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Effect of vehicle driving conditions on the performance of thermoelectric generator

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A B S T R A C T

Thermoelectric generators (TEGs) have become a promising technology for vehicle exhaust heat recovery. Although the complex vehicle driving conditions may lead to significant variation of TEG performance, such influence was rarely paid attention to. In this study, a numerical model of thermoelectric generator (TEG) based on vehicle waste heat recovery is developed. When the acceleration duration is short, the hot side temperature increases quickly at first with an overshoot phenomenon. When the acceleration durations increase or the acceleration range becomes smaller, the overshoot phenomenon becomes weaker. The change of the voltage and power generally follows the same trend. The performance variation of TEGs becomes more significant with faster acceleration or deceleration. The transient response of the hot and cold side temperatures, voltage and power in deceleration is less significant than acceleration, because in deceleration, the cold side temperature increases first due to the weakened heat convection. For the step change of vehicle speed, when the speed is low, the voltage and power curves and the speed curve are more consistent, and a longer step duration leads to better consistency. A higher road grade can increase the power output of TEG significantly, and lead to a faster transient response. The Japanese 10–15 cycle, New European Driving Cycle (NEDC) and Urban Driving Dynamometer Schedule (UDDS) are selected to evaluate the impact of different driving cycles. The results suggest that a highly frequent change of driving condition may have a negative effect on the TEG performance.

1. Introduction

Around 35–40% of the fuel energy supplied to internal combustion engine in vehicle is discharged as waste heat through the exhaust system [1–4], utilization of such waste heat has therefore attracted considerable attention.

Among the different waste heat recovery technologies such as turbocharger [5], Rankine cycle [4,6] and electric turbocompound system [7–9], thermoelectric generator (TEG) for direct conversion of vehicle engine waste heat to electricity is becoming noticeable, because it has the merits of no moving part, quiet operation, compact design, high durability and zero emission [10]. It has been demonstrated that thermoelectric materials with figure of merits of about 1.5 could achieve energy conversion efficiencies of about 5–15% [11].

The fundamental operating principle of TEG is the Seebeck effect, which was discovered in 1821 by Thomas Seebeck [12]. Common thermoelectric (TE) materials include BiTe, SiGe, ZnBe, PbTe and CeFeSb compounds [13,14]. Among these materials, BiTe shows better performance in the low temperature range of about 30–300 °C; for high temperature applications, ZnSb, CeFesb, PbTe, and SiGe are more suitable; therefore, for waste heat recovery applications with large temperature difference (e.g. engine exhaust), different materials might be used together for performance improvement [15].

The utilization of vehicle exhaust waste heat by TEG was first demonstrated in 1963 [16], and with the development of TE materials, researchers have paid significant attention in this area over the last twenty years. Hendricks [17] analyzed the potential of TEG systems in vehicle wasted heat recovery, and optimized the TEG and heat exchanger design. Korzhuev et al. [18] placed TEGs in different locations of vehicle, such as engine, exhaust pipe and cooling system. Kim et al. [19] developed a TEG system with the engine coolant of light-duty vehicles as heat source, and the output power is about 75 W. In their study, the conventional radiators of the existing water cooling system were replaced by the TEG system. Lu et al. [20] investigated the effects of design and operating conditions of muffler, heat exchanger and exhaust pipe. The three-way catalytic converter in the exhaust system for waste heat

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Nomenclature

A	area (m^2)
a	vertical distance (m)
b	horizontal distance (m)
c	specific heat capacity (J kg^{-1} K^{-1})
d	horizontal distance (m)
D	hydraulic diameter (m)
E	Seebeck electromotive force (V)
F	fanning friction factor
h	heat transfer coefficient (W m^{-2} K^{-1})
H	vertical distance (m)
I	current (A)
J	current density (A m^{-2})
k	thermal conductivity (W m^{-1} K^{-1})
m	mass flow rate (kg s^{-1})
Nu	Nusselt number
$P9$	power output (W)
Pr	Prandtl number
Q	heat flow through thermoelectric module (W)
Re	Reynolds number
s	number of legs in one module
t	time (s)
T	temperature (°C)
v	gas velocity (m s^{-1})
V	voltage (V)/speed (km h^{-1})

Greek letters

α	Seebeck coefficient (V K^{-1})
β	grade (%)
Δ	difference
δ	electrical resistivity (Ω m)
φ	increment of power output (%)
μ	dynamic viscosity (kg m^{-1} s^{-1})
ρ	density (kg m^{-3})
τ	Thomson coefficient (V K^{-1})
σ	electrical conductivity (S m^{-1})

Subscripts and superscripts

a	ambient air
c	cold side
ce	ceramic layer
e	exhaust gas
h	hot side
i	the *i*th grid of TE leg and ceramic layer
j	the *j*th segment of exhaust pipe
leg	thermoelectric legs
$load$	load resistance
m	module
$Peltier$	Peltier effect
r	remaining time
te	thermoelectric material
sc	surface of cold side TE module
sh	surface of hot side TE module
veh	vehicle

recovery by TEG was considered by Su et al. [2]. Abdelkefi et al. [14] developed an analytical model for TEG taking into account the variation of TE material properties with temperature. Niu et al. [21] developed a 3-D numerical TEG model, with the detailed geometry of the TEG modules and exhaust channel, and the investigation of various transport phenomena and design optimization were carried out based on the simulation results. Reddy et al. [15,22–24] conducted a series of comprehensive analyses on the heat and electric transfer characteristics of different TEG modules, and novel composite and integrated designs were also proposed for performance improvement.

According to the review of previous studies for exhaust heat recovery by TEG, it is found that these studies mainly focused on the steady-state TEG performance [16–21]. However, there are few studies for the transient behavior of TEG in vehicle dynamic driving conditions and driving cycles [25].

In fact, the TEG used in vehicle waste heat recovery should be assessed under different driving conditions [25,26]. In this study, the TEG system behavior is investigated in details under dynamic driving conditions, such as acceleration and deceleration, speed step change, different road conditions, and practical driving cycles. The effects of TEG on the engine performance improvement in the different driving cycles are estimated as well. For this purpose, a numerical model for TEG based vehicle waste heat recovery is developed.

2. Model description

A typical TE couple is composed of an *n* (negative)-type and a *p* (positive)-type TE legs connected by metal plates. A practical TEG module connects large numbers of these legs electrically in series to increase the operating voltage and thermally in parallel to share the same heat source and heat sink.

2.1. Modeling thermal behavior of TEG

In this study, as shown in Fig. 1, the TEG model is divided into three major regions, namely, hot side ceramic layer, TE leg and cold side ceramic layer. The temperature distribution in TEG can be depicted using a one-dimensional partial differential equation, which is calculated using the finite volume method (FVM) based on the law of energy conservation along the length direction (*x*-direction) of TE leg.

In the hot and cold side ceramic layers, there is only heat conduction, without any thermoelectric effects, the equation can be expressed as

$$\rho_{ce}c_{ce}\frac{\partial T}{\partial t} = \frac{\partial}{\partial x}\left(k_{ce}\frac{\partial T}{\partial x}\right) \tag{1}$$

where ρ (kg m^{-3}), c (J kg^{-1} K^{-1}) and k (W m^{-1} k^{-1}) denote the density, heat capacity and thermal conductivity of the ceramic layer, and the subscript *ce* represents the ceramic layer region.

For the TE leg region, an energy balance analysis leads to the governing equations as follows:

$$\rho_{TE}c_{TE}\frac{\partial T}{\partial t} = \frac{\partial}{\partial x}\left(k_{TE}\frac{\partial T}{\partial x}\right) + \frac{J^2}{\sigma} - \tau J\frac{\partial T}{\partial x} \tag{2}$$

In Eq. (2), σ (S m^{-1}) and τ (V K^{-1}) denote the electrical conductivity and Thomson coefficient, J (A m^{-2}) is the current density, and the subscript *TE* represents the thermoelectric material. The first term on the right side is the heat conduction from hot to cold side. The second term represents the Joule heat, which is also called the Ohmic heat. The third term is the Thomson heat. The Thomson coefficient τ corresponds to a temperature-dependent Seebeck coefficient (α, V K^{-1}):

$$\tau = \alpha\partial T/\partial\alpha \tag{3}$$