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Multiscale modeling of thermoelectric generators for the optimized conversion performance

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ABSTRACT

An attractive option for constructing thermoelectric generators (TEGs) is to incorporate a water-fed heat exchanger with commercially available thermoelectric modules. In this paper, two different thermoelectric models are applied to predict the energy conversion performance of the TEGs. The first model employs a derivation of the Carnot efficiency. The second model presents a rigorous interfacial energy balance by capturing Joule heating, Seebeck, Peltier and Thomson effects, yielding better predictions of the conversion capability. This model is then used to perform a computational examination of the TEGs embedded in 30 different configurations, which allows the identification and quantification of key design parameters including flow types, hot stream inlet temperatures (T_{in_hot}), pressure drops (ΔP), cross-sectional area (A_C), channel length (L_{ch}) and number of channels. The positive effects of T_{in_hot} and ΔP can be easily captured and parallel flows of the hot and cold streams are found to provide greater overall TEG efficiency as compared to counter flows. In general, micro-sized A_C reduces temperature gradients across the channels, providing a greater ΔT across the thermoelectric material. However, enhancements of the conversion capability are eventually limited by the reduced convective heat transport due to increased flow resistance. Finally, further improvements in the power generation are achieved by reducing L_{ch} while increasing the number of channels. The resulting reduction in flow resistance is found to facilitate increases in convective heat transfer, as well as in ΔT, and thus a great increase in conversion efficiency (η).

1. Introduction

Thermoelectrics are in principle, attractive for the conversion of waste heat into electric power. The underlying mechanisms dictating thermoelectric effects were not well understood until the discovery of the electron at the end of the 19th century. It is now known that electrons, or holes, in a solid carry both charge and heat. When a temperature drop is applied across a thermoelectric material, as shown in Fig. 1, this will cause the net diffusion of electrons (holes) from the hot side to the cold side. The electrical potential produced by the temperature difference is known as the Seebeck effect, and devices that generate electrical power by virtue of the Seebeck effect are called thermoelectric generators (TEGs). Alternate electrical connections of the hot sides and cold sides of a series of n- and p-type materials allow the build-up of any desired voltage.

TEGs have great potential in the direct conversion of waste-heat energy from power plants and automotive vehicles into electric power where it is unnecessary to consider the cost of the thermal energy input, and offer reliable power in remote areas such as in space and at mountain top telecommunication sites [1]. Unlike traditional dynamic heat engines, TEGs present several distinct advantages over other technologies, such as being simple, compact and highly reliable, being capable of operating at elevated temperatures, being suited for small-scale and remote applications, and being environmentally friendly [2,3]. A major limitation is, however, the low conversion efficiency of current thermoelectric devices (typically around 5–10% [4]), which is mainly caused by the available thermoelectric materials in the direction of figure of merit and has restricted their use in specialized fields with extensive applications. Since the promotion of the intrinsic efficiencies of the TE materials at device level has yet to be proved, there are ongoing attempts to increase the competitiveness of TEGs by improving the way in which they are currently used, offering some significant guidelines for design optimization [5–7]. The maximum efficiency of TEGs is subject to the constraints of the second law of thermodynamics, with the limit being expressed as $\eta_{max} = \Delta T/T_h$,

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Nomenclature

x	axial distance along fluid flow axis, m
L	TEG length, m
W	TEG width, m
H	TEG height, m
P	pressure in flows, Pa
T	temperatures, K
C_p	specific heat capacity at constant pressure, J/kg K
N_u	Nusselt number
A	area, m^2
G	volume flow rate, m^3/s
Greek symbols	
κ	thermal conductivity, W/K m
σ	electric conductivity of TE material, S/m
δ	Seebeck coefficient of TE material, V/K
ρ	density, kg/m^3
Subscripts	
h, c	hot side and cold side of thermoelectric layer
TE	thermoelectric
ch	channel
avg	average
in_hot, in_cold	inlet of hot and cold stream
1–5	length number
$conv$	convection

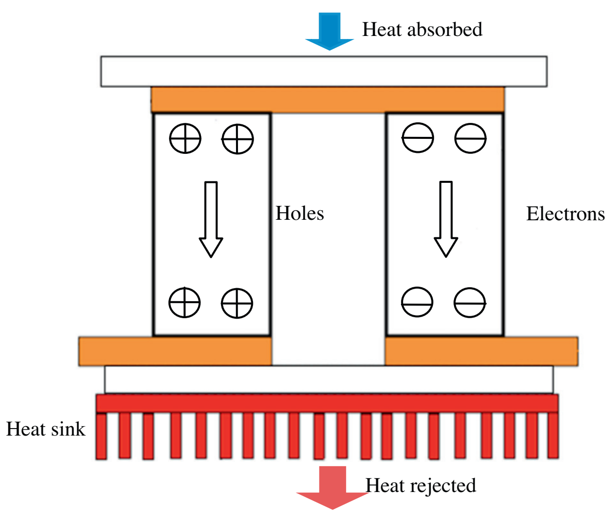

Fig. 1. Schematic illustration of a typical TEG. The construction consists of a pair of p-type and n-type semiconductor materials forming a thermocouple. Electron (Hole) diffusion is shown in this figure driven by a temperature difference.

where T_h is the temperature of the thermoelectric module hot side, and a principal focus has been on improving generator efficiency by maximizing the temperature drop (ΔT) across the thermoelectric modules. Traditional efforts have aimed to achieve this through the design of heat exchangers. Esarte et al. [8] theoretically addressed the optimization of heat exchanger geometries and various operating conditions including fluid flow rates, fluid properties and inlet temperatures. Crane et al. [9] investigated a computational model for the integration of a thermoelectric heat exchanger in a cross flow configuration. In the case of TEGs with large-scale multi-panels [10] and cylindrical multi-tubes [11], a mathematical expression for power output was deduced, considering different geometrical systems. Experiments have also been conducted on TEGs intended for low-temperature waste heat power recovery to assess effects of inlet temperature and flow rate on power output and conversion efficiency [12].

All of these research efforts combined thermoelectric modules with macro-scale heat exchangers, but growing applications such as autonomous micro-systems or wearable electronics look for micro-scale power generators. A micro TEG was proposed to provide electric power for an electronic chip in a domestic gas-monitoring system. In excess of 1.5 V could be produced when ΔT of a few tens of degrees was established [13]. Moreover, the utilization of TEGs in reciprocating internal combustion engines is another novel application. A comprehensive theoretical study of applying a TEG to automotive engine waste heat recovery is conducted [14]. By utilizing ΔT of 563 K between a micro-channel heat sink and exhaust gas, the maximum power of 51.13 mW/cm^2 can be reached.

Enormous amounts of research have been conducted on applications of TEGs. However, these thermoelectric systems are constrained by their low thermodynamic efficiencies, which means that a comparatively large amount of heat is required to produce a given quantity of electricity. Thus, there is a clear need for further improvements in the design of the heat exchangers as well as matching of the heat exchanger and thermoelectric designs. In this paper, the device performance of a water-fed heat exchanger based TEG in a range of scales is estimated by a simulation approach, which offers more detailed predictions than analytical methods, and can be more cost-effective than, or eventually help guide, experiments. The simulations are performed using the commercial FEA package COMSOL™ [15]. Two different thermoelectric models are applied in this paper. The first is the Simple model derived from the Carnot efficiency, and the second is the Coupled-field model presenting a rigorous interfacial energy balance by capturing Joule heating, Seebeck, Peltier, and Thomson effects.

Experiments conducted by Niu et al. [16] are employed here to demonstrate the applicability of the two thermoelectric models for evaluating TEGs device performance. The model showing the best agreement, by comparison with the experimental measurements, is used to perform a computational examination of TEGs embedded in 30 different configurations, which allows the identification and quantification of systematic effects of key design parameters including flow types (parallel flows & counter flows), hot stream inlet temperatures (T_{in_hot}), pressure drops (ΔP), cross-sectional area (A_C), channel length (L_{ch}) and number of channels. The positive effects of T_{in_hot} and ΔP on energy extraction are captured. Micro-scale A_C values provide smaller temperature gradients across the channels and thus a greater ΔT across the thermoelectric material. However, enhancements of the conversion capability are eventually limited by reduced convective heat transport due to increased flow resistance. Finally, further improvements in the power generation are achieved by reducing L_{ch} and increasing the number of channels.

2. Thermoelectric models

2.1. Simple model

In the Simple model established previously by the authors [17], the three-dimensional Navier–Stokes and energy equations combined with the continuity equation are solved simultaneously to