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Fabrication of thermoelectric modules and heat transfer analysis on internal plate fin structures of a thermoelectric generator

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ABSTRACT

Thermoelectric modules (TEMs) are fabricated for a low-temperature waste heat recovery application. Each module has a surface area of 44 × 44 mm and a thickness of 3.6 mm, including a 1-mm-thick ceramic substrate on each side. Prior to fabrication of the system, a series of numerical simulations are conducted to optimize the design of the internal finned structures of a thermoelectric generator. To reduce the difficulty of designing the numerical models, a thermal resistance model is employed to determine the thermal conductivity of the TEM. The optimal number and thickness of the fin structures are determined with respect to the maximum allowable module temperature and the pressure drop characteristics. The accuracy of the numerical model is validated using an existing friction factor correlation and experimental results. The numerical results show that having six 2-mm-thick plate fins on the hot surface of each TEM would provide the most effective temperature fields for TE power generation while keeping the surface temperature of the TEM from exceeding the allowable maximum of ~473 K. The pressure drop across the fins is found to increase with increasing number and thickness of fins. However, the module-level pressure drop is in the range of several pascals, which has a negligible effect on the combustion characteristics of the engine. A thermal resistance equation is proposed to predict the heat transfer characteristics of plate fins employed for thermoelectric generators for heat absorption.

1. Introduction

There are a number of low-temperature waste heat sources, such as exhaust gas flows from internal combustion engines, power stations, and chemical reactors [1–4]. The thermal energy of waste heat can be recovered to improve fuel economy and system efficiency and reduce greenhouse gas emissions [5–7].

Thermoelectric generators (TEGs) have garnered considerable attention as promising devices for use in waste heat recovery. Among the advantages of TEGs over other waste heat recovery systems, such as turbo-machines and systems whose operation is based on thermodynamic cycles, are their lack of moving parts, compact size, and moderate power output performance [8,9]. In the past, the application of TEGs has been limited by the low energy conversion efficiencies of thermoelectric materials. However, as the conversion efficiency of thermoelectric (TE) materials increases because of advances in material science and module fabrication techniques, enhanced power outputs have been reported for TEGs by numerous research groups. Hicks and Dresselhaus [10] obtained a high figure of merit by using quantum-well superlattice structured materials. Ghamaty and Elsner [11] reported that use of quantum-well thermoelectric materials can improve the figure of merit up to 4. It is anticipated that continued improvement in the energy conversion efficiency of TEGs will lead to expansion of the TEG market and their more widespread application in the near future.

It is well known that the performance of TEGs is primarily dependent on the power output of the thermoelectric modules (TEMs), which are components that contain a number of TE semiconductor couples, and the system design, which determines the heat transfer rate from the heat source to the TEMs. Rowe and Min [12] found an increase in the conversion efficiency of a TEM by increasing the height of elements inside the module, while a decrease in the power output is caused by a lower heat transfer rate through the module. Stevens [13] approximately derived an optimal configuration of a thermoelectric module for a low–temperature-difference condition. Besides these several examples, many researchers have focused their attention on the development of high-performance TEMs and TEG structures and evaluation of their TEG performance. However, there is still a shortage of available TEMs for practical use and for research on TEG design.

Additional consideration in TEG fabrication is the heat transfer characteristics of TEGs. This is because the voltage output of

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Nomenclature

A_b	exposed area of the base plate (m^2)
A_c	cross-sectional area
A_{fin}	fin area (m^2)
c_p	specific heat
D_h	hydraulic diameter (m)
f	friction factor for fully developed flow
f_{app}	apparent friction factor
g	gravitational acceleration (m/s^2)
h	average heat transfer coefficient ($W/m^2 \cdot K$)
H	component height, height of fin
k	thermal conductivity ($W/m \cdot K$)
L	length of fin
Nu	Nusselt number
ΔP	pressure drop (Pa)
p	pressure (Pa)
Pr	Prandtl number
R	thermal resistance (K/W)
Re	Reynolds number
T	temperature (K)
U	average velocity (m/s)
v	velocity (m/s)
w_c	space between two adjacent fins

Greek

η	fin efficiency
μ	viscosity ($kg/m \cdot s$)
ρ	density (kg/m^3)

Subscripts

air	air
al	alumina substrate
ave	average
c	cold side
cu	copper plate
f	fluid
h	hot side
int	interstitial
leg	thermoelectric element
m	module
max	maximum
min	minimum
o	overall
out	outlet
ref	reference module
s	surface
tg	thermal grease
tp	thermal pad

thermoelectric modules (TEMs) is proportional to the temperature difference induced across the TEMs. Kumar et al. [14] investigated the effect of exhaust pipe shape on the temperature and velocity profiles in the TEG and thermoelectric power generation. Lu et al. [15] suggested a concept of integrating an exhaust heat exchanger and a muffler for an automotive thermoelectric generator and experimentally studied the effect of the internal structure of the system on temperature uniformity and pressure drop characteristics.

For this reason, fin structures are basically employed in the exhaust gas channel for ensuring the power output of TEGs by augmenting the heat transfer performance [16–18]. Exhaust gas contains volatile and particulate substances that are produced during the combustion procedure. Thus, installation of structures with complex geometries in an exhaust gas pipe has the potential to increase the back pressure in the pipe because of the accumulation of these substances. An increase in the back pressure could lead to unstable combustion of the engine and increased fuel consumption. Therefore, a plate fin structure, which has a simpler geometry than a pin fin structure, is generally used as the extended surface [19,20].

In this study, bismuth telluride (Bi_2Te_3) TEMs was produced for waste heat recovery from low-temperature heat sources. To achieve the desired compactness of the TEG, the dimensions chosen for the TEMs were 1.4 × 1.4 × 0.8 mm. Numerical simulations were carried out to determine the optimal values of the key design parameters of a TEG for recovery of the waste heat in the exhaust gas from an internal combustion engine. In contrast to most heat transfer problems in which the system efficiency is better at a higher heat transfer rate, some other factors need to be considered to optimize the design of a TEG for use in waste heat recovery. One of these factors is the maximum allowable temperature of the TEM. As the solder and the epoxy materials used in fabricating TEMs have relatively low melting points of approximately ~473 K, the maximum allowable temperature of the TEM should be taken into account in the design of the TEG. An internal plate fin structure was employed to improve the TEG power output. A series of numerical analyses were conducted to determine the optimal number and thickness of the fins to ensure the most effective temperature field on the surface of the TEMs at the maximum allowable temperature. The numerical model was validated using an existing correlation and experimental results. The number and thickness of the fins were found to have significant effects on the temperature distribution of the hot surface of the TEM but negligible effects on the pressure drop across the fin structures. The optimized design parameters of the finned structure were reflected in the fabrication of a TEG whose waste heat recovery performance was examined experimentally in Ref. [21]. To simplify the numerical simulation, the thermal conductivity of the TEM was determined by means of a thermal resistance analysis. The calculation of the thermal conductivity of the module made it possible to reduce the computational time while maintaining the accuracy of the numerical results. In addition, a modified thermal resistance equation is suggested to predict the heat transfer characteristics of plate fins formed inside TEGs for thermal energy absorption. It is possible to find the optimum number and thickness of the fins by using the proposed thermal resistance equation for a specified working condition.

2. Materials and methods

2.1. Thermoelectric module preparation

In this study, customized TEMs were fabricated for waste heat recovery. Fig. 1 shows a schematic illustration of the Bi_2Te_3 TEMs produced, with dimensions of 44 × 44 × 3.6 mm. The dimensions of the TEMs were determined on the basis of the dimensions of the assembled TEG. A bulk TE ingot was diced into TE elements with dimensions of 1.4 × 1.4 × 0.8 mm. The TE elements were serially connected using copper plates to form 161 p-n thermoelectric couples in each module. The thermoelectric couples and the copper