International Journal of Thermal Sciences 71 (2013) 302–309

Contents lists available at SciVerse ScienceDirect

International Journal of Thermal Sciences

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

A simulation study of automotive waste heat recovery using a thermoelectric power generator

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ARTICLE INFO

Article history:
Received 13 December 2012
Received in revised form
8 April 2013
Accepted 8 April 2013
Available online 9 May 2013

Keywords:
Automotive waste heat recovery
Thermoelectric generator
Heat exchanger

ABSTRACT

In this work, an energy-harvesting system which extracts heat from an automotive exhaust pipe and turns the heat into electricity by using thermoelectric power generators (TEGs) was investigated. The influences of the number and the coverage rate on the heat-exchanger of the TEGs were explored via simulations. It was found that implementing more TE couples does not necessarily generate more power in total, and most of all the average power per TE couple decreases rapidly. It is because the wall temperature of the exhaust pipe drops quickly along the streamwise direction and also because the downstream TEGs contend for heat with the upstream TEGs, causing a reduction in the temperature difference between the hot and cold sides of the upstream TEGs. Furthermore, it was also found that for a given total number of TE couples, it is better to retain a portion of the heat exchanger uncovered with TE couples at the downstream side so that the downstream wall of the exhaust pipe uncovered with TE couples becomes even hotter than the upstream wall covered with TE couples. Heat is consequently conducted from the downstream wall to the upstream wall and successively to the attached TEGs; a larger total power can be thus obtained.

1. Introduction

Because of the global energy crisis and the environmental protection issues, energy recovery techniques have become significantly demanding for a long time. Some examples of energy recovery techniques are water heat recycling, heat recovery ventilation, heat recovery steam generators, and so on [1]. Waste heat recovery by using thermoelectric power generators (TEGs) is another attempt. TEGs can directly convert thermal energy to electrical energy and have the advantages of light weight, no noise, and no mechanical vibration. Owing to these merits, TEGs have found its potential in many applications, such as space applications, thermal energy sensors, textiles, etc. [2–5].

Waste heat originates from various heat sources at different temperatures, such as human bodies, plants, automobiles, and so on [5]. Human body provides low-temperature heat for TEGs. The electrical energy converted from the human-body heat can be applied directly to wearable electronic products such as watches and electronic medical instruments [6,7]. These small-scale applications can be operated by small temperature differences [8]. Waste heats generated from plants and automobiles are at medium-to-high temperatures and can sustain much larger temperature differences across the TEGs, resulting in large power generation. A 500 kW TEG system for waste heat recovery in a pressurized water reactor power plant was developed by Central Research Institute of Electric Power Industry (CRIEPI) [9]. In addition to the power generation, the reductions in the fuel consumption and in the CO_2 emission resulted by installing TEGs are also noticeable. Chen et al. [10] in use of a Danish district heating system model, estimated the reductions in a system which integrates TEGs into a combined heat and power production (CHP) plant. The results provide useful information for developing energy policies and estimating their environmental impacts.

Waste heat from automotive vehicles is considerable as well. For a typical gasoline-fueled-internal-combustion-engine vehicle, about 40% of the fuel energy is discharged from the exhaust pipe and about 30% is lost into the coolant. Making good use of these waste heats improves the energy efficiency and saves money. Yang [11] indicated that the consumer fuel savings over a three-year period is about $400 for a 23.5 mpg vehicle, under the assumption of $2/gallon, 15,000 miles/yr, and a desired 10% fuel-economy improvement (the overall objective raised by the US Department of Energy in 2004). The commonly utilized components in a vehicle for implementing the TEGs are the radiators and the exhaust system. Hsiao et al. [12] established mathematic models and performed experiments; they found a better performance can be

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http://dx.doi.org/10.1016/j.ijthermalsci.2013.04.008

Nomenclature

c_p	the heat capacity of air
h_e	the characteristic convection heat transfer coefficient of the heat sink
$\overline{h}$	the convection heat transfer coefficient for flat-plate flow
I	the electric current
K	the thermal conductance of the TEG cuboid
k_a	the thermal conductivity of air
k_m	the effective thermal conductivity of a TEG chip
L	the length of the heat exchanger
L_{TEG}	the length of a TEG cuboid
L_c	the total length of the simulated system
M	the weight of the TEG system
$\dot{m}$	the mass flow rate
N	the total number of TE couples in the system
N_x	the number of TE couples along the x-direction in one TEG cuboid
N_z	the number of the TE couples along the z direction in one TEG cuboid
$\overline{Nu}$	the average Nusselt number
P	the power generation rate
P_{max}	the maximum power generation rate
Pr	the Prandtl number
Q_{absorb}	the total amount of heat transferred to the TEGs
Q_C	the heat dissipated at the cold side of a TEG
Q_d	the total amount of heat transferred from the downstream side
Q_H	the heat extracted from the hot side of a TEG
Q_{in}	the input extractable energy
R_m	the measured electric resistance of a TE couple
R_{pn}	the electric resistance of a TE couple
Re_{L_c}	the Reynolds number based on the characteristic length L_c
ΔT	the temperature difference between the hot and cold sides of a TEG
T_a	the ambient temperature
$T_{C,avg}$	the averaged temperature at the cold side of a TEG
$T_{H,avg}$	the averaged temperature at the hot side of a TEG
T_{in}	the inlet temperature
ΔT_{leg}	the temperature difference across a TE leg
V	the speed of the vehicle
W	the side length of the hexagonal pipe
$\dot{W}_{saved}$	the saved engine shaft power
α_m	the measured Seebeck coefficient of a TE couple
α_{pn}	the Seebeck coefficient of a TE couple
$\eta_{alternator}$	the alternator efficiency
η_D	the driveline transmission efficiency
$\eta_{exchanger}$	the efficiency of the exchanger
η_{PCU}	the Power Conditioning Unit (PCU) efficiency
$\eta_{recovery}$	the recovery efficiency
η_{TEG}	the efficiency of the TEG
μ_r	the rolling resistance coefficient

obtained by attaching TEGs to the exhaust system than to the radiators. Directly attaching TEGs to the original equipments in the exhaust system, such as the catalytic converter [13], the muffler, the exhaust pipe, and so forth, is one way to go. Alternatively one can construct a heat exchanger to extract heat from the exhaust pipe to the integrated TEGs.

Depending on the kind of the cooling system, the TE materials, the system size, and the operating conditions, the power generation rate differs in the literature. The Hi-Z Technology, Inc. [14] attached TEGs on the outer surface of an octagonal cast-steel heat exchanger with a hollow displacement body in the center and used eight aluminum water-cooled-heat-sink assemblies. By installing swirl fins on the displacement body and using seventy-two HZ-13 Bi_2Te_3 modules, they obtained 1 kW from a Cummins NTC 350 Diesel engine operated at 300 HP and 1700 RPM. In 2001, in order to solve mechanical problems during the road test, HZ-14 modules were built. A maximum electric power of 900 W was obtained from a Cummins 335 Diesel engine operated at 290 HP and 2100 RPM [15]. Crane and Lagrandeur [16] built a single-layer high-temperature segmented TEG with the most suitable thermoelectric materials for various operating temperature ranges. A power as large as 125 W was obtained by extracting heat from a hot air at 600 °C and at a flow rate of 45 cfm and using a cooling water at 25 °C and at a flow rate of 10 lpm. Karri et al. [17] simulated a TEG-integrated sports utility vehicle which includes sixteen HZQW (quantum-well materials, Si/SiGe and B_4/B_9C) TEG chips. The water coolant system in the vehicle was also used to cool the TEG system. About 450 W was generated at a vehicle speed of 112.7 km/h and about 1.5% fuel savings was obtained after the consideration of the coolant-pumping power loss, blow-down power loss, and the power loss to transport the weight of the TEG system; the fuel saving of the car using Bi_2Te_3 TEGs is negative nonetheless. Hsu et al. [18] proposed a heat exchanger mounted with eight Bi_2Te_3—TEG chips and employed eight air-cooled-heat-sink assembles. A maximum power of 44 W was obtained. In 2012, they enlarged the heat exchanger with a similar interior structure and added a slopping block in the inlet [19]. A maximum power of 12 W was obtained instead when twenty-four TEG chips and twenty-four air-cooled-heat-sink assembles were implemented. Their experimental results surprisingly suggest that a small-size heat exchanger with less TEGs can generate more power.

Most of the studies mentioned above focused on the design of the heat exchangers and the development of the TEG modules. However, according to Hsu's study, the size of the heat exchanger and the number of the TE couples implemented are two other factors that may strongly affect the power generation efficiency. Therefore, the influences of these two factors are of interest in the present work. The investigation was executed by performing full three dimensional simulations in use of the commercial software ANSYS-Fluent. A heat exchanger similar to that employed by the Hi-Z Technology, Inc. [14] was employed. As its total length and the coverage rate with the TE couples were varied, the power generation rate was computed. The optimization of these two parameters is aimed at.

The rest of this paper introduces the simulation model in Section 2, presents the simulation results and discussions in Section 3, and finally gives the conclusion in Section 4.

2. Numerical experiment

2.1. Simulation model

The energy harvesting system consists of a heat exchanger and TEGs as shown in Fig. 1. The heat exchanger, composed of a hexagonal pipe, radial fins, and a hollow center body, is connected to the exhaust pipe of diameter 62 mm on both sides. The hexagonal pipe has an inscribed circle of diameter 140 mm and a length of L. It is connected to the exhaust pipe via a divergent/convergent part. The hollow center body, including a circular pipe of diameter 100 mm and length L as well as two bullet-shape heads of length