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Evaluation of metal foam based thermoelectric generators for automobile waste heat recovery

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ABSTRACT

This paper focuses on harvesting heat emitted by exhaust systems efficiently using thermoelectric generators (TEGs) and converting it to electricity. In a TEG that employs gaseous working fluid, up to 80% of the thermal resistance is due to the gas side. Maximizing the energy transferred from the hot exhaust gas to the hot side of the thermoelectric modules by suitable enhancement techniques can result in an efficiency gain for the TEG. To this end, we have investigated the performance of metal foam-based heat exchangers for reducing thermal resistance of the hot side in TEGs. A computational model of the metal foam-enhanced TEG, solving for the coupled thermal and electrical energy transfer processes, was developed to investigate the enhancement in system performance for a range of metal foam porosities and pore densities, and mass flow rates of the exhaust gas. Skutterudites with multiple cofillers were selected as thermoelectric materials. The primary performance metrics that were analyzed include the electrical power output and the associated pressure drop for various inlet conditions of the exhaust gas. Based on the trade-off between the increased pumping power required to offset the increase in pressure drop, and the gain in heat transfer coefficient with increase in mass flow rate of the exhaust gas, an optimal mass flow rate that maximizes the net electric power produced by the metal foam-enhanced TEG was obtained. The results show a critical exhaust flow rate for different pore densities of metal foam beyond which the net electric power produced by the TEG is less than of the TEG with no metal foam. At this critical flow rate, the maximum net electric power produced from exhaust waste heat by metal foam enhanced TEG is 5.7 (20 PPI) to 7.8 (5 PPI) times higher than that generated by the configuration without metal foam.

1. Introduction

According to a recent report [1], it is estimated that 20–50% of the energy input in transportation, power generation, industrial processes, residential sectors, and many other industries is wasted as heat. Transportation accounts for approximately one quarter of global energy use and is a major consumer of fossil fuels. Nearly two-thirds of the energy produced by a typical gasoline engine is lost through waste heat in the engine's exhaust and coolant [2]. Harvesting the waste heat energy using a thermoelectric generator (TEG) can improve fuel economy by decreasing the electric generator load on the engine. The attendant benefits are reduced greenhouse gas emissions and sustainable development.

A TEG usually consists of four elements: a hot-side heat exchanger, a cold-side heat exchanger, thermoelectric modules (TEM) and a power-conversion system. Thermoelectric modules contain pairs of doped n- and p- type thermoelectric (TE) elements wired electrically in series and thermally in parallel [3]. Thermoelectric generators work based on Seebeck effect and can convert a given temperature differential to voltage differential. Fig. 1 shows a schematic of the TEG design for automobile waste heat recovery. This design consists of thermoelectric modules sandwiched between the exhaust pipe (hot loop) and the coolant pipe (cold loop).

The space constraint in installing thermoelectric generators in automobiles dictates that the TEGs provide excellent power density. The efficiency of a TEG in converting the waste heat into maximum electrical power output, η_{TE} — which is achieved when the electrical load is matched with the TEG electrical resistance — is governed by the following expression [3]:

$$\eta_{TE} = \frac{\Delta T}{T_h} \frac{1}{2 + 4/ZT_h + T_c/T_h} \quad (1)$$

where ΔT is the temperature difference between the hot and cold side of the thermoelectric couples, T_h is the temperature of the

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Nomenclature

Symbol	Quantity
a_s	surface area density of metal foam [m^{-1}]
A_{TE}	cross-sectional area of TE leg [m^2]
b	wall thickness [m]
c_p	specific heat [J/kg-K]
C_F	inertial drag factor
C_μ	empirical constant
d_f	fiber diameter [m]
d_p	pore diameter [m]
G_k	TKE generation due to shear [N/m-s^2]
G_b	TKE generation due to buoyancy [N/m-s^2]
h_s	convective heat transfer coefficient [W/m^2-K]
k	turbulent kinetic energy [J/kg]
K	permeability [m^2]
L	length [m]
PPI	number of pores per inch
Re	Reynolds number
P_e	electric power [W]
P_{ne}	net electric power [W]
P	pressure [Pa]
Q	wall heat flux [Wm^{-2}]
Pr	Prandtl number
R	electrical resistance [ohm]
S_g	source term for momentum
S_h	source term for energy
T	temperature [K]
V	mean velocity [m/s]
ZT	thermoelectric figure of merit
μ_t	eddy viscosity [Pa-s]

Subscripts

a	exhaust gas
c	cold side
e	electric
h	hot side
s	solid metal foam
TE	thermoelectric
TKE	turbulent kinetic energy

Greek symbols

α	seebeck coefficient [V/K]
η_{TE}	thermoelectric efficiency
ϕ	porosity
ε	dissipation rate of TKE [N/m-s^2]
λ	thermal conductivity [W/m-K]
λ_t	eddy thermal conductivity [W/m-K]
μ	dynamic viscosity [Pa-s]
ρ	density [kg/m^3]
σ	electrical resistivity [ohm-m]
σ_t	turbulence Prandtl number
φ	pore density

hot side (exhaust pipe wall), T_c is the temperature of the cold side (coolant pipe wall) and ZT is the figure of merit of the thermoelectric material. From Eq. (1), it can be seen that increasing the temperature differential (ΔT) increases the thermoelectric conversion efficiency, which in turn improves the power density of a TEG.

In a heat exchanger that employs a gaseous working fluid, up to 80% of the thermal resistance is due to the gas side [4]. Maximizing the energy transferred from the hot exhaust gas to the walls of the exhaust pipe by suitable heat transfer enhancement techniques will result in an efficiency gain for a TEG. Athavale et al. [4] presented a numerical analysis of the heat transfer enhancement in an automobile TEG with internal louvered fins inside the exhaust pipe. Kumar et al. [5,6] combined the heat transfer equations based on the thermal resistance model and standard thermoelectric equations including the Seebeck effect, Fourier effect and Joule effect to analyse the performance of various finned heat exchanger and thermoelectric module configurations for automotive-waste-heat recovery systems. Hsiao et al. [7] developed a one-dimensional thermal resistance model for a TEG and illustrated that it performs better on the exhaust pipe than on the radiator. The numerical studies presented in [8,9] analysed the performance of TEGs at various engine operating conditions using plate-fin heat exchangers and commercial bismuth-telluride (Bi_2Te_3) based modules. The effectiveness of longitudinal vortex generators, pin-fin arrays, and heat pipes to enhance the heat transfer between the gas and the wall has been reported in Refs. [10–12]. The main objective of all the heat transfer enhancement techniques presented above is to achieve high levels of convective heat transfer coefficients at relatively lower penalty on the pumping power side.

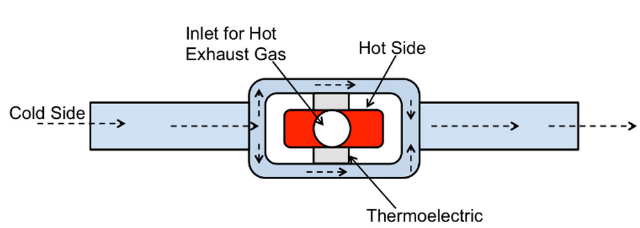

Fig. 1. Schematic of a TEG design.

Metal foam is a porous lightweight structure with continuous metal matrices of high thermal conductivity and is available in high porosities (>85%). These foams are generally manufactured using open-cell polymer foam as templates to create investment casting molds of desired size and shape into which a variety of metals or alloys can be cast [13]. Experimental and numerical studies in the literature with high porosity metal foams have shown significant enhancement in heat transfer performance in various applications such as during forced convection of electronics cooling [14,15] and melting/solidification of phase change material in latent thermal energy storage system [16].

In the present study, we investigate the performance of metal foam based heat exchangers for reducing the thermal resistance of the hot side of TEGs. To this end, a computational analysis is carried out for different design parameters of metal foam (porosity and pore density) and operating conditions.

2. Numerical model

The dimensions of the heat exchanger of the TEG through which the hot exhaust gas flows are the same as used in Ref. [4]. The length of the hot-side heat exchanger section is 0.5 m, width 0.181 m and height 0.0744 m. The thickness of the heat exchanger wall is 0.003 m. The selected computation domain, boundary conditions, and the mesh features are shown in Fig. 2. It is assumed that 80% of the surface area of the TEG is covered by a uniform distribution of TEMs of cross section 0.0508 m × 0.0508 m with 32 thermoelectric couples (n- and p- legs) of cross section 0.004 m × 0.004 m and height 0.004 m in each module. Thus, the total number of thermoelectric n-p legs on either of the top and bottom surfaces of the TEG is $N_{TE} = 900$.