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Research Paper

A comprehensive study on a novel concentric cylindrical thermoelectric power generation system

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HIGHLIGHTS

- A novel thermoelectric module and thermoelectric power generation are proposed.
- Annular TEM has 28.9% larger heat transfer area than that of square TEM.
- Annular TEM can generate 17% more open circuit electric potential than square TEM.
- Concentric cylindrical TEG has the highest heat transfer filling factor at 0.655.

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ABSTRACT

This paper presents the novel designs of a concentric cylindrical thermoelectric generator (CCTEG) and an annular thermoelectric module (ATEM). The simulations are carried out to compare the performance of ATEM and the conventional square-shaped thermoelectric module (STEM). The heat pipe technology is introduced into the heat sink system in order to enhance the heat transfer in the radial direction of exhaust gas flow. A new index termed as the heat transfer filling factor f has been introduced which quantities the level of space utilisation for thermoelectric modules (TEMs). The correlation between the coolant flow rate and TEM performance is also carried out. Experimental work is also carried out to demonstrate the viability of using the heat pipes for heat transfer enhancement as well proving the viability of the design. The simulations indicate that the open circuit electric potential of the ATEM is 17% more than that of the STEM. The experimental results show that the CCTEG system performs well under various conditions. This results also demonstrate that the concept of adding heat pipes to the heat sink system is a practical solution to achieve higher thermoelectric generator (TEG) performance while maintaining the compactness of the TEG system. A heat transfer filling factor of 0.655 is achieved for the CCTEG system which is higher compared to the existing TEG systems. Moreover, a higher coolant flow rate contributes to obtaining a better performance of the TEG system. It is important to note that the introduced index can give guidance for further optimisation design of TEG systems.

1. Introduction

Previous decades have seen enormous developments in the renewable technologies by utilizing the alternative ways to obtain the usable energy. Thermoelectric heat recovery, as one of the most promising clean technologies, has attracted a greater attention due to its unique merits of energy conversion [1]. Unlike the traditional fossil fuel energy systems, TEG system converts waste heat directly into electricity through the Seebeck effect of the semiconductor materials whereby a temperature difference is maintained between the hot and cold side of the TEG module. TEG systems have the advantages of silent operation, high reliability, and they have no moving or mechanically complex components rendering them lasting for a very long time. They also operate at wider operational temperature range than most existing energy recovery systems [2,3]. However, the major challenge of the TEG system is the relatively low heat to electricity conversion efficiency [4]. Therefore, many research groups have made significant efforts on the improvement of the figure of merit for thermoelectric materials, such as BiTe, ZnBe, SiGe, TiO and even new nanocrystal or nanowire thermoelectric materials. Therefore, due to such booming

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research, TEG systems will be possibly applied in automotive waste heat industry in the near future [5–7].

In addition to material research developments, thermal scientists and system engineers focus mainly on the optimisation of geometric parameter of TEMs and heat exchanger. Liu et al. have performed CFD simulation and experimental study on the structural design of the heat exchanger to improve the efficiency of TEG system [8]. Furthermore, the performance of the TEG system under real working conditions is examined and a maximum power output of 944 W is obtained [9]. Lee has studied the optimal design of thermoelectric devices with dimensional analysis [10]. The optimum designs including the power output and the efficiency on the external load resistance as well as the geometry of thermoelectric units. Liu et al. and Liang et al. have investigated the performance of two-stage thermoelectric generator systems [11,12]. The results show that the power output and conversion efficiency of the two-stage TEG increase significantly by changing the heat transfer coefficient of the two stages and are noted to be higher than those of the single-stage TEG.

The influence of the engine working condition and the boundary condition on TEG system performance in the vehicle are also being researched. Yu et al. found out that multiple vehicular driving conditions might lead to the significant variation of TEG performance [13]. The results indicate that the engine speed is a major factor affecting the TEG performance. The results deduce that the higher the vehicle speed, the better the TEG performance. A higher road grade is also spotted to increase the power output of TEG significantly. He et al. have studied the influence of different cooling methods on the performance of TEG system [14]. The results reveals that the power output is higher with liquid cooling than air cooling whereas the counter-flow arrangement leads to higher power output though a much larger area is needed compared to the parallel-flow method. Other factor which needs consideration are the space and weight of the vehicle. It is noted that, in practice, there is limited space in the vehicle exhaust system; so the light weight and the size of the TEG are also vital factors in applying the TEG for fuel economy [15]. Wang et al. presented a TEG design with heat pipes-assisted heat exchanger structure to overcome the common conflicts between the needs for high heat flux into TEG and the limitation of overall heat exchanger dimensions and weights. Therefore, the need of light weighted thermoelectric generator system is very necessary for the development of vehicular TEG systems. The existing TEG systems are often too bulky to be applied in the exhaust system.

In this paper, a novel design of concentric cylindrical thermoelectric generator (CCTEG) system is presented for use in the exhaust system in the passenger car. The new design is capable of adapting to the shape of the exhaust pipe besides accommodating more TEMs unlike other TEG system designs of the same installation length. Given the form of the CCTEG system, a new annular thermoelectric module (ATEM), which is different from the previous square thermoelectric module (STEM), is also designed for the use of CCTEG system. Therefore, a relatively compact heat exchanger is necessary for the TEG system. In addition, heat pipes are applied to enhance the radial heat transfer of the whole system by means of conducting the heat directly into the annular TEM modules [16,17]. Mathematical analysis for the design are presented and experiments are carried out to verify the feasibility of CCTEG. Simulations have been done to investigate the difference in performance between the annular TEM and square TEM. Moreover, different performance indicators of evaluation are used to compare these two different shapes of TEMs and analyse the geometric influence on the TEM. Additionally, a model-scale experimental prototype and test rig for CCTEG are also constructed to examine the feasibility of using of heat pipes in this TEG system.

2. The design of concentric cylindrical thermoelectric generator

The described concentric cylindrical TEG design is as shown in Fig. 1. The main components of this TEG are the hot plates, cooling plates, heat pipes, concentric thermoelectric modules, and water jacket. The arrows indicated that the waste heat of the exhaust gas is conducted by heat pipes towards the hot side of the thermoelectric generator. On the cold side of TEM, the cooling plate also discharges heat to the water jacket via heat pipes. The purpose of using heat pipes is to divert the waste heat in the radial direction from engine exhaust pipe and discharge the heat to the water jacket. In addition, the heat transfer in the radial direction is enhanced due to the characteristic of super heat conductivity of the heat pipes.

The competitive advantage of CCTEG is the less installation space and weight required than conventional bulky TEG system. Since the installation space in vehicle exhaust system is limited in most scenarios, a relatively compact heat exchanger is imperative for the implementation of TEG systems. Moreover, the weight of the overall auxiliary devices is also a key factor for the fuel consumption of vehicles. The application of heat pipes makes it possible to reduce the weight of heat exchanger, rendering the CCTEG lighter than any other TEG systems.

As depicted in Fig. 2, the two sections represent the minimum repeat units of the overall system which can be segregated by the need of power rating. The minimum repeat unit is comprised of 4 ATEMs, 3 hot plates and 2 cooling plates including 12 heat pipes in each plate marked in blue and red colour in Fig. 2 (a) and (b) respectively. The exhaust gas flows throw the inner pipe of the system in Fig. 2(a) while the coolant flows in a constrained space shaped by the heat pipes, the surface of the cooling plate and the shell of the heat exchanger. Considering the various applications and the performance needs, this configuration can be interchanged by switching the channels of the gas and the coolant flows. As described in Fig 2(b), the coolant flow can be arranged in an axial flow by replacing the gas flow in Fig.2(a) baring mind the heat convection in the coolant. The gas flow, therefore, can be allocated at the outer side where the extra heat sinks on the heat pipes can be installed. In this way, a higher power generation performance can be achieved due to the heat transfer enhancement between the heat pipes and gas flow.

3. The modelling of concentric cylindrical thermoelectric generator

The three-dimensional models of STEM and ATEM are analysed in CAD software. Both thermal analysis and thermoelectric performance of these two models are simulated in the CFD software.

3.1. Material properties of TEM for simulation and experiment

The previous studies of the thermoelectric generator mainly focused on the heat exchanger and the improvement of thermoelectric materials, but the influence of the topological shape of thermoelectric modules has not attracted much attention by the researchers. A different design for the thermoelectric module – ATEM is described in this paper. The aim of this module is to fit the novel design of CCTEG system.

The two different shapes of thermoelectric modules that are described in this study are shown in Fig. 3. Both modules share the same number of thermoelectric units and the same material properties. The geometric details of the TEMs are listed in Table 1.

Each TEM in this study contains 210 units. These units are electrically connected in series implying that the electrical currents through them are the same. On the other hand, the heat passes through these units simultaneously, meaning that they are