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Net thermoelectric generator power output using inner channel geometries with alternating flow impeding panels

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HIGHLIGHTS

- Inner flow impedance enhancing thermal transport increases thermoelectric power.
- Test cases include constant thermal input conditions for varying flow rates.
- Optimal insert geometry with alternating flow impeding panels is investigated.
- Net thermoelectric power accounting for pumping penalty is measured and discussed.

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ABSTRACT

Due to an abundance of low cost waste-heat in the industrial and residential sector, many studies in recent years have focused on applications of low grade heat for local energy needs. These include heat reutilization, thermal conversion to mechanical energy and thermal conversion to electricity. The thermoelectric effect presents a promising potential for effective conversion of low grade waste-heat yet is currently limited in application due to a conversion efficiency that is not cost effective. The present work focuses on mechanical methods to improve the thermal tension driving the electromotive force responsible for thermoelectric power production. More specifically, flow impeding geometries are inserted into the flow channels of a liquid-to-liquid thermoelectric generator thereby enhancing the heat transfer near its embedded thermoelectric modules. Consequentially, the thermal dipole across the modules is increased improving the overall power output. Care is taken to measure the adverse pressure drop caused by the use of the flow impeding geometries in order to evaluate the net power output. This net thermoelectric power output is measured, reported and discussed for a fixed inlet temperature difference, a fixed electrical load, varying flow rates and varying insert geometries.

1. Introduction

The conversion of thermal energy to electricity has been the subject of many recent investigations due to an excess of unused residential and industrial waste-heat. The state of the art of currently available conversion technologies is limited in its efficiency making the exploitation of low cost residual heat non-economically viable. Indeed, Wu [1] presents thermoelectric heat recovery as a promising avenue for power generation while highlighting that it requires further advancements in system conversion efficiency in order to render the process cost effective. To this end, efforts to improve the conversion efficiency of practical applications of this phenomenon, known as the Seebeck effect, focus on material and module design and on thermal system management.

Thermoelectric material and module design investigations seek to improve the thermopower production of thermoelectric elements. In these studies, thermopower is measured in terms of the Seebeck coefficient which quantifies the ratio of the electric potential across an element with the difference in temperature at the element's extremities. It represents the ratio of the charge carrier's transported entropy to its charge in an asymmetric thermal field. Since it is the asymmetric nature of this thermal dipole that is

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Nomenclature

Symbol

c_p	Specific heat at constant pressure, J/kg K
D_p	Linear panel density, panels/m
k	Thermal conductivity, W/m K
n	Number of channels
p	Pressure, PSI
P	Power, W
P^-	Net power, W
T	Temperature, K
TEG	Thermoelectric generator
TEM	Thermoelectric module
$\dot{V}$	Volumetric flow rate, m^3/s
$\dot{W}$	Work due to pressure drop, W

Greek letters

α	Seebeck coefficient, V/K
η	Conversion efficiency
ρ	Fluid density, kg/m^3
σ	Electrical conductivity, S/m

Subscripts

C	cold side
ch	channel
H	hot side
in	inlet
out	outlet

responsible for generating the electromotive force which mobilizes the carriers, the element's ability to conduct electricity relative to its ability to conduct heat dictates its thermal to electricity conversion efficiency. This is measured in terms of the dimensionless Figure-of-Merit ZT (e.g., [2]) which is dependent on temperature T, material electrical conductivity σ, material thermal conductivity k and the Seebeck coefficient α, such that

$$ZT = \frac{\alpha\sigma T}{k}. \tag{1}$$

The goal of thermoelectric design studies is to maximize a material's dimensionless Figure-of-Merit in which ZT values greater than unity is indicative of a material with a promising ability to convert thermal energy to electricity.

Conventional wisdom is that thermoelectric modules have the greatest potential for application with low cost heat sources in a temperature range below 450 K. In this range, commercially available thermoelectric modules have embedded semiconductors based on the alloy bismuth (Bi) combined with the alloys antimony (Sb), selenium (Se), and tellurium (Te) (e.g., [2]). Recent advancements have improved the ZT values of thermoelectric materials for target temperature ranges by investigating novel alloy combinations and semiconductor compositions (e.g., [3,4]). Similarly, some studies aim to improve thermoelectric efficiency through innovative module design in which geometric enhancement methods are investigated and segmented thermoelectric elements are combined in an effort to increase charge carrier concentration (e.g., [5,6]). Furthermore, studies such as that of Montecucco [7] solve the heat equation for thermoelectric materials thereby describing its thermal transport behaviour and in turn enabling an analysis of the effectiveness of newly developed materials.

Thermal system management is also necessary to maximize the thermoelectric efficiency of a device since the ability to transfer heat from the heat source to one side of the thermoelectric modules and to transfer heat to the heat sink from the other side of the modules partially dictates the conversion efficiency of the device. Thermal system efficiency studies therefore aim to maximize the thermal dipole across embedded thermoelectric elements by best managing the thermal transfer mechanisms of the available heat source and heat sink. For example, studies such as those of Guo et al. [8] and of Bélanger and Gosselin [9] aim to optimize system thermoelectric power production of a device with embedded commercially available thermoelectric modules by managing the thermal characteristics of flowing fluids. The characteristics of the modules themselves with respect to heat load and electric load are commonly investigated in order to better understand the appropriate working conditions for these thermoelectric converters (e.g., [10,11]). Similarly, Jang et al. [12] describe the optimizing methods for thermoelectric waste-heat recovery of a gaseous flow in which the optimal spacing of the modules over the working surface area is shown to be dependent on the waste gas heat transfer coefficient.

The present work focuses on the thermal management of practical thermoelectric applications. In general, commercially available Bismuth Telluride (Bi_2Te_3) modules are most common in such studies (e.g., [13–15]) since modules containing these alloys have been shown by Karabetoglu et al. [16] and others to have the highest dimensionless Figure-of-Merit values in the temperature range of 273–473 K corresponding well with various low cost heat sources. Such applications include O'Shaughnessy et al.'s [17] thermoelectric biomass cook stove in which the excess heat from a typical wood stove is used to charge an electric battery. In their study, they found that adding ventilation to the cold side of the module enhanced the thermoelectric power offsetting the energy consumption of the ventilation unit. Their study illustrates the importance of managing the entire thermal system of a thermoelectric device.

A growing number of studies focus on the thermal transport mechanisms of flow channels supplying and removing heat from a thermoelectric device (e.g., [18–24]). This is due to the potential to couple a thermoelectric device with large scale industrial liquid-to-liquid heat exchangers which process a non-exploited source of energy. These fluid-to-fluid exchangers expel unwanted heat from the industry environment for operation and safety purposes. Typically, they offer a heat source and heat sink that could supply a thermoelectric device with the necessary thermal dipole if the thermal system were managed such that the power output off-set the pumping penalty. In order to improve the functional efficiency of a thermoelectric liquid-to-liquid generator, Lesage et al. [25] demonstrated that flow impeding channel inserts of specific geometry for a fixed flow rate and varying thermal input conditions can enhance thermopower reaching a 50% net power enhancement when considering the pumping penalty associated with the presence of the obstructing geometries.

The present work builds upon this prospective of enhancing thermal transport in the pipe walls in order to increase power output of a thermoelectric generator. Specifically, a thermoelectric generator is commissioned containing Bi_2Te_3 thermoelectric modules with hot and cold flow channels acting as a heat source and heat sink respectively. The thermal transfer properties associated with geometries made up of alternating flow impeding panels is measured over varying flow rates for fixed thermal input