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Thermoelectric-hydraulic performance of a multistage integrated thermoelectric power generator

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ABSTRACT

A thermoelectric element made of *p*- and *n*-type semiconductor plates bonded onto a highly thermal and electrical conducting inter-connector material with an integrated flow channel can be treated as an integrated thermoelectric device (iTED). The performance of an iTED with multiple elements connected electrically in series and thermally in parallel has been investigated using numerical simulations. The top and bottom surfaces of the device are subjected to a constant cold temperature while the inter-connector channel walls are exposed to a hot fluid. The thermoelectric-hydraulic behavior of an iTED is analyzed in terms of heat input, power output, conversion efficiency, produced electric current, Ohmic and Seebeck voltages, and pressure drops for various hot fluid flow rates Re and inlet temperatures T_{in}, thermoelectric material sizes d, and number of modules N. For a single module iTED with fixed d and T_{in} values, the power output and efficiency are increased five- and twofold, respectively at $Re = 500$ when compared with the values of $Re = 100$. For given Re and d values, increasing T_{in} resulted in enhanced device performance. Furthermore, increasing d increased internal resistance and resulted in a decrease of heat input. The influence of d on power output is phenomenal; for a given set of geometric and thermal boundary conditions, there exists an optimum d where a maximum power output is achieved. The addition of modules N resulted in a significant improvement in power output and a reduction in produced electric current and efficiency. For instance, device with $N = 5$ showed more than a twofold increase in power output and nearly a 33% reduction in both efficiency and electric current when compared to $N = 1$ values.

1. Introduction

There is an ever-increasing amount of green-house gas and waste-heat released into the atmosphere from the fossil-fuel power generation plants, automobiles, and industrial heating or cooling systems in response to continual energy demands. Approximately two -thirds of the supplied energy into these systems is rejected as a waste-heat to the surroundings. There is an urgent need to explore novel, environmentally-friendly technologies that can replace or improve the performance of the existing systems. Solid-state thermoelectric devices are a viable technology for recovering waste-heat and convert it into electricity while mitigating the emission of green-house gases.

Thermoelectric devices (TEDs) are constructed by joining two different electrically and thermally conductive materials at a junction. Using the Seebeck effect, TEDs work as electric power generators when the two material junctions are exposed to a temperature differential. Similarly, TEDs act as a refrigerators via the Peltier effect when an electric current is applied across the terminals, creating a temperature differential at the material junction [1]. However, the current thermoelectric materials with a figure of merit ≈1.5 achieve thermal conversion efficiencies of 5–15% and coefficients of performance (COP) of 0.5–1. Due to their scalable, reliable, stable, compact and noise free operation, TEDs are suitable in novel applications such as waste-heat recovery from exhaust streams and other low-grade heat sources, electric power generation for remote radio and satellite stations, pocket electronics, bio-thermal batteries to power pacemakers, localized cooling in electronic components and space cooling in automobile seats.

The efficiency of TEDs has been increased via the methods of nano-structuring and fabrication [2–4], novel designs [5–10] and use of new bulk materials [1]. Caillat et al. [5] developed a segmented TED using novel *p*- and *n*-type materials, and achieved a conversion efficiency of 15%. El-Genk et al. [6] reported peak efficiencies of 16.69% and 7.4% respectively for skutterudite and SiGe segmented TEDs. Further, Punnachaiya et al. [7] studied cascaded TEDs and showed a low conversion efficiency of 0.47% with $T_h = 96\,^{\circ}C$ and temperature differential (T_h–T_c) of 25 °C. Liang et al. [8] investigated the performance of a multistage TED and

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Nomenclature

A	cross-sectional area, mm^2
c_p	specific heat of fluid, $\mathrm{Jkg^{-1}\,K^{-1}}$
d	size of semiconductor material, mm
D	depth of the thermoelectric leg, mm
D_h	hydraulic diameter of main flow channel $\left(\frac{4(H-2d)\times D}{2(H-2d+D)}\right)$, mm
H	height of the leg, mm
I	electric current, A
J	electric current density $\mathrm{A\,m^{-2}}$
$\mathbf{J}$	current density vector
k	thermal conductivity, $\mathrm{Wm^{-1}\,K^{-1}}$
L	distance between the legs, mm
N	number of thermoelectric modules
P	pressure, $\mathrm{N\,m^{-2}}$
P_0	power output (I^2R_L), W
Q	heat transfer, W
R	electrical resistance, Ω
Re	Reynolds number ($\rho UD_h/\mu$)
t	connector thickness, mm
T	temperature, K
U	inlet velocity, $\mathrm{m\,s^{-1}}$
$\mathbf{v}$	velocity vector
V	voltage, V
u, v, w	velocities in x, y, z directions, $\mathrm{m\,s^{-1}}$
W	width, mm
x, y, z	coordinates, mm

Greek symbols

α	Seebeck coefficient or thermopower, $\mathrm{V\,K^{-1}}$
μ	dynamic viscosity, $\mathrm{N\,s\,m^{-2}}$
ρ	electrical resistivity, $\Omega\,\mathrm{m}$
ρ_f	density of fluid, $\mathrm{kg\,m^{-3}}$
η	thermoelectric conversion efficiency, dimensionless

Subscripts

c	cold wall/conductor
in	inlet
f	fluid
h	hot wall
i	internal/integrated
ic	inter-connector
L	load
n	n-type semiconductor
O	Ohmic potential
p	p-type semiconductor
S	Seebeck potential
ξ	direction normal to the surface

they demonstrated that the thermal contact resistance between the TED module and heat source or sink plays a substantial role in the power output. Recently, Crane et al. [9] built a full-scale cylindrical-shaped thermoelectric generator using segmented and high-power density elements and produced a power output of 608 W.

Using analytical solutions and experiments, Gou et al. [11] showed that expanding the heat sink surface area and enhancing the cold side heat transfer in proper ranges can have significant effects on TEDs performance when compared to increasing the waste-heat temperature and addition of modules in series. Further, Hasio et al. [12] investigated TED applied to waste-heat recovery from an automobile engine and showed that the TED performs better on the exhaust pipe than radiator. Even though electric and temperature fields in TEDs are multidimensional, most of the works in literature were conducted with one-dimensional analytical solutions for simplified cases. However, for accurate system design and optimization of TEDs, the three-dimensional (3D) numerical studies have been conducted in the articles [13–20,22]. Further, Karri et al. [21] investigated the performance of various modeling approaches for thermoelectric elements and their merits and demerits under given geometric and thermal boundary conditions.

Harris et al. [13] studied the influence of inert gas and insulating materials, and interface contact resistances on TED performance using finite volume numerical methods. Considering the convection and radiation effects, Ziolkowski et al. [14] studied the performance of TED in ANSYS software for various pellet aspect ratios and contact resistances. Gould et al. [22] simulated the TED configured for low power generation using TCAD package. In the articles [15,16], the authors used numerical simulations to study the optimum geometries of TEDs to achieve a maximum conversion efficiency. Furthermore, the researchers [17,19] proposed and implemented a 3D numerical model for thermoelectric generators in FLUENT UDS environment and their model accounts for all temperature-dependent properties of materials and non-linear fluid-thermal-electric multi-physics coupled effects. Recently, by coupling both temperature and electric potential fields Wang et al. [18,20] studied the steady and transient response of TEDs using 3D multi-physics models.

It is observed from literature that the conventional TED designs applied to waste-heat recovery induce large thermal resistance between the working fluid and the thermoelectric junctions via the heat exchanger, ceramic plate, and the interface materials, and also they require great amounts of semiconductor materials for module construction due to the demand of constant leg heights for fabrication ease. Keeping this in mind, the authors proposed an integrated thermoelectric device (iTED) [23,24] where the hot-side inter-connector is re-designed to incorporate an integrated heat exchanger. By doing so, this novel design reduces the thermal resistances attributed to the heat sinks and ceramic plates, which are present in convectional design. Further, by adjusting the height of the inter-connector heat exchanger, this design would help in using different semiconductor element heights for achieving maximum power output and efficiency while keeping the height of the module invariant. In essence, this design enhances reliability and performance of TED. In this study, using numerical methods the thermoelectric-hydraulic performance of such a iTED with multiple modules connected electrically in series and thermally parallel is investigated. The effects of heat exchanger hot fluid flow rates and inlet temperatures, thermoelectric element sizes, and the number of modules on the performance of an iTED applied to waste-heat recovery under steady state conditions (the performance variation with respect to the time is zero) are studied in detail.

2. Geometry, governing equations, and boundary conditions

The schematic of the three-dimensional single-stage integrated thermoelectric device (iTED) being investigated is shown in Fig. 1a. The device consists of two vertical legs connected electrically in series and thermally in parallel via connectors made of highly electrical conducting material. Each thermoelectric leg is constructed