Energy Conversion and Management 75 (2013) 532–541

Contents lists available at SciVerse ScienceDirect

Energy Conversion and Management

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

A study on heat transfer enhancement using flow channel inserts for thermoelectric power generation

Frédéric J. Lesage [a,b,*], Éric V. Sempels [c], Nathaniel Lalande-Bertrand [d]

[a] Cégep de l'Outaouais, 333 boul. de la Cité-des-Jeunes, Gatineau J8Y 6M4, Canada
[b] McMaster University, 1280 Main Street West, Hamilton L8S 4L7, Canada
[c] École Polytechnique de Montréal, 2900 Boulevard Edouard-Montpetit, Montréal H3T 1J4, Canada
[d] École de technologie supérieure, 1100 Rue Notre-Dame Ouest, Montréal H3C 1K3, Canada

ARTICLE INFO

Article history:
Received 9 May 2013
Accepted 3 July 2013

Keywords:
Thermoelectric generator
Heat transfer enhancement
Flow turbulence
Pressure drop

ABSTRACT

Thermoelectric power production has many potential applications that range from microelectronics heat management to large scale industrial waste-heat recovery. A low thermoelectric conversion efficiency of the current state of the art prevents wide spread use of thermoelectric modules. The difficulties lie in material conversion efficiency, module design, and thermal system management. The present study investigates thermoelectric power improvement due to heat transfer enhancement at the channel walls of a liquid-to-liquid thermoelectric generator brought upon by flow turbulating inserts. Care is taken to measure the adverse pressure drop due to the presence of flow impeding obstacles in order to measure the net thermoelectric power enhancement relative to an absence of inserts. The results illustrate the power enhancement performance of three different geometric forms fitted into the channels of a thermoelectric generator. Spiral inserts are shown to offer a minimal improvement in thermoelectric power production whereas inserts with protruding panels are shown to be the most effective. Measurements of the thermal enhancement factor which represents the ratio of heat flux into heat flux out of a channel and numerical simulations of the internal flow velocity field attribute the thermal enhancement resulting in the thermoelectric power improvement to thermal and velocity field synergy.

1. Introduction

The conversion of thermal energy to electricity has garnered interest in recent years due to the abundance of low cost industrial waste-heat. This resource has yet to be fully exploited for local energy needs due to efficiency limitations of the current available conversion technologies. A promising avenue for low grade waste-heat recovery stems from the Seebeck effect in which an electromotive force is generated by a thermal dipole across a semiconductor. The current difficulties in applying this phenomenon pertain to the thermoelectric conversion efficiency which limits the cost effectiveness of the technology. The ongoing efforts to improve thermoelectric conversion efficiency may be grouped into three categories: (1) material conversion efficiency; (2) thermocouple design efficiency; and (3) thermal system efficiency.

In the material conversion efficiency category, the capacity of thermoelements to generate an electromotive force from a thermal dipole is investigated. This thermoelectric phenomenon is quantified in terms of the dimensionless Figure-of-Merit ZT [1] which is a function of temperature, electrical conductivity, thermal conductivity and the Seebeck coefficient (ratio of carrier's transported entropy to its charge); the greater the Figure-of-Merit the greater the material's thermoelectric conversion efficiency. For a temperature range below 450 K, commercially available materials with a Figure-of-Merit greater than unity are based on the alloy bismuth (Bi) combined with antimony (Sb), selenium (Se), and tellurium (Te) [1]. In an effort to improve material thermoelectric efficiency, many studies such as those of André et al. [2] and Poudeu et al. [3] aim to engineer materials with higher Figure-of-Merit values for target temperature ranges by investigating different alloy combinations and different compositions. Thermocouple design efficiency studies such as those of Ebling et al. [4] and Hadjistassou et al. [5] investigate improvements to module performance. This was done with geometrical investigations and segmented pellet leg investigations in an attempt to enhance charge carrier concentration.

The heat transfer efficiency of the thermal system maintaining the thermal dipole dictates the thermoelectric conversion potential of the device. For this reason, thermal system efficiency studies investigate the heat flux in and out of the system in an effort to

* Corresponding author at: Cégep de l'Outaouais, 333 boul. de la Cité-des-Jeunes, Gatineau J8Y 6M4, Canada. Tel.: +1 819 770 4012; fax: +1 819 770 8167.

E-mail addresses: Frederic.Lesage@cegepoutaouais.qc.ca (F.J. Lesage), eric_sempels@hotmail.com (É.V. Sempels), nathanielbertrand@gmail.com (N. Lalande-Bertrand).

0196-8904/$ - see front matter © 2013 Elsevier Ltd. All rights reserved.
http://dx.doi.org/10.1016/j.enconman.2013.07.002

Nomenclature

Symbol	Description
c_p	specific heat at constant pressure (J/kg K)
n	number of channels (–)
p	pressure (PSI)
P	power (W)
P^*	P_i/P_o (–)
P^+	$P^* - \dot{W}_{\Delta p}/P_o$ (–)
q	heat transfer rate (W)
r	radial axis (m)
R_L	electrical load resistance (Ω)
T	temperature (K)
$\dot{V}$	volumetric flow rate (m^3/s)
$\dot{W}_{\Delta p}$	pumping penalty (W)
x	central channel axis (m)

Greek letters

α	Seebeck coefficient (V/K)
ρ	fluid density (kg/m^3)
η	q_i/q_o (–)
τ_r	shear stress (N/m^2)

Subscripts

C	cold side (–)
H	hot side (–)
i	flow with inserts (–)
in	inlet (–)
o	flow without inserts (–)
out	outlet (–)

maximize the temperature gradient across its embedded thermoelectric modules. The aim of these studies varies depending on the particular heat sources and heat sinks that are available. For the most part, thermal efficiency system studies consider a low-cost low-grade heat source [6,7,8] and aim to maximize the power output of commercially available thermoelectric modules by minimizing the pumping penalty of the heat sink. Bismuth Telluride (Bi_2Te_3) modules are common in thermal system studies [9,10,11] since they have been identified by Karabetoglu et al. [12] (among others) as the most efficient thermoelectric module for low-cost heat sources within the temperature range of 273–473 K. For example, [13–17] investigated thermoelectric system efficiency using vehicle heat exhaust, O'Shaughnessy et al. [18] harnessed thermoelectric power from biomass cook stove residual heat, [19–22] proposed thermoelectric systems exploiting solar radiation, [23–25] investigated system efficiency of a thermoelectric conversion of excess heat of a photovoltaic panel, and many studies such as [26,27,28,29,30,31,32] investigated flow channel thermoelectric systems for industrial Waste-heat recovery applications. Many industrial liquid-to-liquid heat exchangers are commonly used for expelling excess heat from the working instruments and operating environment for production and security needs. Such heat exchangers offer a thermal system that could potentially maintain a thermal dipole for thermoelectric power production if the gain in power can offset the pumping penalty that results from the presence of the generator. In this way, a liquid-to-liquid thermoelectric generator which achieves the necessary efficiency to offset the pumping penalty would contribute to the industry's local electrical energy needs.

The present work studies thermal enhancement in a liquid-to-liquid thermoelectric generator resulting in an increase in the thermal dipole thereby increasing the charge carrier concentration in the embedded Bi_2Te_3 materials. The method of investigation considers flow channels fitted with turbulating inserts of different geometry and under varying thermal input conditions. The ability for the inserts to enhance heat transfer by way of field synergy and their ability to enhance thermoelectric power sufficiently to offset the adverse pressure drop are measured and discussed.

1.1. Thermoelectric power

Thermoelectric power is a result of the thermoelectric phenomenon in which a charge carrier in an electrical conductor is mobilised once subject to a thermal field maintaining a thermal dipole across the conductor. In order to create a circuit, the chosen conductor is separated into thermoelements that are either doped to favour positive charge carrier mobility (p-type) or negative charge carrier mobility (n-type). The thermoelements are then placed in an alternating series in the thermal field in order to circulate an electric current. A p-type thermoelement and an n-type thermoelement pair constitutes a thermocouple. As previously discussed, conversion efficiency may be investigated by the materials and by the module design for greater charge carrier concentration and less thermal conduction across the module. The present study however investigates methods for managing the thermal field that is maintaining the thermal dipole responsible for generating the electromotive force. More specifically, as illustrated in Fig. 1, a heat flux from a heat source to a thermoelectric module and a heat flux from the module to the heat sink are necessary and represent a critical step in system thermoelectric conversion efficiency. This is due to the fact that thermoelectric power sensitively increases in efficiency with an increasing temperature dissimilitude across the conductor elements. Indeed, Hodes [33] demonstrated that the maximum power output of a single thermocouple is proportional to the square of $\Delta T = T_H - T_C$ in which T_H is the hot side temperature and T_C is the cold side temperature such that for a single thermocouple,

$$P = \frac{(\Delta T \alpha)^2}{4R_L} \tag{1}$$

In Eq. (1) α is the material Seebeck coefficient and R_L is the electrical load.

System efficiency of thermoelectric applications therefore pertains to maximizing the thermal transport from the available heat source to the surface of the hot side of the thermoelectric module. Similarly, the thermal system seeks to increase efficiency by optimizing the thermal transport from the cold side of the module to the available heat sink.

In the present study, the thermal transport enhancement brought upon by turbulating inserts in a liquid-to-liquid generator with embedded thermoelectric modules is investigated. The heat source is hot water in a flow channel at a constant flow rate and the heat sink is cold water in a flow channel at a constant flow rate.

2. Experimental setup

2.1. Test stand

A test stand is built in order to measure the influence of different flow turbulence characteristics on thermoelectric power