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A Novel Design of Thermoelectric Generator for Automotive Waste Heat Recovery

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Abstract

With progressively stringent fuel consumption regulations, many researchers and engineers are focusing on the employment of waste heat recovery technologies for automotive applications. Regarded as a promising method of waste heat recovery, the thermoelectric generator (TEG) has been given increasing attention over the whole automotive industry for the last decade. In this study, we first give a brief review of improvements in thermoelectric materials and heat exchangers for TEG systems. We then present a novel design for a concentric cylindrical TEG system that addresses the existing weaknesses of the heat exchanger. In place of the typical square-shaped thermoelectric module, our proposed concentric cylindrical TEG system uses an annular thermoelectric module and employs the advantages of the heat pipe to enhance the heat transfer in the radial direction. The simulations we carried out to verify the performance of the proposed system showed better power output among the existing TEG system, and a comparison of water-inside and gas-inside arrangements showed that the water-inside concentric cylindrical TEG system produced a higher power output.

Keywords Waste heat recovery · Thermoelectric generator · Heat pipe · Heat transfer enhancement · Numerical simulation

1 Introduction

It is known that even the most advanced internal combustion engines (ICEs) can only convert maximum 35–40% of their fuel energy into mechanical power. Immediately after leaving the engine's combustion chamber, the exhaust gas can have a temperature as high as 800–900 °C. Consequently, the exhaust gas has a high heat content, carrying away as much as 33% of the fuel energy into the environment, not only wasting energy resources, but also accelerating the serious issue of carbon emissions. With the rapid growth in the number of vehicles over the last several decades,

combined with the increasingly stringent fuel consumption and emission regulations, recovering waste heat from vehicles is becoming an important issue for our societies. There are several approaches to improving the overall thermal efficiency of vehicles, including turbocharging, the Rankine cycle model and the thermoelectric generator (TEG). These three technologies all have their own advantages and disadvantages. Table 1 lists the strengths and weaknesses of each technology [1,2].

Based on its advantages and compared with the other two technologies, the TEG must be the most suitable for application to light-duty passenger vehicles. The working principle of the TEG is based on the Seebeck effect, which translates the temperature difference between the hot and cold sides of the TEG directly into electricity. This benefit makes the TEG a promising waste heat recovery (WHR) technology for ICEs, because it does not rely on traditional fossil fuel energy and can convert waste heat directly into electricity [3]. Several existing studies have demonstrated the feasibility of applying TEG devices to the recovery of waste heat from vehicles. Agudelo et al. [4] and Stevens et al. [5] analysed the potential for energy recovery from the exhaust gases and the theoretical limits of thermoelectric generators for a given exhaust system configuration.

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Table 1 Strengths and weaknesses of waste heat recovery technologies

WHR method	Strength	Weakness
Turbo-charging (TC)	Most successful methods for diesel engines	Increased back pressure Demand for complex diesel after-treatment systems
Rankine cycle (RC)	Utilize at both low and medium temperature Regardless of ICE load or drive cycle	Response to transients Efficiency tends to be low Large space needed
Thermoelectric generator (TEG)	No mechanically rotating parts Compact package No noise and vibration High reliability	Low conversion efficiency relatively high costs of thermoelectric materials

Their results showed that the muffler was the source of the greatest energy loss, making it the ideal place from which to recover waste energy in the exhaust system. Additionally, there is an optimum number of thermoelectric leg pairs that will maximize the power extracted by any TEG system.

Each technology has its own advantages and challenges, but the major challenge with the TEG device is the relatively low heat-to-electricity conversion efficiency. Despite the obstacle presented by thermoelectric materials, there are many device-level challenges that prevent TEG devices from being used in real applications. In our study, we reviewed the literature on the technological development of thermoelectric generators and identified the main challenges presented by the TEG system. We then developed a novel design for a concentric cylindrical TEG system that solves the problems with existing systems. Our TEG system has a novel structure based on a different concept of the heat exchanger that introduces the use of heat pipes to significantly improve the heat transfer in the radial direction. We then carried out simulations to investigate the temperature and working performance of the new system.

2 Recent Research on Thermoelectric Generators

2.1 Improvements to Thermoelectric Materials

The thermoelectric effect has been known since 1821, when it was discovered by Thomas Johann Seebeck. The Seebeck effect refers to the voltage that is generated between the hot and cold sides of a conductor or semiconductor when a temperature difference is maintained between them. This effect forms the basis of the thermocouple and can be employed to generate heat-to-electrical energy [6,7].

The maximum efficiency of a thermoelectric material for both thermoelectric power generation and cooling is determined by the dimensionless figure of merit ZT , given by

$$ZT = \frac{S^2 \sigma}{\kappa} T \quad (1)$$

where S is the Seebeck coefficient, σ is the electrical conductivity, $S^2 \sigma$ is the power factor and κ is the thermal conductivity.

Equation (1) shows that achieving a high ZT value requires a material that simultaneously possesses a high Seebeck coefficient and high electrical conductivity while also maintaining a low thermal conductivity. This is a challenge as these requirements are often contradictory [8]. Figure 1 shows the relationships between the power factor and the Seebeck coefficient, the electrical conductivity and the thermal conductivity for different materials. With incremental lowering of the electrical conductivity, the Seebeck coefficient presents a declining curve, demonstrating that semiconductors have the highest power factor of all the materials. Improvements in thermoelectric materials have been achieved largely through modifications to the thermal conductivity; thus, most research on thermoelectric materials focuses on the physical mechanisms that give rise to their thermal properties [9].

Classical thermoelectric materials are based on Bi_2Te_3 and its alloys, PbTe and its alloys and SiGe alloys. Alloying reduces the thermal conductivity, and this strategy has proved to be effective in all thermoelectric materials. These materials were identified in the 1950s [10]. Nevertheless, research efforts to develop the materials decreased because the efficiency of these materials could not be improved enough to be applied in practice and compete with conventional mechanical systems. At the beginning of the 1990s, interest in thermoelectric re-emerged because of the increasing global energy crisis and global warming issues.

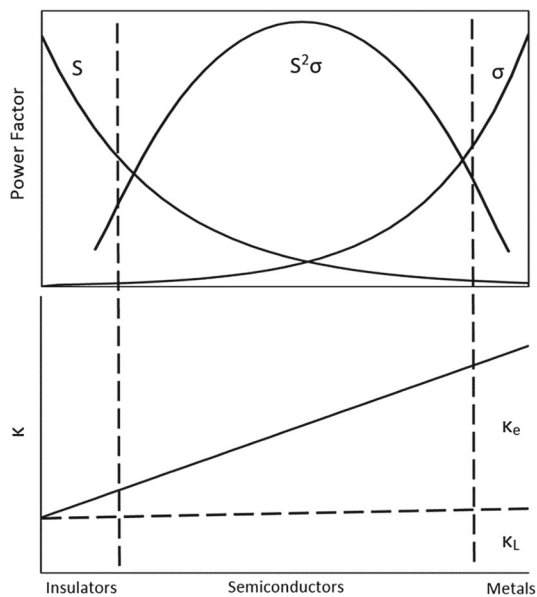


Fig. 1 Seebeck coefficient, electrical conductivity and thermal conductivity of different materials

Thermoelectric devices often consist of many pairs of *p*-type and *n*-type semiconductors legs, which are connected in series electrically and in parallel thermally. For maximum efficiency, both *p*-type and *n*-type legs need to be optimized, because the true *ZT* value of a specific pair is dependent on a combination of the properties of the two legs [11]. Figure 2 shows the *ZT* values for different *p*-type and *n*-type materials.

Recent years have witnessed impressive progress in thermoelectric materials, stimulated by new ideas in bulk materials [12] and nanostructures [13]. The figure of merit of

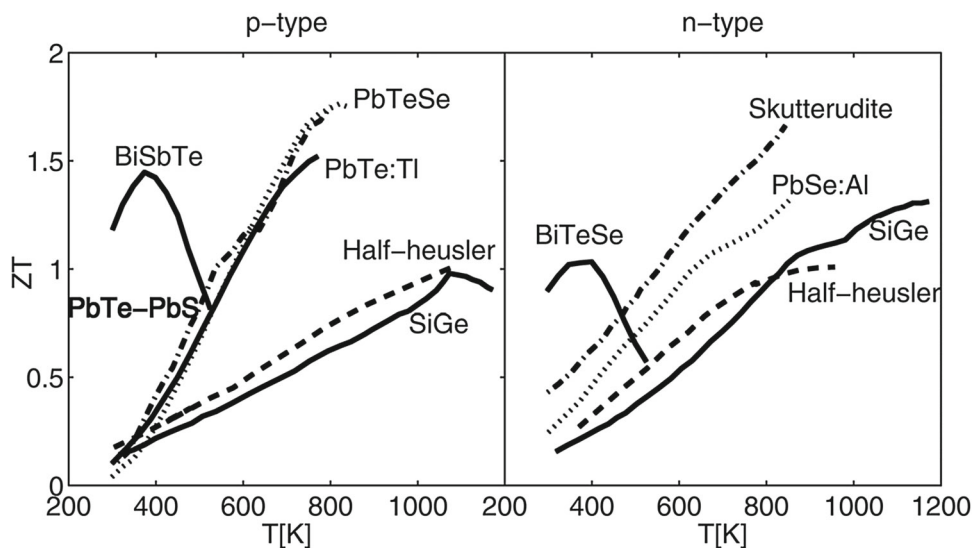
the TEG has risen from 0.7 to over 1.5, or even 2 in some laboratory prototypes. There have been many studies covering different aspects of thermoelectric materials, including bulk thermoelectric materials, individual nanostructures and bulk nanostructures [14]. Nevertheless, there is still plenty of space for innovation and development of thermoelectric materials that takes advantage of their solid-state nature, scalability, silent operation and environmental friendliness [15]. The imminent development of materials that are suitable for use in TEG systems is highly anticipated by the automotive waste heat industry [16].

Alongside technological developments in thermoelectric materials, another significant consideration in WHR applications is the reduction in manufacturing costs. The power generation cost metric adopted by LeBlanc et al. [17] as the evaluating factor for a cost-effective TEG system is cost per watt, which is important in ensuring that TEGs are commercially feasible in a wide variety of WHR applications. Their results indicate that material costs are too high for typical materials used in thermoelectric power generation applications at mean temperatures below 135 °C. Above 275 °C, many bulk thermoelectric materials can achieve costs below \$1/W. The major barrier to economical thermoelectric power generation at these higher temperatures results from system costs for heat exchangers and ceramic plates.

2.2 Improvements at the TEG System Level

Despite the increasing amounts of research into thermoelectric materials, there are still many device-level challenges that prevent TEG devices from being used in real applications, and many researchers have focused on numerical simulations of the performance of TEG devices. The major issue

Fig. 2 Figure of merit *ZT* for different thermoelectric materials versus temperature for *p*-type and *n*-type legs. This figure is adapted from the one presented in [11]



with recent simulations of the thermoelectric generator is the accuracy of the simulation, because the physical parameters of thermoelectric materials are temperature dependent and affected by the details of the geometry itself [18]. Zhang [19] was the first to develop a numerical model that took into account the influence of the properties of temperature-dependent materials, the spatially dependent rate of heat flow in the thermoelements and the heat and electrical losses at the junctions in calculating the performance of TEG devices. Hogblom and Andersson [20] established a simulation methodology for characterization and simulation of TEG systems that allowed for accurate prediction of the voltage and current as well as the heat flow in the steady state. Montecucco and Knox [21] presented an accurate model for simulating the nonlinear electrothermal coupled effects that occur during changes in the operating conditions and compared the simulation results to their experimental data. In addition to progress in simulation methodology, several researchers have presented studies simulating TEGs at the system level. He et al. [22] presented a mathematical model for a thermoelectric performance study under four different cooling methods. Liang et al. [23] presented a mathematical model for a two-stage TEG and analysed its performance by simulating the effect of relevant factors. Their results showed that the output power and conversion efficiency of the two-stage TEG are higher than for the single-stage TEG. Yu et al. [24] investigated the transient behaviour of a TEG system in different start-up modes using different heat transfer coefficients related to engine speed. They concluded that a higher vehicle speed improves the TEG performance and accelerates the transient response.

Besides research based on numerical simulation, several researchers investigated the performance of TEG devices through experiments. Liu et al. [25,26] performed an experimental study on different structural designs for the heat exchanger aimed at improving the efficiency of a TEG system for which a maximum power output of 944 W was obtained in the revolving drum test under real working conditions. Wang et al. [27] and Su et al. [28] performed a series of experimental tests on a thermoelectric generator system based on a new type of open-cell metal foam-filled plate heat exchanger, achieving a heat exchange efficiency between heated air and cold water of 83.56%.

In parallel with the progress in simulation and experimental studies of the performance of TEG devices, attention has also focused on the heat transfer performance. In most cases, it is poor heat transfer design that inhibits achieving the ideal efficiency. Accordingly, thermal scientists and system engineers focus mainly on enhancing the heat transfer to and from the TEG device to improve the overall efficiency of vehicle TEG systems [29]. Beyond heat transfer enhancements, novel designs for heat exchangers for TEG devices have also

been presented. Aranguren et al. [30] built a new thermoelectric generator prototype which could produce 21.56 W of net energy covering 0.25 m² of space. In terms of heat dissipation, they obtained 43% more net power through the use of heat pipes in a finned heat exchanger. Ma et al. [31] investigated numerically the effects of longitudinal vortex generators (LVGs) on the performance of a TEG with a plate-fin heat exchanger. Their results indicated that the heat input and open circuit voltage of a TEG with LVGs increased by between 41 and 75% compared to a TEG with a smooth channel. Wang et al. [32] presented an innovative design for a cylindrical TEG heat exchanger for light-duty passenger cars. Their paper presents an effective solution to enhancing the heat transfer for the gas flow in a direction radial to the TEG.

Yu et al. [33] and Vale et al. [34] investigated the influence of the geometrical parameters on the performance of a TEG system. They showed that the optimal geometry differs for maximum output power, power density and power output per unit area, and that the values of the optimal geometrical parameters will be affected by the volume of the thermoelectric material and the thermal input. Their results can be used as the basis for optimizing the performance of thermoelectric modules, but there is still significant room for further improvement and optimization based on the design of the thermoelectric modules.

3 Concentric Cylindrical TEG System

As discussed in the previous section, research into thermoelectric systems for vehicles has attracted more attention since 2005. Most of the existing research is based on numerical and experimental analysis of the influence of external conditions such as the temperature and mass flow rate in the heat exchanger for the TEG system. However, the installation space and weight of the TEG system are rarely discussed. In practice, space in the vehicle exhaust system is very limited and therefore should be optimized. Moreover, the weight of the TEG is also a vital factor in an effort to achieve fuel economy [35]. System optimization, especially for automotive applications, is therefore crucial; hence, both the thermoelectric devices and the heat exchanger should be developed together to match the heat flux requirements. A proper method for better thermal distribution in the thermoelectric modules may be needed to solve the heating mismatch along the exhaust pipe, as the temperature along the flow direction in common exhaust heat recovery systems varies significantly.

3.1 Schematic of Concentric Cylindrical TEG System

Our current study presents a novel design for a concentric cylindrical thermoelectric generator system for use in the

Fig. 3 Schematic of the concentric cylindrical TEG system: **a** Water-inside concentric cylindrical TEG system, **b** gas-inside concentric cylindrical TEG system

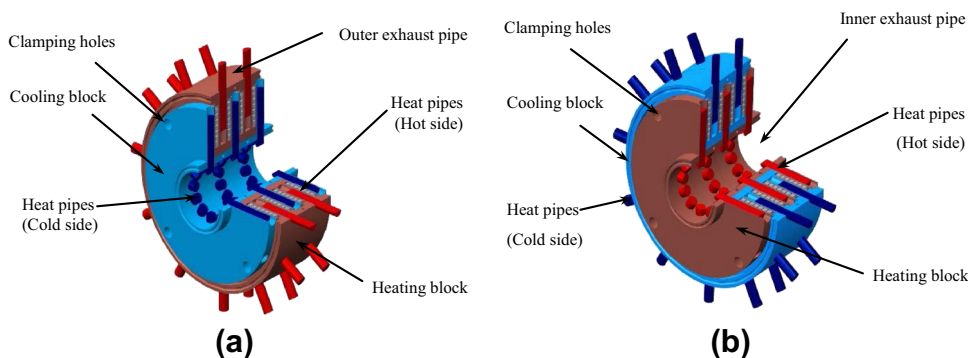
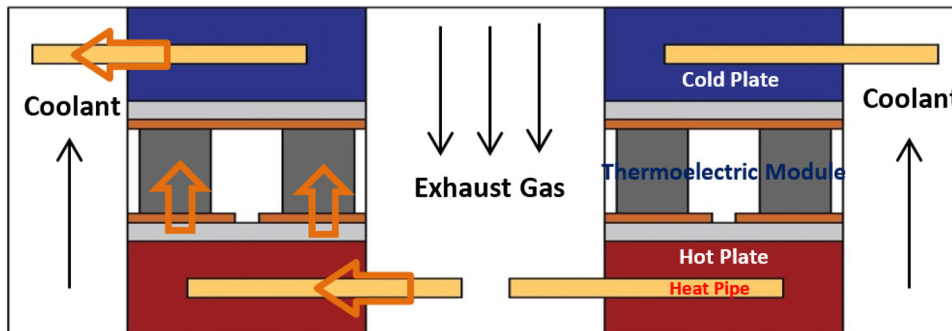


Fig. 4 Heat flow in the concentric cylindrical TEG system



exhaust system of vehicles. Our novel TEG system introduces a compact and lightweight heat sink which is assisted by heat pipes. The merits of utilizing heat pipes in the concentric TEG modules are explored regarding the improvement in heat flux and the simplicity of system integration. This configuration achieves a better filling ratio for the whole TEG system, and the deployment of heat pipe arrays enhances the heat transfer in the radial direction. A reliable and efficient heat transfer component, the heat pipe has been widely used for the thermal management of electronic devices. Heat pipes bring the advantages of high heat conductivity, fast thermal response and lightweight [36,37]. The combination of heat pipes with a heat exchanger is anticipated to reduce both the weight of the TEG system and the whole vehicle, with consequent improvements in the fuel economy.

The TEG system shown in Fig. 3 consists of a series of repeat units that are segregated along the exhaust stream and shaped into a practical exhaust pipe. The repeat unit is made up of concentric thermoelectric modules, hot plates and cooling plates; the twelve heat pipes in each plate are highlighted in blue and red. The exhaust stream interacts with the heat pipes and transfers the heat into the TEG in the radial direction of the exhaust stream. On the cold side of the thermoelectric modules, the cold plate also discharges heat to a water jacket via the heat pipes. Figure 4 shows the heat flow in the concentric cylindrical TEG system. Based

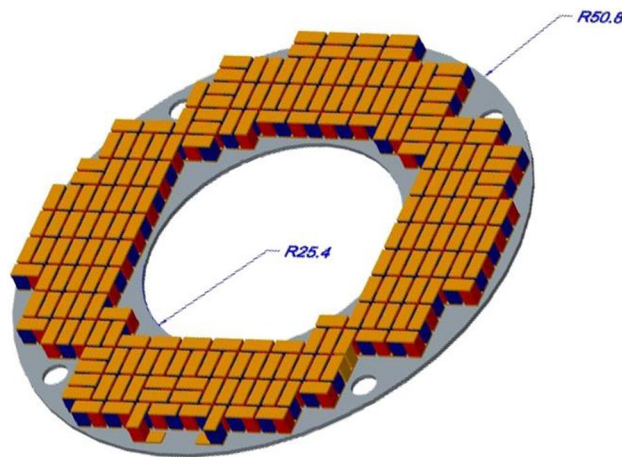


Fig. 5 Schematic of the annular thermoelectric module

on the power output demand, this configuration can be easily modified by exchanging the channels for the exhaust and coolant flows and by adjusting the number of repeat units. An annular thermoelectric module (shown in Fig. 5) is used in this TEG system instead of the usual square-shaped module, incorporating a self-clamping method to adjacent modules to further reduce the need for a single fixture on each module. Unlike the conventional TEG system with square-shaped thermoelectric modules, the concentric cylindrical-shaped TEG system can easily accommodate a circular exhaust pipe.

The modified clamping mode in this new design, which replaces a single fixture with four simple self-locking metal cables that are bolted through the bore of the thermoelectric modules, is expected to minimize the uneven thermomechanical stress on the components.

Specifically, Fig. 3b shows how the coolant flow can be distributed to the internal axial flow by replacing the exhaust flow associated with the external axial flow channel, in order to utilize the merits of the higher heat capacity of the water coolant. In addition, extruded fin stacks can be mounted on the heat pipes to enhance the heat transfer convection in the exhaust streams.

4 Investigating the Performance of the Concentric Cylindrical TEG System

We performed simulations using commercially available CFD software COMSOL Multiphysics to investigate the performance of the concentric cylindrical TEG system.

4.1 System Performance of the Repeat Units in the TEG

Figure 6 shows the best results for our simulation of a single repeat units in the concentric cylindrical TEG system. The major features shown in the U-I-P curves in the figure are matched load voltage, matched load current and matched load power output.

The maximum output power for the water-inside concentric cylindrical TEG system is 29.8 W, achieved when the matched load resistance reached 0.7Ω , which was equal to the internal resistance of the thermoelectric modules. The matched load voltage obtained was 4.5 V under the same

load resistance conditions with a matched load output current of 6.62 A.

The maximum matched load output power achieved for the gas-inside concentric cylindrical TEG system was less than 5 W even under the best convective conditions, which is far less than that for water-inside system, as shown in Fig. 6. The limited heat transfer area could be the major reason for these unexpectedly negative results. There is still room for improvement by increasing the hot side temperature of the thermoelectric modules. However, it should be noted that the fin stacks, which are not simulated in this case, might contribute to a higher heat transfer coefficient at the interface of the exhaust and the heat pipes. The main obstacle to applying extra fin stacks is the limited space within the standard exhaust pipe. The advantage of the water-inside system is that fin stacks can easily be applied to the hot side of the heat pipes in the external channel. Therefore, a higher power rating can be anticipated.

4.2 Temperature Distribution

Figure 7 shows the best results for the temperature distribution of the TEG system in the radial direction. The two different configurations result in different heating impacts on the components in the TEG system. With the higher heat transfer coefficient in the exhaust channel, the TEG system exhibits a higher temperature profile at the hot side heat pipe, as Fig. 7 shows. This is consistent with other investigations where a major decline in the hot side temperature and temperature gradient was noted due to the parameter variations at the hot side of the thermoelectric module. This decline inevitably contributes to adverse effects on the power output of the TEG system. Extra heat enhancement measures are needed to deal with this factor.

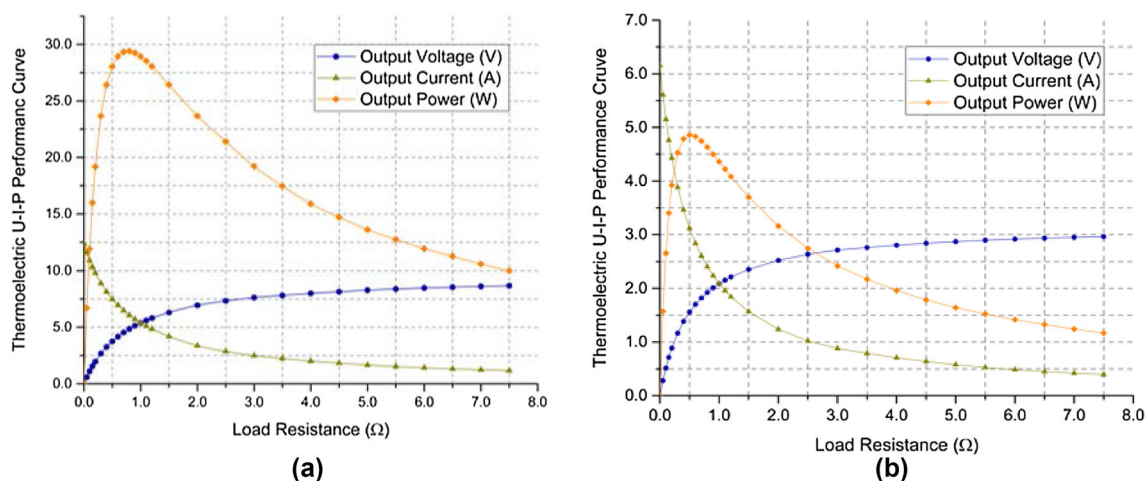


Fig. 6 U-I-P curves for **a** the water-inside system; **b** the gas-inside system with a matched load

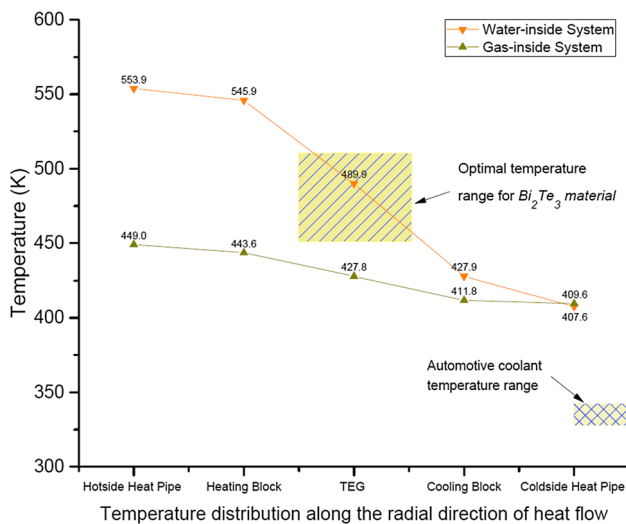


Fig. 7 Temperature distribution and heat flow across the TEG system in the radial direction

According to current material development, the optimum temperature for a TEG based on Bi_2Te_3 should be in the range of 450 K to 520 K. Any increase or decrease in temperature will reduce the efficiency of the material and increase the thermal stress on the thermoelectric legs. In addition, the optimum operating temperature range of the conventional copper–water combination also needs to be considered in structuring the TEG system.

Figure 7 shows the temperature at the hot side of TEM for the system of water-inside is 545.9 K, which is 102.3 K higher than that the hot side of TEM for the system of gas-inside. The higher heat capacity of the water coolant and the higher heat transfer area of the heat exchanger for the system of water-inside is the reason why the temperature difference in the hot side of TEM between these two systems exists. The system of water-inside thus has a higher heating block temperature. Although the temperature at the hot side of TEM in these two systems shows a difference of 102.3 K, the temperature difference in the cold side of TEM is only 16 K. This gives a total temperature difference between the two sides of TEM for the water-inside system of 118 K, compared with 31.8 K for the system of gas-inside, which shows a dispersion of 86.2 K. This variation is the result of the enhanced exhaust heat exchange assembly in the external channel in the water-inside system. This result shows good consistency with the previous results, shown in Fig. 6, in terms of the power outputs of the two systems.

The two shaded sections in the temperature distribution in Fig. 7 indicate the optimal temperature range for Bi_2Te_3 and the automotive coolant temperature range. In practice, these two areas form the optimum working temperature for the system when assembled in the motor vehicle. Note that the optimal temperature range for the Bi_2Te_3 thermoelec-

tric modules in the water-inside system lies between these two curves. This also gives the water-inside system a higher power output than the gas-inside system.

5 Conclusion

This paper presents a review of recent improvements in thermoelectric materials. Over the past several decades, significant progress has been made in thermoelectric materials; the figure of merit has been improved and is now approaching a relatively high value of 3, which is sufficient for most high efficiency thermoelectric applications. Other than semi-conductors, many new materials have been investigated and have exhibited satisfactory figures of merit. Moreover, both physical and chemical methods for increasing the figure of merit for existing materials are being developed.

In parallel with the progress in thermoelectric materials, enhancements to TEG devices are being made at the system level. Various papers have been published on improvements to heat exchangers for TEG systems, and there are numerous innovations for reducing the thermal resistance and enhancing the heat transfer. The geometry of thermoelectric modules has also been the subject of many papers, which can provide useful guidance for future designs.

This current study presents a novel design for a concentric cylindrical TEG system. Instead of the usual square-shaped thermoelectric module, we designed an annular thermoelectric module that matches the shape of the concentric cylindrical TEG system. Our new system uses the advantages of the heat pipe to enhance the heat transfer in the radial direction. This also gives the thermoelectric modules a better temperature distribution, which can reduce the thermal stress on the modules and improve the conversion efficiency.

We carried out simulations to verify the performance of the proposed TEG system and compared the gas-inside and water-inside arrangements. Our results showed that the water-inside system produced a higher temperature gradient between the hot and cold sides of the thermoelectric module at 118 K, which was 86.2 K higher than for the gas-inside system. This difference in the temperature gradients of the two systems resulted in the water-inside concentric cylindrical TEG system producing a higher power output of 29.8 W compared with the gas-inside system, which could only produce a power output of 4.8 W. In addition, the thermoelectric modules in the water-inside system were working at the optimal temperature range for Bi_2Te_3 , which will also improve the conversion efficiency of the whole system.

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