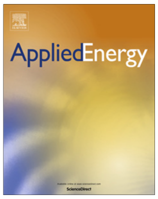
Applied Energy xxx (2016) xxx–xxx

Contents lists available at ScienceDirect

Applied Energy

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



# Numerical study on thermoelectric–hydraulic performance of a thermoelectric power generator with a plate-fin heat exchanger with longitudinal vortex generators

Ting Ma [a,b], Xing Lu [a], Jaideep Pandit [b], Srinath V. Ekkad [b], Scott T. Huxtable [b], Samruddhi Deshpande [b], Qiu-wang Wang [a,*]

[a] Key Laboratory of Thermo-Fluid Science and Engineering, MOE, Xi'an Jiaotong University, Xi'an, Shaanxi 710049, China
[b] Department of Mechanical Engineering, Virginia Tech, Blacksburg, VA 24061, USA

## HIGHLIGHTS

- LVGs are proposed to enhance thermal–electrical conversion performance of TEGs.
- Open circuit voltage of TEGs with LVGs is increased by 41–75% in baseline cases.
- Reynolds number and hot-side inlet temperature have significant effects on TEGs.
- Cold-side temperature has a smaller effect on TEGs.

## ARTICLE INFO

*Article history:*
Received 4 September 2015
Received in revised form 27 December 2015
Accepted 22 January 2016
Available online xxxx

*Keywords:*
Thermoelectric power generator
Longitudinal vortex generator
Equivalent thermal–electrical properties
Heat transfer enhancement
Plate-fin heat exchanger

## ABSTRACT

In this paper, the effect of longitudinal vortex generators (LVGs) on the performance of a thermoelectric power generator (TEG) with a plate-fin heat exchanger is investigated. A fluid-thermal-electric multi-physics coupled model for the TEG is established on the COMSOL® platform, in which the Seebeck, Peltier, Thomson, and Joule heating effects are taken into account. The equivalent thermal–electrical properties of the thermoelectric (TE) module are used in the numerical simulation. The results indicate that the LVGs produce complex three-dimensional vortices in the cross section downstream from the LVGs, thus enhancing the heat transfer and electric performance compared to a TEG without LVGs. Under baseline operating conditions, the heat input and open circuit voltage of the TEG with LVGs are increased by 41–75% compared to a TEG with smooth channel. The simulations also show that the Reynolds number and hot-side inlet temperature have significant effects on the net power and thermal efficiency of the TEG, but the cold-side temperature has a smaller effect. Additionally, the performance of the TEG under a constant heat transfer coefficient boundary condition is almost the same as the performance under a constant temperature boundary condition. Overall, this work demonstrates that LVGs have great potential to enhance the performance of TEGs for waste heat recovery from vehicle exhaust.

## 1. Introduction

As a solid-state energy converter, a thermoelectric (TE) material can directly convert thermal energy into electrical energy without additional power generation devices. Poor efficiency for TE devices has limited their competitiveness with vapor compression systems, such as in air-conditioning or heat pump applications. However, the TE devices have been used in smaller-scale applications such as in automobile seats, night-vision imaging systems, and electrical-enclosure cooling [1]. Additionally, many recent advances in materials research have given promise for improved TE devices in the near future. For example, the dimensionless figure of merit in bismuth antimony telluride (BiSbTe) bulk alloys has been increased from 1.0 to 1.4 at 100 °C through the use of nanostructuring [2]. Using similar nanostructured TE materials, the efficiency of solar thermoelectric generators has shown to be 7–8 times higher than the traditional flat-panel solar thermoelectric generators (TEGs) [3]. Recently, TE devices have attracted considerable attention in the automobile industry since 70% of the

---

[*] Corresponding author. Tel.: +86 (29)82665539; fax: +86 (29)82663502.
*E-mail address:* wangqw@mail.xjtu.edu.cn (Q.-w. Wang).

http://dx.doi.org/10.1016/j.apenergy.2016.01.078
0306-2619/© 2016 Elsevier Ltd. All rights reserved.

Please cite this article in press as: Ma T et al. Numerical study on thermoelectric–hydraulic performance of a thermoelectric power generator with a plate-fin heat exchanger with longitudinal vortex generators. Appl Energy (2016), http://dx.doi.org/10.1016/j.apenergy.2016.01.078

**Nomenclature**

| | |
|---|---|
| $A$ | cross sectional area of TE leg or TE module, m$^2$ |
| $c_p$ | specific heat, J/(kg K) |
| $D_h$ | hydraulic diameter, mm |
| $\mathbf{E}$ | electric field intensity vector, V/m |
| $I$ | electric current, A |
| $\mathbf{J}$ | electric current density vector, A/m$^2$ |
| $k$ | thermal conductivity, W/(m K) |
| $m$ | mass flow rate, kg/s |
| $L$ | length, mm |
| $N$ | number of TE legs |
| $p$ | static pressure, Pa |
| $P_o$ | total power output, W |
| $Q_h$ | hot-side heat transfer rate, W |
| $R$ | electric resistance, Ω |
| $Re$ | Reynolds number |
| $T$ | temperature, K |
| $U$ | area-averaged velocity, m/s |
| $\mathbf{u}$ | velocity vector, m/s |
| $V$ | voltage, V |
| $V_{oc}$ | open circuit voltage, V |
| $\dot{V}$ | volumetric flow rate, m$^3$/s |
| $W_{net}$ | net power, W |
| $W_{\Delta p}$ | pumping power, W |
| *Greek* | |
| $\alpha$ | Seebeck coefficient, V/K |
| $\rho$ | density, kg/m$^3$; Electrical resistivity, Ω m |
| $k$ | thermal conductivity, W/(m K) |
| $\sigma$ | electrical conductivity, S/m |
| $\mu$ | dynamic viscosity, Pa s |
| $\eta$ | thermal conversion efficiency |
| *Subscripts* | |
| c | cold side |
| E | equivalent thermal–electrical properties for a TE module |
| f | fluid |
| h | hot side |
| i | the *i*th TE leg |
| in | inlet |
| leg | a single TE leg |
| o | outlet |
| s | solid |

energy released from the fuel is lost in the form of waste heat through the exhaust gases or cooling system [4]. Many automotive manufacturers and researchers are exploring the use of TEGs to convert some of the waste heat from the exhaust gas into useful electric power. Hsiao et al. [4] investigated the feasibility of applying TE modules to the exhaust pipe and radiator in an automobile, and showed that a maximum power density of about 50 mW/cm$^2$ was possible. In et al. [5] examined the performance of a TEG heated by the exhaust gas from an actual engine under various thermal conditions. Their work indicated that the temperature difference between the hot and cold ends of TE module and the differential pressure of the exhaust gas had significant effects on the power generation performance of system. Liu et al. [6] proposed a "four-TEGs" system for the automobile, and a maximum power of 944 W was obtained in the revolving drum test for a temperature difference of 240 °C. Favarel et al. [7] optimized the thermoelectric systems from the view of examining the position of the TE couples or occupancy rate along the system. The result showed that the maximum output electrical power was obtained for a configuration where TE modules did not completely cover the hot heat exchanger. Liang et al. [8] conducted a numerical simulation to study the performance of a two-stage TEG using the exhaust gas of an internal combustion engine as the heat source, and showed that the peak output power and conversion efficiency had a strong dependence on the thermocouple ratio. Yu et al. [9] analyzed the transient behavior of a TEG capturing heat from the vehicle exhaust under different start-up modes. Their results indicated that a higher vehicle speed could accelerate the transient response. Chen et al. [10] optimized the TEG performance using the Taguchi method, and showed that the output power of the TEG system could be further enhanced by around 6% by optimizing a second-stage TEG.

In addition to the performance of the TE material, the TE module and system, the thermo-hydraulic performance of the heat exchangers also plays an important role on the overall efficiency of TEGs. Crane and Jackson [11] conducted a numerical simulation to optimize the thermoelectric waste heat recovery system with air cooling in a cross flow heat exchanger. They found that the optimal configuration was obtained at intermediate cooling air and hot fluid flow rates due to increasing power losses from the air fan and fluid pump at high flow rates. Lu et al. [12] performed an experiment to test the thermal uniformity and pressure drop of the muffler-like exhaust heat exchangers with different structures, and quantified the interdependence of the flow rate, pressure drop, and temperature distribution. Zhou et al. [13] examined the effect of flow types, hot stream inlet temperatures, pressure drops, cross sectional area, channel length and number of channels on the thermoelectric–hydraulic performance of TEG. Their work demonstrated the complicated nature of system optimization, and showed the importance of having a well-mixed exhaust gas stream in order to promote high heat transfer.

Recently, many groups have examined a variety of methods for enhancing the heat transfer to and from the TE devices in order to improve the overall efficiency of the TEG systems. Lesage et al. [14] and Amaral et al. [15] applied turbulating inserts into the fluid channel in a liquid-to-liquid TEG. These studies showed that panel inserts could enhance the power up to 110% [14]. However, there was an upper flow rate threshold beyond which the pressure drop caused by the flow impeding inserts might offset its power enhancement [15]. Reddy et al. [16] conducted a numerical simulation to compare the thermoelectric performance of an integrated TE device with rectangular, round end slots, and circular flow channel designs. Their results showed that the integrated TE device with a circular flow channel had better performance than those with round end slots and rectangular flow channels under fixed operating conditions. Metal foams have also been used to enhance heat transfer in a TEG with a plate heat exchanger [17]. This work showed that metal foams with large porosity could effectively increase heat transfer without a significant pressure drop penalty. Pandit et al. [18] examined three-dimensional partial pin fin arrays on the hot-side walls in a gas-to-liquid TEG. The results indicated that the diamond pin fins had the best heat transfer performance, and lower pin–fin channel heights with 50% clearance provided significantly higher heat transfer coefficients.

Longitudinal vortex generators (LVGs) have also attracted much attention for heat transfer enhancement in both plate heat exchangers and tube-and-fin heat exchangers. Liu et al. [19] found that the LVGs could improve the heat transfer performance of a

Please cite this article in press as: Ma T et al. Numerical study on thermoelectric–hydraulic performance of a thermoelectric power generator with a plate-fin heat exchanger with longitudinal vortex generators. Appl Energy (2016), http://dx.doi.org/10.1016/j.apenergy.2016.01.078