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Simulation of thermoelectric-hydraulic performance of a thermoelectric power generator with longitudinal vortex generators

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ABSTRACT

This work investigates the feasibility of using LVGs (longitudinal vortex generators) to improve heat transfer in TEG (thermoelectric generator) systems. A coupled fluid-thermal-electric model is established with COMSOL Multiphysics® to study the effects of LVG height, LVG attack angle, and hot-side inlet gas temperature. We find that LVGs can significantly enhance the heat transfer performance, power output, and thermal conversion efficiency due to the generated longitudinal vortices, especially at small LVG attack angles. The performance of the thermoelectric generators with LVGs is best for LVGs that span the full height of the channel at the highest temperature examined (550 K), where the heat input, net power and thermal conversion efficiency are enhanced by 29%–38%, 90%–104% and 31%–36%, respectively, compared to smooth flow channel. As the hot-side inlet gas temperature decreases, the pumping power remains constant and requires a larger portion of the power output since the heat input and power output are significantly reduced. Therefore, it is not beneficial to use tall LVGs at lower hot-side inlet temperatures and higher inlet Reynolds numbers due to the large ratio of pressure drop to power output, but smaller LVGs are still useful under these conditions.

1. Introduction

The use of fossil fuels in automobiles is expensive in both monetary and environmental terms. In the Otto cycle, only about 30% of the energy released from the fuel is converted to useful work while the remaining 70% is lost primarily as heat discharged through the exhaust gases or expelled by the cooling system [1]. Recently, many automotive manufacturers have explored the use of thermoelectric generators in order to convert some fraction of the waste heat contained in the exhaust gas into useful electric power.

The potential use of thermoelectric devices for waste heat recovery has received considerable attention in recent years. Wang et al. [2] developed a general and three-dimensional numerical model for a thermoelectric device. Their results indicated that including the effects of temperature dependent properties and heat losses to the ambient gas had significant effects on the TEG (thermoelectric generator) system performance. Liang et al. [3] established a two-stage thermoelectric model using exhaust gas from an internal combustion engine as the heat source. They examined the effects of temperature and heat transfer coefficients for the hot and cold sides, and found that the performance increased with increasing heat transfer coefficient up to 400 W/m^2-K, and that there was an optimum ratio of thermoelectric elements for the two stages to maximize power and efficiency. Nguyen and Pochiraju [4] developed a thermoelectric model to study a thermoelectric generator for a hot side subject to a transient heat source and natural convection on the cold side and compared their results with experiments. They showed that the Thomson effect played an important role on the power generation while it was insignificant with regard to the temperature distributions. Sandoz-Rosado and Stevens [5] examined the effects of solder, ceramic interfaces, electrical contact thickness and leg spacing on the performance of thermoelectric modules. These effects were studied with standard one-dimensional constant property models that were commonly used in thermoelectric module design along with a

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Nomenclature

c_p	specific heat, J/(kg·K)
D	thickness, mm
D_h	hydraulic diameter, mm
$\mathbf{E}$	electric field intensity vector, V/m
H	height, mm
I	electric current, A
$\mathbf{J}$	electric current density vector, A/m^2
k	thermal conductivity, W/(m·K)
L	length, mm
p	static pressure, Pa
P_l	longitudinal pitch, mm
P_o	power output, W
P_t	transverse pitch, mm
Q_h	hot-side heat transfer rate, W
Re	Reynolds number
T	temperature, K
U	area-averaged velocity in inlet section, m/s
$\mathbf{u}$	velocity vector, m/s
V	voltage, V
$\dot{V}$	volumetric flow rate, m^3/s
W	width, mm
W_{net}	net power, W
$W_{\Delta p}$	pumping power, W

Greek

α	seebeck coefficient, V/K
β	attack angle, °
ρ	density, kg/m^3
σ	electrical conductivity, S/m
Π	Peltier coefficient, V
μ	dynamic viscosity, Pa·s
η	thermal conversion efficiency

Subscripts

c	cold
f	fluid
h	hot
v	longitudinal vortex generator

new three-dimensional, device-level model using COMSOL®. Their results showed that the one-dimensional model resulted in 10–20% error compared to the three-dimensional multiphysics model. Al-Merbati et al. [6] used finite element methods to evaluate the impact of thermoelectric generator geometry on thermal stress, thermal efficiency, and output power, and found that the geometric configuration had an impact on the thermal efficiency and the thermal stresses could be reduced to improve device lifetime. Fraisse et al. [7] compared the benefits and drawbacks of simplified models, finite element methods, and one improved simplified model using two different Seebeck coefficients with a constant Thomson coefficient. Their work demonstrated the importance of proper accounting for the Thomson coefficient.

Unlike the above mentioned studies, Chen et al. [8] focused more attention on the effect of the fluid flowing in the channel, and developed a fluid-thermal-electric multi-physics coupled model based on a FLUENT® platform for the purpose of supporting a more realistic thermal boundary condition for the thermoelectric generator rather than using constant temperature or constant heat flux boundary conditions. Suzuki et al. [9] investigated the effects of flow patterns, i.e., counter-flow and split-flow, on the fluid velocity, temperature distribution, pressure drop and electromotive force, and showed that the power required to circulate fluids was not negligible. Rezania and Rosendahl [10] evaluated the impact of the location of the thermoelectric legs, applied heat flux, variation of pressure drop along the heat sink, and the arrangement of inlet plenum in a thermoelectric generator with parallel microchannel heat sinks. They showed that with proper arrangement the pumping power could be kept small compared with the improvement in thermal performance. Lu et al. [11] developed a test bench to examine different locations for the placement of a TEG in the exhaust system of an automobile. They found that the best location for a TEG system was between the catalytic converter and the muffler since this location provided more uniform flow, lower backpressure, and higher surface temperature. Zhou et al. [12] compared a simple TE model derived from Carnot efficiency with a detailed model based on an interfacial energy balance, and determined that the more rigorous coupled-field model was more accurate in comparison with previous experiments. They also showed that it was important to maintain turbulent flow within the channels of the heat exchanger. Reddy et al. [13] proposed an integrated thermoelectric device with the interconnector designed as an internal heat exchanger, which could reduce the thermal stress, materials usage, and thermal resistances. The effects of load circuitry resistance, hot-side inlet temperature, semiconductor material size, and flow rate on the performance were discussed using a developed numerical model based on a FLUENT® platform, and they also recommended that coupled field simulations be used for accurate modeling of TEG systems [14].

To further improve the power output and efficiency of TEGs, researchers have placed a greater emphasis on heat transfer enhancement from the heat exchanger in the thermoelectric generator system. Lesage et al. [15] and Amaral et al. [16] investigated the thermoelectric power improvement by adding turbulating inserts into the fluid channel in a liquid-to-liquid thermoelectric generator, and found that the inserts could improve performance but should be tailored for the desired thermal input parameters for a particular application. Pandit et al. [17] applied three-dimensional partial pin fin arrays of circular, triangular, hexagonal, and diamond shapes on the walls of a rectangular channel to improve heat transfer from the hot gas side of a thermoelectric generator system. They showed that significant improvements could be made with pin fins that were only 15% of the channel height, and that the shape, configuration, and height of the pin fins were all important parameters.

In addition to the aforementioned examples for TEGs, there are many other heat transfer enhancement methods that have been used in a variety of heating, ventilation, air-conditioning, and refrigeration systems. One specific example worthy of further study is a LVG (longitudinal vortex generator). As the name suggests, an LVG produces longitudinal vortices in the cross section in addition to transverse vortices in the streamwise direction, creating a more three-dimensional phenomena than commonly used boundary layer trips or ribs. Several groups have conducted numerical and experimental studies on heat transfer and pressure drop effects of LVGs, and significant heat transfer enhancements have been obtained [18–20].

Here, our study investigates the feasibility of using LVGs with thermoelectric generator systems in the COMSOL® platform [21]. We use the novel integrated thermoelectric device proposed by