterudite [10–12], zinit phase [13–17], lead telluride (PbTe) [18–20], silicon germanium (SiGe) [21,22], zinc antimony (Zn-Sb) [23], copper selenide (Cu_2Se) [24], Cu-Se derivatives [25–28], lanthanum telluride [29], and even organic materials [30] are investigated with respect to their temperature. At temperature below 230 °C, Bi_2Te_3 (both n-type and p-type) is regarded as the best performing material. Other materials, such as PbTe, Zn_4Sb_3, skutterudites, Cu_2Se, and half-heusler alloys demonstrate high performance within a medium temperature range of 230–730 °C [31]. At the high temperature range (730–930 °C), the zinit (p-type), lanthanum telluride (n-type), and silicon germanium (p and n type) are considered as the best available materials (without including some possible high temperature oxides such as ZnO:Al,Ga [32] and $Ca_3Co_2O_9$ [33]). Currently, almost 90% of commercial TE modules (TEMs) are manufactured from Bi_2Te_3 [34]. Several groups around the

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https://doi.org/10.1016/j.enconman.2018.08.019
Received 5 April 2018; Received in revised form 14 July 2018; Accepted 6 August 2018
0196-8904/

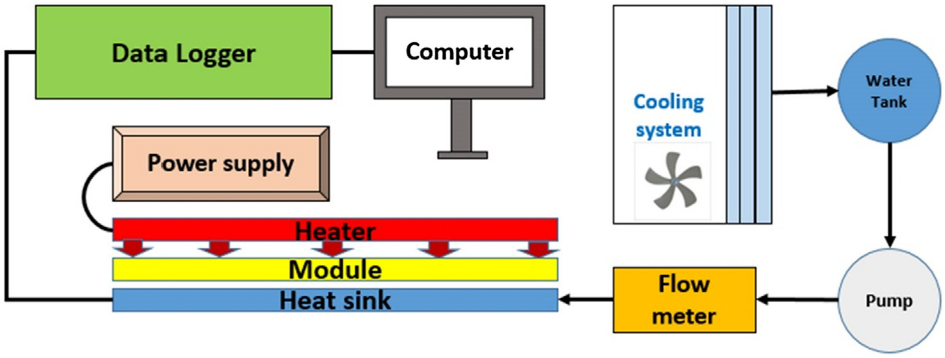

Fig. 1. Schematic diagram of the test rig's components.

world are currently working on TEMs, and exhaustive reviews have been published elsewhere [1,31,35–39].

An output performance (essentially power) of TEMs can be attained by thermoelectric power generation (TEPG) systems either from intentionally supplied heat sources or waste heat sources. Test rig or test stand is often called for the TEPG systems, which acquire intentionally supplied heat sources in the form of laboratory electrical heater with fixed wattage. Obtaining the maximum output performance of TEMs with respect to applications is a main objective of test rigs. In such a case, the maximum output power (P_{out}) would be gained if the cold side temperature is minimized into the lowest extend. This can be achieved mainly by improving the design of cooling units, which can be only derived from active cooling mechanism (fan-based or liquid circulation-based units) as widely reported in the literature. For all intents and purposes, producing more temperature difference (ΔT) requires more sophisticated and costlier test rigs, especially in the cooling part; besides heat transfer and insulation issues which are also pivotal. On the other hand, TEPG systems from waste heat sources is the another field of research interest, which is largely dealing with a realistic power generation produced by various prototypes. These prototypes utilize both active and passive cooling despite test rig to the contrary. A reliable, cost efficient and acceptable net power are the main emphasizes here. In addition to the cooling techniques, the design of heat exchanger to recover the maximum temperature from waste heat sources is a matter of concern [40].

There are many applications that TEPG systems can contribute positively such as, robots in space [41,42], electrification of isolated rural homes [43], self-powered residential heating system [44], military [45], sensors (gas and heat) [46,47], remote telecommunication [48], watches [49] and wearable devices [50,51], navigation, and instrument protection [52]. In small-scale applications, the focus is more on the development of new efficient TEMs, whereas large-scale applications require both efficient TEMs as well as well-optimized TEPG systems [53,54]. So far, this technology has been applied only in expensive applications (space and military) [55,56] since the conversion efficiency of TEMs is comparatively low and immature (~0.04% per degree of ΔT [57]). Therefore, waste heat is an ideal heat source for the TEPG systems in order to move towards commercialization [4,58]. The overall cost of TEPG systems usually consists of the TEM's cost and operating/maintenance cost [4,59]. In order for wider deployment of the TEPG systems, it is imperative to reduce the cost-per-watt. This can be done by optimizing the TE geometry, improving the manufacturing quality, and operating the device at a larger ΔT [60,61].

Tremendous progress has been seen in the deployment of TEMs as an environmentally friendly approach by utilizing waste heat. Waste heat can be generated by the human body (37 °C); photovoltaic (PV) modules (50–70 °C) [62,63]; central processing units (CPUs) (60–70 °C) [64]; foundries and wood burning stoves (140 °C) [65]; fuel cell (60–800 °C) [66–68]; exhaust pipes from automobiles (200–300 °C) [69,70]; and vast number of industrial operation components such as gasifiers (350–500 °C) [71], boilers (200–1200 °C) [72,73], combustion chambers (250–550 °C) [74,75], marine waste incinerators (340–1150 °C) [76–78], and incineration municipal solid waste [79]. There are numerous prototypes by researchers to utilize waste heat from various sources and convert it to high-grade electricity [80]. So far, abundant researches in the literature discuss about the performance of TEMs. However, a comprehensive compilation of research and development (R&D) on the research methodology of existing test rigs and prototypes, is still a missing link although some reviews have been published with different themes [81,82]. In this review paper, various facts concerning the design of test rigs and prototypes such as stabilizers or heat exchangers for the heat recovery, interfaces (material, dimension, and thickness), contact pressure (clamping), insulations, and heat sink for the heat dissipation are studied in detail. Furthermore, the scope of power generation either through test rigs or prototypes is carefully reviewed by observation on their methodologies.

2. Elements of TEPG systems

In order to obtain satisfactory P_{out} from the TEM, special attention must be paid to certain details of test rigs or prototypes as well as troubleshooting. Throughout their design, both cold and hot sources need to be infinite to ensure decent thermal uniformity, which results in a maximum thermal energy output. Concerning test rigs, it is essential to be able to test TEMs with different types and dimensions under similar conditions [83,84]. Moreover, a clamp is utilized to hold both heat source and sink to the TEM, which significantly influences the corresponding performance. For the elaborate monitoring of the test rigs, thermocouples must be accurately set up. These thermocouples are responsible for measuring the hot and the cold surface temperatures. Generated data from the test rig is logged and gathered by using a data logger linked to a computer. Fig. 1 illustrates the schematic diagram of different components of the test rig. Several parameters that affect the performance of test rigs and prototypes are explored and discussed in the following subsections.

2.1. Stabilizer and interface

Based on the interaction between the heat source and dissipation, the process of heat transfer can be divided into four categories, detailed in Fig. 2 (they all exist within the thermal boundary conditions for TE applications). One of the most investigated boundary conditions (Fig. 2(a)) utilizes the assumption that the hot and cold sides are isotropic at temperatures T_h and T_c, respectively. This condition is fixed in the majority of studies or testing measurements; however, it is achieved rarely in practice. The configurations shown in Fig. 2(b–d), replacing either isotropic boundary with a convective media as source or sink for thermal power, are quite ubiquitous in current applications. If it is assumed that the thermal power, q_h, goes through the hot side of the TEM at temperature, T_h, and the unconverted heat, q_c, is dissipated at