Applied Thermal Engineering 71 (2014) 501–507

Contents lists available at ScienceDirect

Applied Thermal Engineering

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

Analysis of a symbiotic thermoelectric system for power generation and liquid preheating

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HIGHLIGHTS

- A symbiotic TE system can generate electricity with no heat rejection.
- Overall thermal–electrical efficiency is the same as the heater's efficiency.
- A TE generator may be installed on a liquid heater as an "add-on" apparatus.

ARTICLE INFO

Article history:
Received 22 October 2013
Accepted 6 July 2014
Available online 15 July 2014

Keywords:
Thermoelectric
Symbiotic
Power generation
Cogeneration
Energy conversion
Add-on power generator

ABSTRACT

Thermoelectrics have long been recognized as a unique energy conversion technology due to their capability to convert heat directly into electricity having no moving parts. Despite this potential, except for specialised situations, thermoelectric devices have limited applications because of their low efficiency. Generally they exhibit low conversion efficiency because of the relatively small figure-of-merit (*ZT*) of currently available thermoelectric materials. Many efforts have been made over recent years on improving thermoelectric conversion efficiency by increasing *ZT*, with only marginal success. In this research an alternative solution was provided to overcome the main drawback of thermoelectric devices. The idea is to operate the thermoelectric generator in a combined heat and power generation mode. This configuration consists of a stacked assembly of several thermoelectric modules sandwiched between three rectangular cold and hot liquid passages appropriately connected to an ordinary liquid (e.g. water) heater. It is shown that the combined system can produce heat and electricity with nearly zero heat dissipation to the surroundings by re-using rejected heat from thermoelectric modules for inlet liquid preheating.

1. Introduction

A thermoelectric generator is a unique heat engine, in which charge carriers serve as the working fluid. It can produce electricity through having a temperature difference across its sides [1]. Thermoelectric generators have several major advantages including being highly reliable, having no moving or complex parts, being environmentally friendly, being maintenance free and silent in operation, having no position-dependence, having long life cycles (more than 100,000 h steady-state operation), being light and having modular structure as well as adaptability to various sources and types of fuel [2]. Because of the advantages explained above, there has been worldwide emphasis on the development of thermoelectric generators for a variety of applications over recent decades [3].

However, except for specialised situations where reliability is a major concern like spaceship's power source, most recent developments in applications of thermoelectric generation in electrical power generation, have occurred in fields related to high temperature thermoelectric waste heat recovery through recovery of either exhaust heat in the automotive industry or emissions from industrial utilities since it is unnecessary to consider the cost of input thermal energy. Concentration on these areas is at the expense of the wider exploitations of thermoelectric conversion with other sources of thermal energy, and in particular natural occurring and low temperature heat, receiving little, if any, attention [4–6].

Fig. 1 shows the basic configuration of thermoelectric power generation. A thermoelectric module is sandwiched between a heat source and a heat sink. Heat flows from the hot side through the

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http://dx.doi.org/10.1016/j.applthermaleng.2014.07.013
1359-4311/

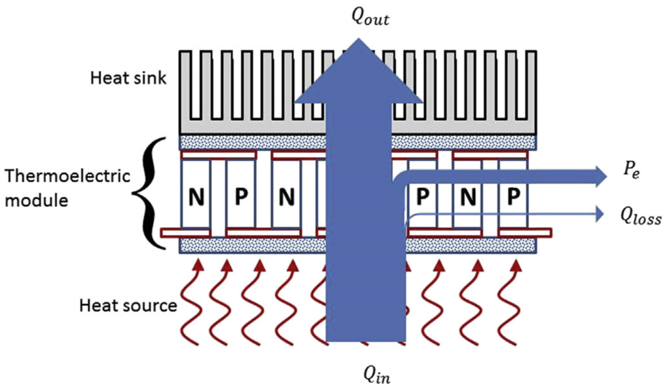

Fig. 1. Power distribution in a typical thermoelectric power generation system. Q_{in} is the heat supplied by the heat source, Q_{out} is the heat dissipated to the heat sink, P_e is the electrical power produced and Q_{loss} is the heat wasted through the sides of thermoelements to the surroundings.

module and is dissipated through the heat sink to the surrounding. This thermal energy movement excites thermoelement semiconductors and electrical power will be generated based on Seebeck effect. Conversion efficiency of a thermoelectric module can be a function of "goodness" of its semiconductor materials. Goodness or figure-of-merit of thermoelectric materials can be expressed as $Z = \alpha^2\sigma/\lambda$, where Z is a figure-of-merit, α the Seebeck coefficient and σ and λ are the electrical and thermal conductivities, respectively. This figure-of-merit can be made dimensionless through multiplying by the average temperature T of the sides of the module. In that case, $ZT = \alpha^2\sigma T/\lambda$. For the reason that the figure-of-merit of commercial thermoelectric materials are usually low ($ZT < 1$), a thermoelectric power generator exhibits low conversion efficiency. As over the past five decades, improvement in the efficiency of thermoelectric material has been marginal, many researches have been carried out to find methods to increase the conversion efficiency of thermoelectric power generation systems independent of the figure-of-merit of the thermoelectric material [7,8].

As an example, "waste heat" recovery is one of the promising areas where thermoelectric power generation can be economically competitive. As the supply of heat in the case of waste heat is almost free, conversion efficiency of the thermoelectric device is not a significant concern.

In addition to progress in the waste heat recovery area, the concept of "parasitic" or "symbiotic" application of thermoelectric conversion has been introduced by Rowe and Min in 2002 [7]. Through this method, a thermoelectric module is used as a generator and an efficient heat exchanger. In this approach, Q_{out} in Fig. 1, instead of being discharged to the surroundings, is absorbed by a liquid as a means of preheating. In this study, design, fabrication, analysis and discussion of a thermoelectric heat exchanger/power generator is presented.

2. Thermoelectric module for power generation and liquid pre-heating

Although there are obvious merits in thermoelectric waste heat recovery, the modules still dissipate a large portion of the absorbed heat to the ambient. In order to overcome this drawback, a system incorporating a heat exchanger and thermoelectric generator is introduced. Fig. 2 represents a cross section view of a system which is here called ELEGANT; an acronym from "Efficient Liquid-based Electricity Generation Apparatus iNside Thermoelectrics". In this configuration, thermoelectric modules are incorporated into a liquid heater by sandwiching modules between three aluminium channels. The middle channel, conducts hot liquid and heats the hot sides of the thermoelectric modules. The side channels conduct cold liquid and cool the cold sides of the thermoelectric modules. Although the main purpose of such a system is to produce hot liquid, a very small portion of heat from the outlet of the heater will flow through a bypass, consisting of the thermoelectric modules, and will be converted to electricity. The advantage of this cogeneration system is that the heat dissipated from modules returns to the system through preheating the inlet liquid.

While there may exist other thermoelectric cogeneration systems that use dissipated heat from thermoelectric power generator to heat a liquid, the main advantage of this system is that the system can be used as an "add-on power generator" so that no alterations in the system have to be made [9].

For the heating system without thermoelectric modules and ignoring heat loss, the overall efficiency of heat production is the efficiency of the liquid heater. It is given by,

$$\eta_{th} = \frac{Q_h - Q_c}{W_1} \tag{1}$$

where η_{th} is the thermal efficiency of the system without thermoelectric modules. Q_h–Q_c and W_1 are the amount of heat produced and input energy to the heater, respectively. In the case of considering thermoelectric modules and ignoring heat loss, Q_{loss}, wasted through the sides of thermoelectric modules the efficiency of total energy production (thermal and electrical) can be expressed as:

$$\eta_{to} = \frac{Q_{ho} - Q_c + 2P_e}{W_2} \tag{2}$$

where Q_{ho} is the heat energy carried out of the system by liquid, W_2 is the energy input related to the new configuration (incorporating thermoelectric modules) and P_e the electrical power generated by thermoelectric modules. It can be seen from Fig. 2 that,

$$Q_h - Q_{ho} = 2Q_{hc} + 2P_e \tag{3}$$

If we assume that the efficiency of the heater is independent of the inlet liquid temperature, it will remain unchanged regardless of preheating. Therefore,

$$\eta_{th}W_2 = Q_h - (Q_c + 2Q_{hc}) \tag{4}$$

Using Equations (1) and (4),

$$W_2 = \frac{Q_h - Q_c - 2Q_{hc}}{Q_h - Q_c} W_1 \tag{5}$$

Finally using Equations (1), (3)–(5),

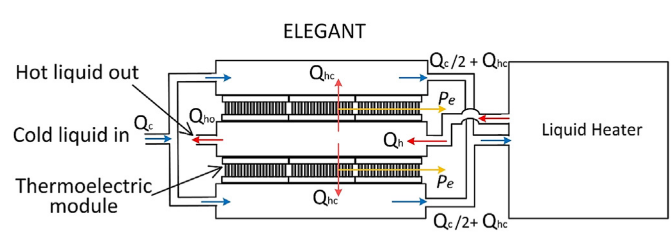

Fig. 2. Cross section view of ELEGANT. The heat dissipated from thermoelectric modules (Q_{hc}) is not wasted. Instead, it is used to preheat the cold liquid (heat wasted through sides of thermoelectric modules, Q_{loss} is assumed to be negligible).