A REVIEW ON THERMOELECTRIC-HYDRAULIC PERFORMANCE AND HEAT TRANSFER ENHANCEMENT TECHNOLOGIES OF THERMOELECTRIC POWER GENERATOR SYSTEM

by

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The thermoelectric material is considered to a good choice to recycle the waste heat in the power and energy systems because the thermoelectric material is a solid-state energy converter which can directly convert thermal energy into electrical energy, especially suitable for high temperature power and energy systems due to the large temperature difference. However, the figure of merit of thermoelectric material is very low, and the thermoelectric power of generator system is even lower. This work reviews the recent progress on the thermoelectric power generator system from the view of heat transfer, including the theoretical analysis and numerical simulation on thermoelectric-hydraulic performance, conventional heat transfer enhancement technologies, radial and flow-directional segmented enhancement technologies for the thermoelectric power generator system. Review ends with the discussion of the future research directions of numerical simulation methods and heat transfer enhancement technologies used for the thermoelectric power generator in high temperature power and energy systems.

Key words: *thermoelectric power generator, heat exchanger, numerical simulation, heat transfer enhancement, segmented enhancement technology*

Introduction

In recent years, high-efficiency energy and power systems are urgent due to the exhaustion of fossil energy, which often operate at high temperature to achieve high-efficiency energy utilization. For example, the intermediate heat exchanger in the very high temperature gas-cooled reactor cycle system proposed by the U. S. Department of Energy operates at temperature up to 900 °C [1]. The operating temperature of recuperator in the externally fired gas turbine system is up to 1100 °C [2], while in the micro-turbine cycle it is often higher than 600 °C [3]. The solar energy receiver usually works up to 900 °C [4], while the temperature of exhaust gases in the vehicle engine [5], biomass combustion systems [6] and matrix-stabilized porous medium combustion [7] can reach 500 °C. The hot flue gases emitted from these high-temperature energy and power systems carry large amounts of waste heat. If the waste heat is unused, the efficiency of systems will be seriously reduced, and thus increasing the operating cost and thermal pollution. For example, the temperature of exhaust gas emitted from micro-turbine system without recuperator can reach 600 °C, and thus the nitrogen oxide

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emissions significantly increase and the efficiency of system is below 20%, but the efficiency of system with a recuperator is greater than 30% [8]. In the vehicle engines, only 30% of the energy released from the fuel is converted into an effective mechanical energy, while about 30% is lost by the engine cooling system and about 40% is discharged through the exhaust gases into atmosphere [9]. Therefore, in the high temperature power and energy systems, there is a great potential for waste heat recovery. It is necessary to develop high-efficient and low-cost waste heat recovery technologies.

Thermoelectric (TE) materials have been used to recycle waste heat in various kinds of heat sources including biomass combustion, solar energy, industrial waste gases, engine exhaust gas, radioactive isotopes, hydrocarbons, liquid nitrogen and liquefied natural gas, *etc.* Because the TE material is a kind of solid materials that directly converts thermal energy into electrical energy by using solid carriers, it has no mechanical transmission parts and working fluids. It also has the advantages of no noise, high safety, long reliability, no pollution, flexible installation and little influence on the original thermodynamic cycle. Due to these advantages of TE materials, thermoelectric generator (TEG) system has been proposed for many energy and power systems for waste heat recovery. The TEG system is especially suitable for high temperature energy and power systems because the TE conversion efficiency of TEG system is proportion to the temperature difference between the hot-side end and cold-side end of TE module. For example, in a Rolls-Royce MT-30 gas turbine with supercritical CO_2 system, the addition of TEG systems could improve the net power of the gas turbine by 5% [10]. In an SR30 micro gas turbine, adding TEG systems could recover exhaust heat to extract a resistive load of 192 W at 18 A of power [11]. When the TEG systems were applied to the steam turbine system [12], the addition of TEG systems could minimize the payback of initial cost per unit power output as well as fuel consumption per unit power output. The TEG systems were also proposed to be used for micro-turbine system embedded in the combustor, recuperator and flue gas recovery, which could improve the electrical power efficiency of micro-turbine system from 16-17% to 29-32% [13]. The TEG systems used for other applications are summarized in tab. 1. However, the applications of TEG system are still limited due to the low figure of merit (*ZT*) of TE materials. Much attention has been paid on developing novel TE materials with high *ZT*. The recent development of TE materials were overviewed by many researchers, as shown in tab. 1. The *ZT* of bulk materials such as silicon-germanium (SiGe), bismuth telluride (Bi_2Te_3) and lead telluride (PbTe) is less than 1 [14]. Although the *ZT* of superlattices may reach 2.5 at room temperature, the fabrication is too expensive to mass production [14]. It was reported that the *ZT* of TE materials should be greater than 4 for practical application [22].

The efficiency of TE module is much lower than that of TE system. The efficiency of TE module is the electrical power generated divided by the ideal input energy at a specified temperature difference between the hot-side end and cold-side end of TE module. The efficiency of TEG system is the electrical power generated divided by the maximum input energy that could be transferred from the hot-side fluid in the hot-side heat exchanger, in which the heat transfer performances on both the hot-side and cold-side heat exchangers have significant effects on the maximum input energy. During the analysis of TEG systems, the mechanical energy of auxiliary systems needed to operate TEG system and losses in electrical converter that transforms electrical power to an appropriate voltage level are usually neglected. Figure 1 illustrates the TE conversion efficiency of TE modules and systems in several typical waste heat recovery systems. It can be seen that the efficiency of TE module in the vehicle waste heat recovery system is about 2.1%, while the efficiency of system with TEG is 33% lower th-

Table 1. Representative review literatures on TE material and TEG

Authors	Published year	Review focus	TEG applications
Alam and Ramakrishna [14]	2013	TE materials (ZT challenges, improving approaches in bulk and nano materials)	–
Martín-Gonzalez *et al.* [15]	2013	TE materials (nano-structuring, polymers, thermionic materials, zintl phases, spin caloritronics)	–
Zheng *et al.* [16]	2014	TE materials (super-lattice, plasma treatment, segmented material, nano-composite, nano-wires/nano-tubes, structure/geometry), and applications	Automobile, aerospace, industries, domestic and thin film application
Elsheikh *et al.* [17]	2014	TE materials (basic knowledge, ZT affecting factors), and applications	Body-mounted electronic devices, waste heat, solar and radioisotope
He *et al.* [18]	2015	TE materials (semiconductor, ceramics, polymers), TEG (simulation, optimization, heat resource, applications), *etc.*	Space, automobile, building, flexible device
Twaha *et al.* [19]	2016	TE materials, applications, modelling methods, and performance improvement technologies of TEG	Automobile, building, geothermal, solar, biomass, *etc.*
Siddique *et al.* [20]	2017	State of the science and challenges of wearable TEG	Human body
Champier [21]	2017	TE materials, design, optimization and applications of TEG	Space, waste heat recovery, decentralized domestic power, sensors, microelectronics, solar, *etc.*

an that of TE module. The TE conversion efficiency of water heater and industrial furnace systems is 32% and 59% lower than their TE modules, respectively [23]. It can be found that there is still a big difference between systems' efficiency and TE modules' efficiency. Therefore, there is a great potential to improve the net TE conversion efficiency by optimizing the TE systems. For the short term, developing more efficient TEG systems based on available TE materials is of great significance to promote the practical applications of TEG systems. However, much attention has been paid on the recent development of TE materials and TEG applications in most review literatures, as shown in tab. 1.

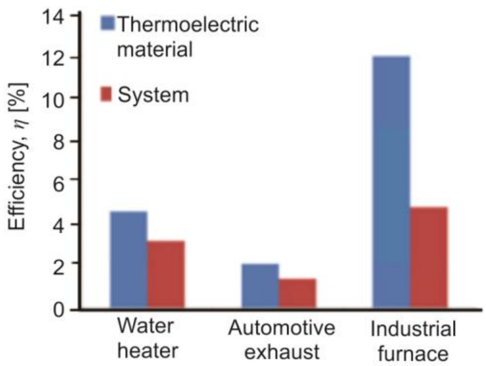


Figure 1. Comparison of TE conversion efficiency between TE materials and systems in several typical waste heat recovery systems [23]

Although it is pointed out that heat transfer performance of heat exchangers has significant effect on the efficiency of TEG system by many researchers, to our best knowledge, there are no systematical overview of TEG system from the view of heat transfer, especially the TEG system used for high temperature power and energy systems. This review focus on the recent progress of TEG systems from the view of heat transfer, including the theoretical analysis and numerical simulation on TE-hydraulic performance, conventional heat transfer enhancement technologies, radial and flow-directional segmented enhancement technologies for TEG systems.

Theoretical analysis of TEG system

In the fields of material science and physics, researchers often study the TE properties of TE materials by loading constant temperature boundaries at the hot-side end and cold-side end of TE modules. However, in addition to TE modules, a TEG system usually includes a hot-side heat exchanger, a cold-side heat exchanger, thermal interface materials and an electrical resistance, as shown in fig. 2. The TEG system is different from TE materials or TE modules because its performance is also significantly influenced by the thermo-hydraulic performance of heat exchangers [24]. Therefore, it is necessary to study the TE-hydraulic performance of TEG system.

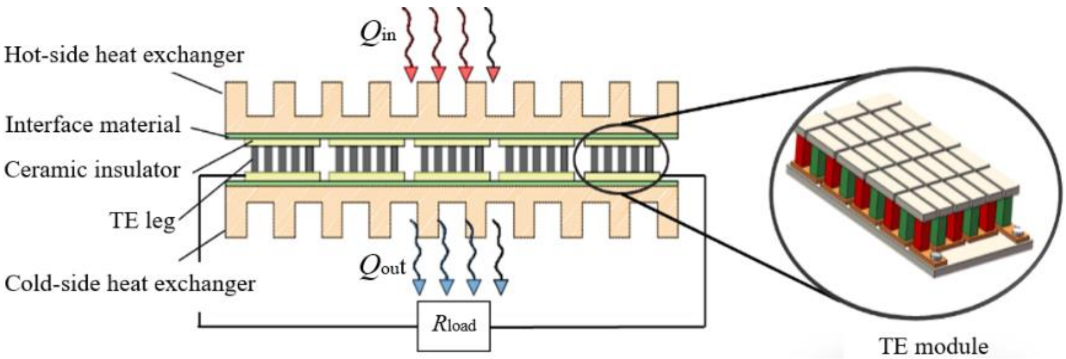


Figure 2. Diagram of a typical TEG system

In the theoretical analysis, the thermal boundary conditions at the cold-side and hot-side ends of TE modules are usually assumed to be constant wall temperature, and the TE properties of TE materials are usually assumed to be constant. Angrist [25] provided a basic formula for calculating the output power and conversion efficiency of the TE system. It was also pointed out that the assumption of constant TE properties of TE materials might cause large errors due to strong nonlinear variation of TE properties of TE materials. It is important to determine the optimal geometric parameters of TE modules. Rowe and Min [26] proposed a theory for TE module design, which gave the relationship between the output power/conversion efficiency and the geometric parameters. An indicator called *economic parameter* was put forward as one standard for the design of TE modules. The corresponding relations and diagrams were provided. This model only considered the case that the cold-side and hot-side temperatures of TE module was constant. Liang *et al.* [27] provided an analytical model for parallel TEG and obtained the theoretical expressions of current and output power. The theoretical results agreed well with the experimental results at heat source temperature from 350 K to 450 K. The deviation between them was caused by the assumption that the heat conduction between thermocouples was neglected. Yazawa and Shakouri [28] studied the TE model with asymmetric thermal resistance. It was assumed that the hot-side and cold-side thermal boundary conditions of TE modules were constant wall temperature, and the heat exchangers on both sides were equivalent to the asymmetric thermal resistance. The temperature and geometrical conditions of the maximum output power could be solved by using the Lagrange multiplication. The results showed that the maximum output power could be reached when the ratio of the load resistance to the internal resistance was $(1 + ZT)^{1/2}$. Most theoretical models of TEG systems in open literature were simplistic so that the results were limited to the guidance of realistic power systems [29]. Hence, the impact of heat exchangers on both sides were considered as equivalent thermal resistances. The results were consistent with Yazawa *et al.* [28]. Based on the analogy theory, the output power of the system reached the maximum value when the thermal resistance ratio was $(1 + ZT)^{1/2}$, but the previous literature using simplified assumptions concluded that the output power reached the maximum value when the load resistance and internal resistance of TE module was the same. Therefore, for the TEG system design, the hot-side and cold-side heat exchangers have significant effects on the maximum output power. It may result in different results whether considering the hot-side and cold-side heat exchangers or not. Mackey *et al.* [30] established an analytical model of a TE couple with rectangular and circular cross sections. The influence of actual lateral heat transfer and thermal resistance in a TE couple was considered by introducing fin factor and device design factor. The maximum conversion efficiency at realistic values of the device design factor such as 0.38 reduced from 6.15% to 2.28%, in which the convective heat transfer coefficient of TE leg ends was 500 W/m^{2}K. Using practical values of the fin factor such as 1.00, it reduced from 6.15% to 5.33%, in which the convective heat transfer coefficient of TE leg sides was 50 W/m^{2}K.

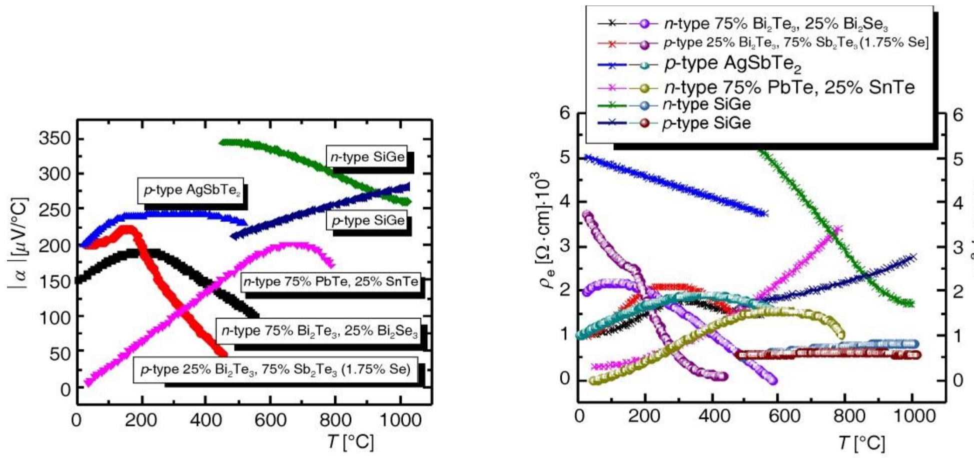


Figure 3. The TE properties of TE materials *vs.* temperature: (a) Seebeck coefficient, (b) electrical conductivity (data taken from [25]) (*for color image see journal web site*)

However, for high temperature power and energy systems, there are usually large temperature difference between the hot-side heat exchanger and cold-side heat exchanger, and large temperature drop along the streamwise direction of hot-side heat exchanger and cold-side heat exchanger. Therefore, the assumption of constant TE properties for TE materials may result in large errors in the design of high temperature TEG systems. Generally speaking, the variation trends of TE properties of TE materials with temperature have strong nonlinear characteristics, including Seebeck coefficient, thermal conductivity, electrical conductivity and figure of merit, as shown in fig. 3. The temperature-dependent Seebeck coefficient will further lead to Thomson effect. Therefore, it is necessary to consider the nonlinear variations of TE properties of TE materials as well as Thomson effect in the analysis. Ramousse *et al.* [31] established a TE conversion model considering the temperature-dependent TE properties of TE materials. The Thomson effect was calculated by introducing an equivalent Seebeck coefficient. Constant temperature was specified to the boundaries and the TE material was Bi_2Te_3. The results indicated that the Joule and Thomson effects were low at T_c = 270 K and T_h = 300 K or T_h = 330 K, but they became more important as the temperature difference increased. Kumar *et al.* [32] provided a 1-D model with variable TE properties of TE materials as well as Thomson effect. Two numerical examples with uniform heat transfer/temperature and different heat transfer/temperature were compared at exhaust gas and heat exchanger temperatures ranged from 100 °C to over 600 °C. The skutterudite module with n-type $Ba_{0.08}La_{0.05}Yb_{0.04}Co_4Sb_{12}$ and p-type $DD_{0.76}Fe_{3.4}Ni_{0.6}Sb_{12}$ was selected as the TE materials. It was found that there was large difference between the two numerical examples, and the results showed the significant effect of variable TE properties of TE materials as well as Thomson effect. To guide the design of TE modules at large temperature difference, the maximum efficiency formulae based on cumulative temperature dependence model including corrected Joule and Thomson heat were derived by Kim *et al.* [33]. The p-SKU/n-SKU, p-PbTe/n-PbSe and p-SnSe/n-PbSe at temperature difference up to 400 K were examined. The formulae could predict the efficiency and output power more reliably than the conventional constant property model. The theoretical analysis models could provide a quick and rough prediction of thermohydraulic performance for TEG system. However, the above theoretical analysis models are still limited to 1-D or 2-D analysis, which cannot reflect the 3-D characteristics of TE-hydraulic performance of TEG system.

Numerical simulation of TEG system

Numerical simulation based on finite element method can be used to examine the 3-D characteristics of TEG system with nonlinear variable TE properties of TE materials, Thomson effect, hot-side and cold-side heat exchangers including fluids. Heghmanns and Beitelschmidt [34] used the finite element method to simulate the performance of TE modules. It was found that the best TE performance and the best stress performance could be obtained by optimizing the geometric parameters. Rezania and Rosendahl [35] established a numerical model in ANSYS platform to study the influence of cold-side heat exchanger on the TEG system. The water flowed in the cold-side heat exchanger with an inlet temperature of 290 K and an inlet velocity ranged from 0.01 m/s to 0.7 m/s. The temperature at the TEG hot junction was specified at 350 K and 450 K. The hydraulic diameter of cold-side heat exchangers is 75 μm. The Bi_2Te_3 was assumed to be constant. Jia and Gao [36] used ANSYS software to simulate TE pairs with the linear array. The results showed that under large temperature difference, the nonlinear variation of TE material properties increased with the increase of temperature gradient along the length direction, and the Thomson effect should be considered. Wang *et al.* [37] studied the 3-D temperature and electric fields of TE cooler modules with the ratio of cross-sectional area to the height of 0.25 mm, in which the temperature-dependent physical properties of TE materials using $Bi_2(Te_{0.94}Se_{0.06})_3$ as n-type and $(Bi_{0.25}Sb_{0.75})Te_3$ as p-type were included. Jang and Tsai *et al.* [38] imported the equivalent constant TE properties of TE modules into the numerical model of TEG system. Each TE module included 31 pairs of p-type and n-type TE legs made of Bi_2Te_3 with dimensions of 30 mm × 30 mm × 3.42 mm. The numerical data for the power *vs.* current curve were in good agreement (within 8%) with the experimental data when the temperature differences between the waste gas and the cooling water were less than 200 K. Shi *et al.* [39] studied the 3-D TEG by using the finite element method. The temperature and electric fields of TE material were calculated under the constant heat flux boundary condition. Kossyvakis *et al.* [40] used ANSYS software to simulate a TE module with 71 pairs of TE legs. Silaen *et al.* [41] put forward the design of high temperature heat recovery by installing the TE module on the water wall of boiler and simulated the simplified TE module by using the finite element method. Meng *et al.* [42] developed an in-house 3-D numerical TEG model under constant wall temperature boundary on both sides. By comparing to the classical thermal resistance model, it was found that the assumption of constant physical properties of TE materials could result in unrealistic high performance and underestimated thermal conversion efficiency. Bjork [43] analyzed the effects of contact thermal resistance and contact electric resistance of TE materials by using COMSOL software. The hot-side end temperature was selected based on the peak *ZT* temperature for the hot-side TE material, while the cold-side end temperature was kept constant at 20 °C. The thermal contact resistance should be less than 20% for zero electrical contact resistance to keep the efficiency decrease less than 20%. Hu *et al.* [44] built a 3-D model of TE module by using COMSOL software, in which the Joule effect, Peltier effect, Thomson effect and temperature-dependent TE properties of TE materials were considered. The results were in good agreement with experimental results and the relative errors of open circuit voltage and heat flux were 10% and 35%, respectively. Antonova *et al.* [45] studied the effect of temperature-dependent TE properties of TE materials on the TE performance of TE leg by using ANSYS software. A TEG included a couple of TE legs at T_c = 27 °C and T_h = 327 °C was examined, in which the length is 1 cm for both the p-type and n-type TE legs, and the cross-sectional areas are 1.24 cm^2 and 1 cm^2, respectively. It was found that the thermal efficiency was reduced by 15% as a result of taking into account the temperature-dependence variations of TE material properties. Zhou *et al.* [46] established a coupled fluid-thermal-electric model with COMSOL software and found that the coupled numerical method could predict better results than simple theoretical method compared to experimental results. The physical properties of Bi_2Te_3 material were assumed to be constant and the dimensions of the TEG are 12 mm × 14 mm × 30 mm. Ma *et al.* [47] found that the numerical results obtained by coupled fluid-thermal-electric models established in ANSYS software and COMSOL software were similar to the analytical result during the calculation of Case 1 with constant TE properties of TE materials, but were significantly different from the analytical result during the calculation of Case 2 with temperature-dependent TE properties of TE materials, as shown in tab. 2. The TEG examined in the tab. 2 had the same geometrical structure and dimensions as [45]. The numerical method based on the COMSOL software was further used to study the effect of longitudinal vortex generators (LVG) on the performance of an integrated TEG system which only included one pair of TE legs. In order to investigate the large-scale TEG system including hundreds of TE legs, the equivalent TE properties of TE module combined with fluid-thermal-electric models established in COMSOL software were used in the numerical simulation [48]. However, as we all known, the finite element method usually needs large computational resource during the simulation of complex fluid flow. This disadvantage may restrict the application of these fluid-thermal-electric models based on finite element method in the large-scale TEG system.

Unlike the above finite element method, a fluid-thermal-electric coupled model based on the finite volume method was developed in FLUENT software by Chen *et al.* [49]. The equations governing the TE conversion phenomena were solved by using the external user defined functions and user defined scalars to fulfill the calculation of the electric related scalars, including the Ohmic voltage, Seebeck voltage and circuit current and inner electric resistance. The temperature-dependent TE properties of TE materials were included in the simulation. Using the similar fluid-thermal-electric coupled model based on the finite volume method, a novel integrated TEG system was studied by Reddy *et al.* [50], in which the flow channel was integrated into the inter-connectors. The studied ranges were from 350 K to 550 K for the inlet temperature of hot fluid, from 0.25 mm to 7 mm for TE leg sizes and from 1 to 5 for the number of TE modules. To examine the coupling effect of streamwise temperature

Table 2. Performance comparison of TE module using different numerical methods [47]

Cases	Parameter	Analytical [21]	ANSYS [41]	COMSOL [43]
Case 1 (constant TE properties)	Q_h [W]	13.04	13.03	12.99
	P_o [W]	1.44	1.43	1.42
	η [%]	11.00	11.00	10.93
	I [A]	19.20	19.10	19.03
Case 2 (temperature-dependent TE properties)	Q_h [W]	–	11.07	11.06
	P_o [W]	–	1.05	1.05
	η [%]	–	9.50	9.47
	I [A]	–	16.40	16.35

gradient and local heat flux non-uniformity in the hot-side heat exchanger on the TE-hydraulic performance of TEG system, a fluid-thermal-electric coupled model based on the finite volume method was developed by Lu *et al.* [51]. The dimensions of the hot fluid channel were 400 mm × 40 mm × 3 mm and four TE modules made of n-type (75% Bi_2Te_3 25% Bi_2Se_3), p-type (25% Bi_2Te_3 75% Sb_2Te_3 (1.75% excess Se) materials were located along the streamwise direction between the hot fluid channel and cold fluid channel. The Reynolds number ranged from 65 to 600 and the inlet temperature of hot fluid ranged from 600 K to 800 K were examined. Compared with the simplified model with prescribed convective heat transfer coefficient and fluid temperature, when the Reynolds number was less than 100, the deviation of thermal conversion efficiency between the two models was larger than 10%, but the deviation was smaller than 5% when the Reynolds number was larger than 200, as shown in fig. 4. However, huge amounts of grid elements in these fluid-thermal-electric coupled models based on finite volume method are still needed. It is necessary to develop the multi-scale numerical method for the large TEG system considered the temperature-dependent TE properties of TE materials.

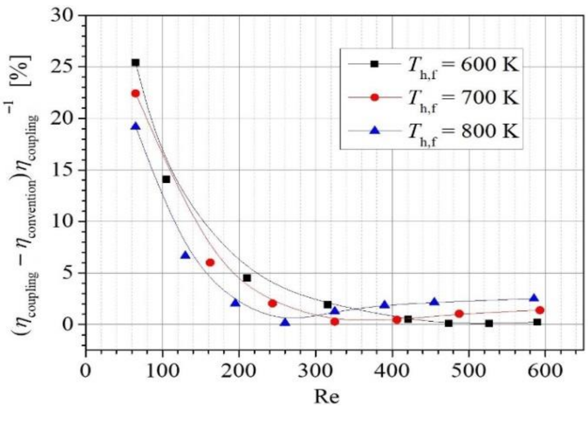


Figure 4. Relative deviation between fluid-thermal-electric coupled model and simplified model [51]

Heat transfer enhancement technologies for TEG system

As mentioned in the theoretical analysis and numerical simulation of TEG system, it can be found that the thermo-hydraulic performance of heat exchangers plays an important role on the overall efficiency of TEG system. More specifically, the inlet temperature of hot liquid, flow type, pressure drop, and geometric parameters of hot-side heat exchanger had significant effect on the TE-hydraulic performance of TEG [46]. It was suggested that the flow in the hot-side heat exchanger should be operated at turbulent flow. According to the parametric study on the TEG system with air cooling in a cross-flow heat exchanger, the design trade-offs between pressure drop of air and performance of TEG system were found to be very important [52]. The inlet temperature and flow rate of hot fluid in a TEG system with multi-layer plate heat exchangers had great effect on the maximum power output and conversion efficiency [53]. Due to the importance of heat exchangers, much work has been paid on the heat transfer enhancement of heat exchangers in order to improve the efficiency of TEG systems. In this section, the net efficiency of TEG system is the net power divided by the maximum input energy that could be transferred from the hot-side fluid in the hot-side heat exchanger, while the net power is the difference between the totally generated power output and pumping power consumed by the fluids in the cold-side and hot-side heat exchangers.

To enhance the performance of liquid-to-liquid TEG systems, three different turbulating inserts including spiral insert, 8 mm protruding panel insert and 16 mm protruding panel insert were inserted into the fluid channels of the liquid-to-liquid TEG, as shown in fig. 5. The protruding panels had better performance than spiral inserts, whose power output could be improved by up to 110% [54]. However, there was an upper flow rate threshold for increasing panel density beyond which the pressure drop caused by the protruding panel inserts might offset its power enhancement [55].

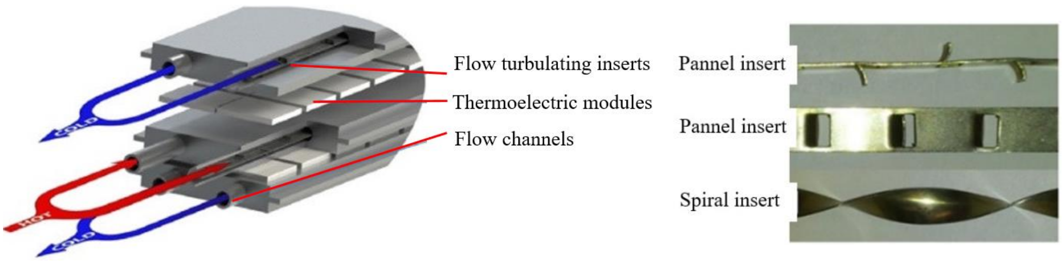


Figure 5. Inserts enhancement; (a) liquid-to-liquid TEG [54]; (b) different turbulating inserts [55]

Unlike conventional TEG systems, a novel integrated TEG system was proposed, in which a hollow copper interconnector designed as an internal hot-side heat exchanger was sandwiched between p-type and n-type TE materials [56], as shown in fig. 6. Another two copper connectors were attached to the top surface of p-type material and the bottom surface of n-type material, respectively. This novel design could reduce the thermal stress, material

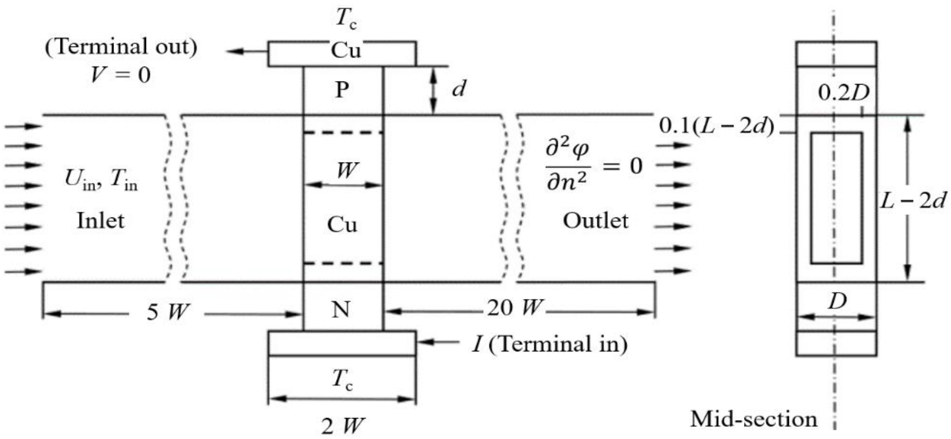


Figure 6. Integrated TEG system [56]

usage and thermal resistances. According to the 1-D analytical solution, the power output and hot-side heat transfer in the novel design were improved by nearly eight times, while the electric current was increased by nearly four times compared to the conventional TEG system at a fixed temperature differential [57]. Three different hot-side channels in the integrated TEG system including rectangular, round end slots, and circular flow channels were compared by the numerical simulations [58]. The results indicated that the circular flow channel had better performance than other channels under fixed operating conditions. Compared to the rectangular channel, the power output and thermal conversion efficiency in the circular flow channel were increased by 2.27 times and 1.41 times, respectively.

In the gas-liquid TEG system, the main thermal resistance exists in the hot-side channel. The LVG were used to enhance the heat transfer of hot-side channel in an integrated TEG system [47], as shown in fig. 7(a). In the studied cases, the heat input, net power and thermal conversion efficiency of the TEG system with LVG were maximally improved by 29%-38%, 90%-104% and 31%-36%, respectively, compared to the TEG system with smooth hot-side channel. The effect of LVG on the performance of TEG system with plate-fin heat exchanger as its hot-side flow channel was also examined [48], as shown in fig. 7(b). Under the baseline operating condition, the heat input and open circuit voltage of the TEG system with LVG were enhanced by 41-75%, compared to the TEG system with the smooth hot-side channel.

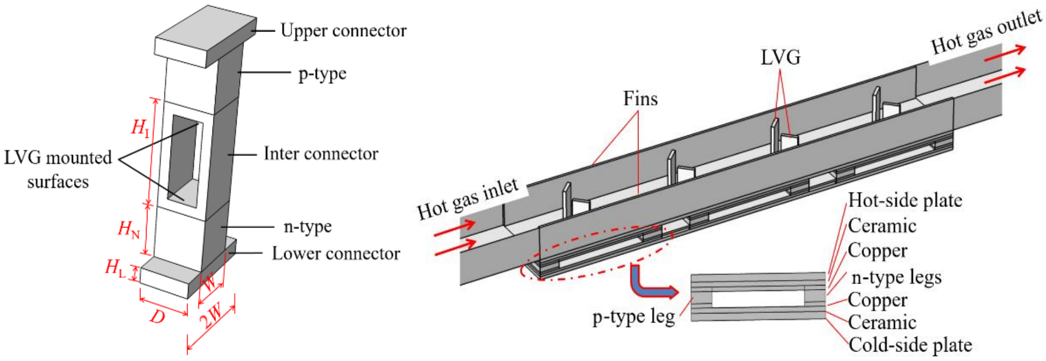


Figure 7. The LVG enhancement; (a) integrated TEG [47]; (b) TEG with plate-fin heat exchanger [48]

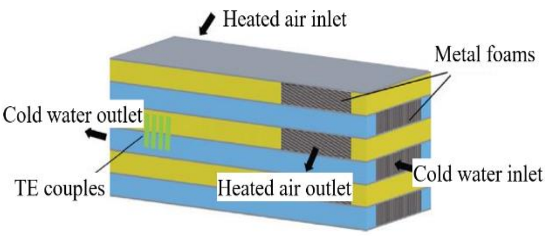


Figure 8. The TEG system with metal foam-filled plate heat exchanger [59]

The metal foams were applied to the gas side to enhance the heat transfer in a gas-liquid TEG system with a plate heat exchanger [59], as shown in fig. 8. It was found that the metal foams had significant effect on the heat transfer process. The heat transfer efficiency was up to 83.56%, and the maximum open circuit voltage of TEG system with 16 TE modules was 108.1 mV.

The effects of two plate-fin heat exchangers made of stainless steel and silicon carbide on the TEG system for vehicles were examined [60], as shown in fig. 9. The numerical results showed that the heat exchanger material had a significant effect on the maximum fuel efficiency. Compared to stainless steel heat exchangers, using silicon carbide heat exchangers

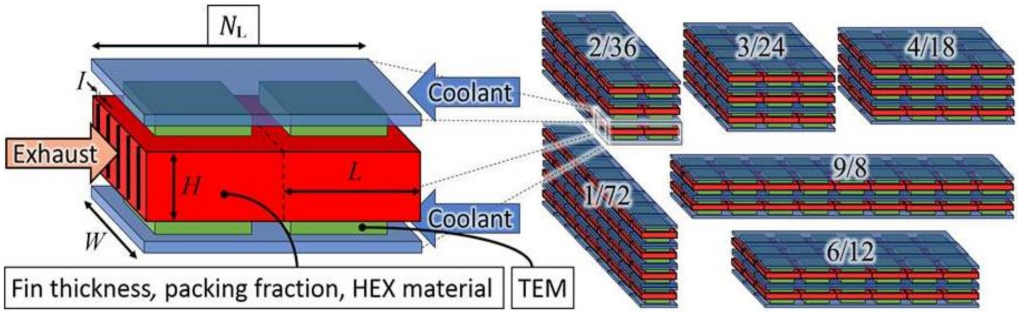
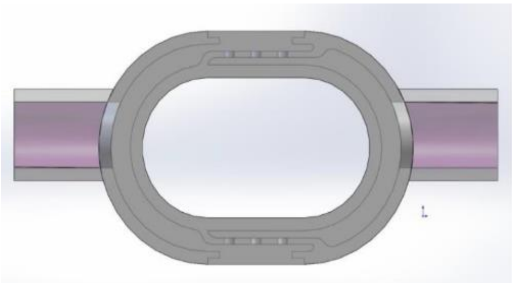


Figure 9. The TEG system with stainless steel and silicon carbide heat exchangers [60]

at taller fins and a longer configuration of TE modules along the exhaust flow direction could provide higher fuel efficiency.

To ensure the largest temperature differential across the TE modules, the pin fins and jet impingement were provided for the cold-side and hot-side flow channels, respectively [61], as shown in figs. 10 and 11. The experiment demonstrated the significant improvement in the efficiency of TEG system. Compared to the baseline design, the efficiency of TEG system was increased from about 3.5% to about 4% by implementing heat transfer enhancement technologies on both the cold-side channel and hot-side flow channel.



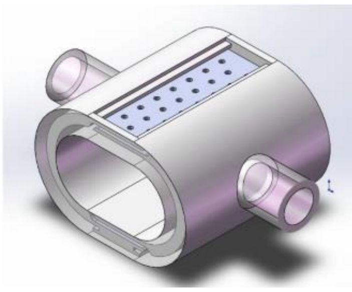


Figure 10. Front and isometric views of cold-side impingement jet geometry for TEG system [61]

Besides the heat transfer performance, the pressure drop caused by the heat transfer enhancement technologies also has significant effect on the comprehensive performance of TEG systems. A weak heat transfer in heat sink might even cause negative net power output from the TEG system [35]. Therefore, a modified cross-cut fin heat sink was proposed to reduce the pumping power of heat sink in TEG system, as shown in fig. 12. Here, the fins were only located in the surfaces near the TE legs in a non-uniform arrangement. It was found that the maximum net power output of TEG with cross-cut fin heat sink was higher than that with plate-fin heat sink at high velocity due to smaller pressure loss. Compared to the TEG with uniform fins, the TEG with non-uniform fins had similar thermal resistance but decreased the pumping power by 19% [62].

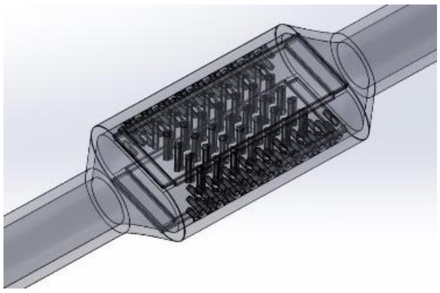


Figure 11. Hot-side pin fin geometry for TEG system [61]

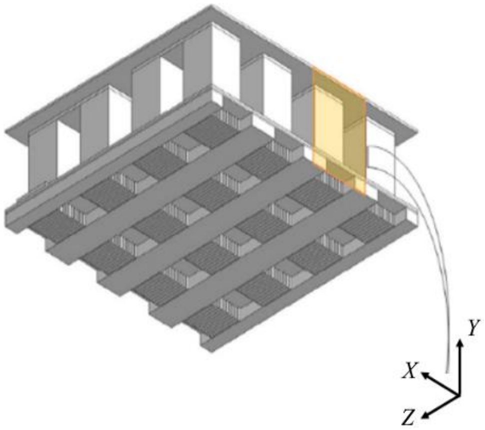


Figure 12. The TEG system with cross-cut heat sink [35]

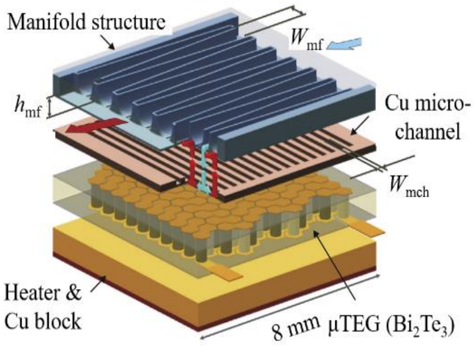


Figure 13. The TEG system with micro fluidic heat exchanger [63]

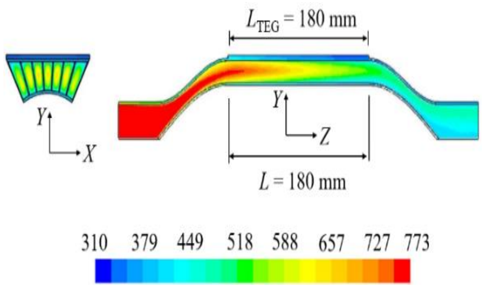


Figure 14. Temperature distribution in a typical exhaust pipe of vehicle [64]

A micro fluidic heat exchanger was applied to reduce the thermal contact resistance and performance of TEG system [63]. As shown in fig. 13, the micro-fluidic heat exchanger included two layers, which were consisted of a copper microchannel layer and a polymeric manifold channel layer. A net output power of 126 mW/cm^2 was achieved when the system worked at a fluid flow rate of 0.07 L per minute, an applied temperature differential of 95 K and the figure of merit for TE material was 0.1. It was also found that there was a trade-off between the heat transfer and consumed pumping power for the micro fluidic heat exchanger. At small operating temperature differences, the small flow rate and wide channel could provide high net output power. Otherwise, the large flow rate and small channel could be used at large operating temperature differences.

Radial and flow-directional segmented enhancement technologies for TEG system

Different from the low temperature energy and power systems, both the operating temperature and temperature gradient in the high temperature energy and power systems are large. Along the flow direction, only a small portion of total heat input is continually used by the TE modules because most heat input is absorbed by the cold-side heat exchanger, which leads to a large temperature gradient both in the flow direction and radial direction. Figure 14 shows the exhaust gas temperature distribution of in a typical vehicle exhaust pipe. It can be seen that the temperature differential in the radial and flow directions of a typical exhaust pipe is up to 300-400 °C. The temperature differential in the flow directions of a typical micro-turbine recuperator is about 450 °C, as shown in fig. 15.

However, the TE properties of TE materials exhibit serious non-linear variation characteristics with the change of temperature, so that one kind of TE materials may not always work in its optimum performance under a certain temperature range. As shown in fig. 16, among the listed 16 TE materials, the BiTe-based TE materials have the largest figure of merit below 200 °C, but the figure of merit of PbTe-based TE materials are the largest in the range of 200-500 °C.

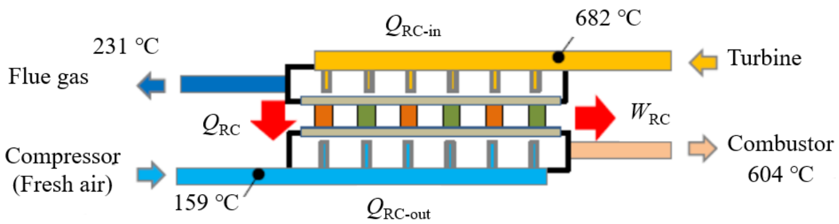


Figure 15. Temperature distribution in a typical micro-turbine recuperator [13]

In fact, the temperature uniformity had a significant effect on the electric power output [65]. To maximize the electric power output, the fin distribution of hot-side shutter-fin heat exchanger was optimized for a given vehicle TEG system [65]. The optimized result showed that the pitch of upstream fins positioned 0.5 mm larger than down-stream fins gave the best temperature uniformity, which could result in larger power output. Huang *et al.* [66] conducted a 3-D thermal resistance analysis to examine the temperature differential and power output of TEG system with a fin-structured hot-side channel. The result indicated that the positions of TE modules and the uniformity of the internal flow of velocity profile had strong influence on the power output of TEG system.

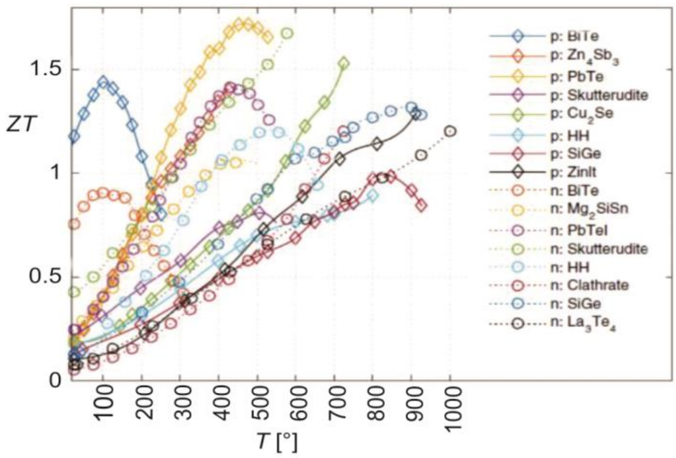


Figure 16. Variation of figure of merit of TE materials with temperature [43] (*for color image see journal web site*)

As mentioned before, the radial temperature differential between hot-side and cold-side heat exchangers is very large and the TE materials exhibit the optimum performance over a relatively narrow temperature range. In order to maximize the thermal conversion efficiency, individual TE elements are usually formed from two and sometimes three different TE materials laminated together in the direction of current flow to form segmented TE elements [67]. A compatibility factor was derived by Snyder and Ursell [68] to facilitate the rational materials selection, device design and the engineering of functionally grade materials for TEG. The performance of segmented TE modules was inefficient when the compatibility factors of TE materials were dissimilar. The segmentation of $(AgSbTe_2)_{0.15}(GeTe)_{0.85}$ with a compatible filled skutterudite could produce twice the increase in efficiency compared to that with tin telluride (SnTe) [69]. Ming *et al.* [70] analyzed the TE properties of segmented TE modules. The low temperature, medium temperature and high temperature zones were made of Bi_2Te_3, Zn_4Sb_3 and $CeFe_4Sb_{12}$, respectively. Norris *et al.* [71] studied the performance of segmented TEG made of nanoscale silicon. In the U.S. space program, the isotope fuel cell was made of segmented TE modules, which was formed by the high temperature TE material of SiGe and the low temperature TE materials [72] so that each TE material operated at its optimum temperature range.

Although there is also a large temperature differential along the flow direction, conventional heat transfer technologies using uniformly-spaced heat transfer elements or TE modules are still widely used in the TEG systems. However, a few novel segmented heat transfer technologies along the flow direction have been examined in recent years. In order to make the TE modules exhibit the optimum performance, a flow-directional segmented enhancement technology was proposed, in which the occupancy rates and materials of TE modules varied along with the flow-directional temperature variation [73]. The right side of fig. 17(a) shows the original flow-directional segmented technology, in which the occupancy rate of TE modules is 100%, and the TE materials are Bi_2Te_3 (model 1) and Bi_2Te_3 (model 2), respectively along the flow direction. The left side of fig. 17(a) shows the optimized flow-directional segmented technology, in which along the flow direction, the occupancy rates of TE modules are 34%, 57%, 82% and 67%, respectively, while the TE materials are PbTe, Bi_2Te_3 (model 1), Bi_2Te_3 (model 2) and Bi_2Te_3 (model 1). The comparison of electrical power between the two flow-directional segmented technologies is shown in fig. 17(b). It showed that along the flow direction, only the first module's output in the optimized flow-directional segmented technology was less than that of the original one, and the total power generation capacity was increased by 18%. An experiment further demonstrated that using the suitable occupancy rates and materials of TE modules along the flow direction could effectively improve the power output, maximize the use of heat and save the TE materials [74].

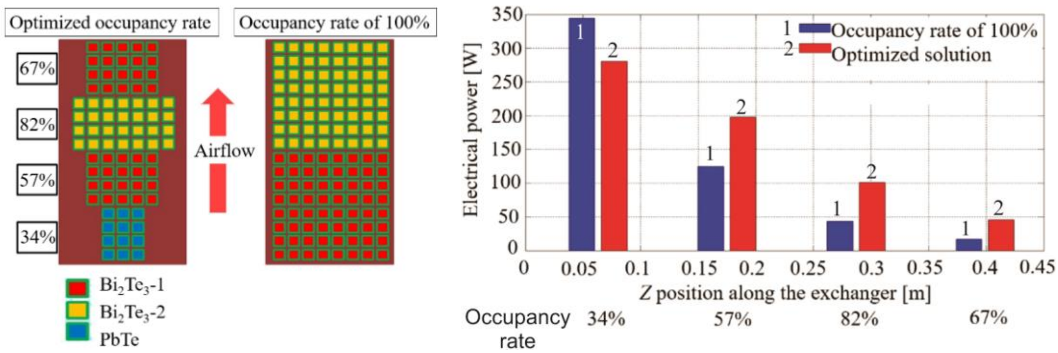


Figure 17. Flow-directional segmented enhancement technologies for TE modules; (a) different layouts, (b) comparison of electrical power between two TEG systems with different flow-directional segmented enhancement technologies for TE modules [73]

In the conventional heat transfer channel, the uniformly-spaced heat transfer elements are usually added to enhance the heat transfer, as shown in figs. 18(a) and 18(b). Due to the waste heat recovery with large stream-wise temperature drop, a non-uniform heat exchanger for TEG system with the same number of winglet vortex generators as fig. 18(b) was proposed, but different number of winglet vortex generators were used at different locations along the flow direction, as shown in fig. 18(c). In fig. 18(c), denser winglet vortex generators were located at upstream, while fewer winglet vortex generators were located at downstream. The experimental results showed that compared to TEG system with a smooth heat exchanger, the total and net power output of TEG system with a uniform heat exchanger were enhanced by 97.5% and 77.7% in average, whereas those with a non-uniform heat exchanger were increased by 189.1% and 177.4%, as shown in fig. 19. It was interesting to observe that this kind of flow-directional segmented enhancement technology for heat transfer elements

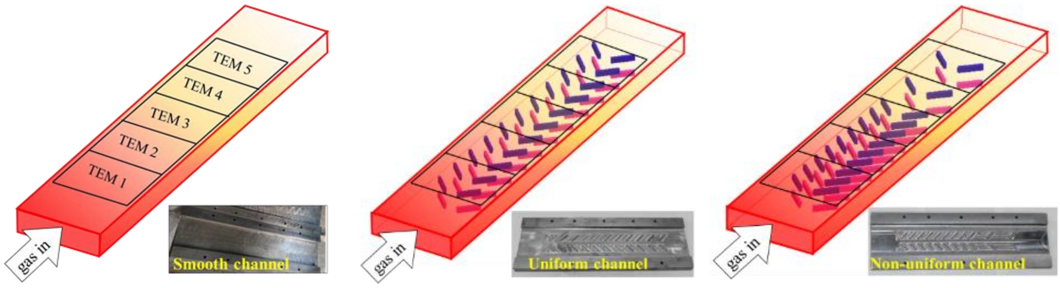


Figure 18. The TEG systems with different heat transfer enhancement elements [75]: (a) smooth heat exchanger; (b) uniform heat exchanger; (c) non-uniform heat exchanger

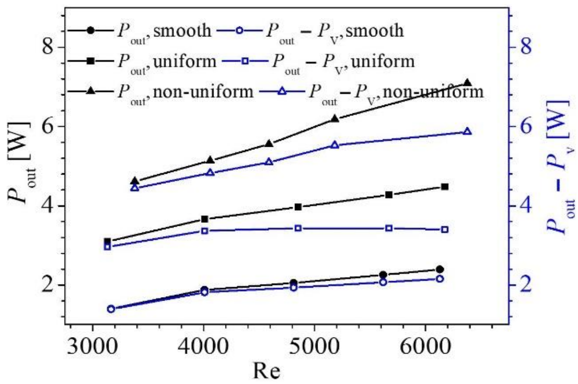


Figure 19. Comparison of power output and net power output among three TEG systems with different heat transfer enhancement elements [75]

could enhance the power output of TEG system without increasing the pumping power. However, this work only provided a preliminary design ideal for the flow-directional segmented enhancement technology, and it needs quantitative design criterion. Moreover, the combined radial and flow-directional segmented enhancement technologies may result in better improvement for the TEG system, but no report was found in open literature.

Conclusions

In the high temperature power and energy systems, there is a great potential for waste heat recovery because the temperature of exhaust gas is usually very high. The TEG system can be used to recycle the waste heat in these systems since the TE material is a solid-state energy converter. However, there is a big difference between TEG system's efficiency and TE module's efficiency. Therefore, there is a great potential to improve the whole TE conversion efficiency by optimizing the TE system. This paper reviews the recent progress on the TEG system from the view of heat transfer, including the theoretical analysis and numerical simulation on TE-hydraulic performance, conventional heat transfer enhancement technologies, radial and flow-directional segmented enhancement technologies for the TEG system. The main conclusions are summarized as follows.

- In the high temperature power and energy systems, there is large temperature diference both in the radial direction and flow direction; the Seebeck coefficient, thermal conductivity and electrical conductivity of TE materials show strongly non-linear temperature-dependent characteristics and the Thomson effect should be considered; the theoretical analysis models could provide a quick and rough prediction of thermohydraulic performance for TEG system, however, they are still limited to 1-D or 2-D analysis, which cannot reflect the 3-D characteristics of TE-hydraulic performance of TEG system; the numerical methods have made great progress on the coupled fluid-thermal-electric simulation of TEG system, especially the numerical method using the finite volume method, huge amounts of grid elements in these fluid-thermal-electric coupled models are still needed; it is necessary to develop the multi-scale numerical method for the large TEG system considered the temperature-dependent TE properties of TE materials.

- In addition to the TE material and TE module, the thermohydraulic performance of heat exchangers plays an important role on the overall efficiency of TEG system; in order to improve the overall efficiency of TEG system, many heat transfer enhancement technologies used for heat exchanger have been examined, such as turbulating inserts, integrated TEG system, LVG, pin fin, jet impingement, metal foam, silicon carbide heat exchanger, cross-cut heat sink and micro fluidic heat exchanger; it should be noted that there is a trade-off between the heat transfer and consumed pumping power for heat exchanger because a weak heat transfer may even cause negative net power output for the TEG system; especially in some high temperature power and energy systems such as gas turbine, steam turbine, micro-turbine, and automobile, the pressure losses caused by the TEG should be kept within acceptable ranges where the LVG, pin fin, and cross-cut heat sink seem suitable for these applications.
- In the high temperature power and energy systems, there is large temperature differential both in the radial direction and flow direction, but the TE materials exhibit the optimum performance only in a relatively narrow temperature range; in order to maximize the conversion efficiency, the radial segmented enhancement technologies for the TEG system have received considerable attention, but only a few works start to study the flow-directional segmented enhancement technology; according to the limited open literature, the flow-directional segmented enhancement technology seems to be a promising method for performance enhancement of TEG system, especially suitable for the applications which have strict restrictions of pressure drop; the flow-directional segmented enhancement technology, as well as the combined radial and flow-directional segmented enhancement technologies need to be further studied.

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