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Comparison of the two-stage and traditional single-stage thermoelectric generator in recovering the waste heat of the high temperature exhaust gas of internal combustion engine

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ABSTRACT

Models of two-stage serial and parallel thermoelectric generators have been established in this paper. Low-temperature thermoelectric material bismuth telluride and medium-temperature skutterudite are employed in the models and the exhaust gas of internal combustion engine is used as heat source. The properties of the thermoelectric materials are found to be temperature dependent. The performances including the output power, conversion efficiency and exergy efficiency vary with the temperatures of the heat and cold sources, the heat transfer coefficient between the hot and cold sides. The performances are influenced by the external resistances of the serial/parallel two-stage thermoelectric generators and the single-stage thermoelectric generator. The results show that the heat source temperature plays a key role in selection of the design of a thermoelectric generator when the heat transfer coefficient is more than 400 W/m^2 K. The performances of the single-stage thermoelectric generator of thermoelectric material bismuth telluride is better than those of the two stage thermoelectric generator when the heat source temperature is less than 600 K; the maximum values of the output power and conversion efficiency of a serial two-stage thermoelectric generator are 10.9% and 12.4% higher, the maximum exergy efficiency is 12.5% higher than those of the single-stage one, when the temperature of the heat source is 800 K.

1. Introduction

Environmental pollution and energy crisis have been attracting the world's attentions. The technologies of energy saving and emission reduction have been applied in various industries. The waste heat recovery has become one of important ways in automobile industry for energy saving and emission reduction. He et al. [1] made a steady-state heat balance test on FAW TOYOTA 8A-FE gasoline engine. The results showed that only about one third of a fuel's chemical energy was converted into effective work and the rest of the energy was wasted in the form of exhaust gas. Wang et al. [2] and Dolz et al. [3] analyzed the heat balance of Gasoline and Diesel engines and obtained similar results. That is to say, the quantity of the exhaust gas energy is promising. According to the research conducted by Wang et al. [4], the temperature of the exhaust gas was around 500 °C, which is of relatively high thermal quality. By effectively recycling the energy of the exhaust gas, the efficiency of ICE (internal combustion energy) can be improved, which would lead to huge economic and social benefits.

TEG (thermoelectric generation) as one of the ICE waste heat recovery technologies has an optimistic prospect [5], because it has small volume, light weight, no pollution and no moving parts. An ETEG (exhaust-based thermoelectric generator) has been developed since 1963. In the past 20 years, the thermoelectric power generation has become one of important research topics [6]. Hi-Z Company designed ETEG, which was able to produce 1 kW, but when it was applied in 14L, Cummins NTC 325 engine for the energy recovery, it was only able to produce 400 W. The target was met by the improved design [7]. Nissan company [8] used the self-developed 72 pieces of thermoelectric module recycling the energy of the gasoline engine exhaust gas, the research results showed that when vehicle climbing speed was 60 km/h, the exhaust temperature was 868 K, input and output temperatures of the TEG were 856 K and 791 K, the temperature difference was 65 K, the heat exchange efficiency of the generator from the primary exhaust gas energy flux was estimated to be 11%. The maximum temperature difference of both the hot and cold sides of the modules was 396 K and the minimum temperature difference was 372 K for the water cooling generators, the generated power through the generator was 0.9% of the energy of the heat flux, and the output power was

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35.6 W. The experimental results of 300 W produced by ETEG were published by Clarkson University and Delphi systems in 2004 in the research project funded by NYSERDA and the Department of Energy. The ETEG actually did not generate the most power since it was used in a light truck [9]. A TEG was developed by GM Ltd in the United States in 2008 in order to recycle the waste heat of the exhaust gas of an engine [10]. The test results of the TEG showed that under high speeds and the working conditions of FTP (federal test procedure), the thermoelectric generator was able to respectively recycle 350 W and 600 W of power. It was able to improve the fuel economy by nearly 5%. From a view of the current application of the thermoelectric generator in automobiles, thermoelectric generation has become one of methods for improving thermal efficiency of internal combustion engines, in the major automobile companies of the developed countries. Since the output power and conversion efficiency of thermoelectric generation are low so that it is still in development and has not been widely used. In recent years, with the development of thermoelectric materials [11], application of thermoelectric generation technology in automobiles has become one of hot research areas.

To improve the efficiency of TEG, TEM design of TEG has been studied in deep details. Shiho [12] derived an analytic model describing the internal temperature difference as a function of the load current of a TEG. Hsu et al. [13] constructed a system comprised of 24 TEGs to recover waste heat, and established a fundamental low-temperature waste heat TEG system. The TEG performance was also studied from the reversible to the irreversible by some researchers. Gou et al. [14] established a TEG model based on basic principles of TEG and finite time thermodynamics. Crane et al. [15] developed steady-state and transient models in a MATLAB/Simulink environment for high-power-density TEG. Some of researchers studied TEG from the stationary-stage to the dynamic-stage. Tilmann et al. [16] developed a dynamic model of the exhaust gas heat exchanger employing the moving-boundary principle. Meng et al. [17] developed a complete, three-dimensional and transient model to investigate the dynamic response characteristics of TEG. Shu et al. [18] combined TEG with organic Rankine cycle to recover the waste heat of ICE. Wang et al. [19] developed a heat exchanger of thermoelectric generation for the two-stage optimization to improve the performance of TEG. The TEG output power density was increased by 88.70%. Weng et al. [20] explored the relationship between the power generation performance and the quantities of TEMs. It was found that implementing more TE (thermoelectric) couples does not necessarily generate more power in total. Sahin et al. [21] studied the performance of thermoelectric generator from the irreversible point of view. The output power and conversion efficiency of TEG has a close relationship with the entropy generation.

Wang et al. [4] presented a mathematical model of a TEG device using the vehicle exhaust gas as a heat source. This model demonstrated that using the phase-change thermoelectric material could improve the performance of TEG. It disclosed that the ZT value variation depended on the temperature variation. The ZT value of thermoelectric material was closely related to the output power. During the last 50 years, a fairly large number of semiconductor materials for have been studied for thermoelectricity [11]. About ten of thermoelectric materials can be considered to have potentials for use in vehicular generators. Among these ten materials, appropriate couples of N- and P-type thermoelectric generators were selected, yielding a total of six couples of thermoelectric generators. The heat source temperature is high when using TEG to recover the exhaust gas heat of ICE. That is to say, the temperature difference of the two sides in TEM is large. Considering the nature of thermoelectric material, a model of two-stage serial and parallel thermoelectric generator will be presented where the low-temperature thermoelectric material bismuth telluride and medium-temperature skutterudite are employed and the exhaust gas of internal combustion engine will be used as a heat source, which resolves the problem of the poor conversion efficiency of TEG. Chen et al. [22] showed that the effects of the thermocouple number and the heat transfer area on the performance of the TTEG (two-stage thermoelectric generator), which was subjected to the low temperature and the variation of the thermoelectric material property with temperature. The single-stage TEM (thermoelectric model), two-stage TEM and multi-stage TEM were studied on solar thermoelectric generator by Xiao et al. [23]. Reasonable thermal design of solar thermoelectric generator took a full advantage of the characteristics of thermoelectric materials and effectively improved the power generation performance. High performance of thermoelectric module can be achieved within the large temperature difference by using a multi-stage thermoelectric module. In a word, it is possible to recover the exhaust waste heat of ICE using a two-stage TEG.

The performance characteristics of the single-stage and two-stage TEGs will be discussed in this paper where different conditions, including different temperatures of the heat and cold sources, different external resistance, and different the heat transfer coefficients on the cold and heat sides are applied. Higher conversion efficiency of a TEG design is expected from this research work, which will provide a guidance or direction for TEG to recover the exhaust waste heat of ICE.

2. Model of thermoelectric generator

2.1. Model of single-stage thermoelectric generator

Fig. 1(a) shows the model of single-stage thermoelectric generator. The TEM (thermoelectric module) consists of a number of thermocouples and thermal ceramic. Each thermocouple is composed of the P-type and N-type semiconductor legs. The TEM absorbs heat from the heat source, and then the heat flows to the cold source through the thermocouples, which leads to the temperature difference on the two sides of the thermocouples. The heat energy is then transformed into electrical energy. The TEM is connected with external resistance to form a closed circuit. Since the thermocouples are serial, the current is same for each of the thermocouples.

2.2. Model of two-stage thermoelectric generator

Thermoelectric generator consists of a lot of thermoelectric modules combined in different forms (serial or parallel). The performance of one TEM will be simulated by MATLAB in this article. The two-stage TEG has two different forms: serial (Fig. 1(b)) and parallel (Fig. 1(c)) for the top and bottom stages. The difference between the two-stage TEG and TEG is that the two-stage TEG thermocouples have two layer arrangements, materials and quantity of thermocouples in the top and bottom stages can be different, which is different from the single-stage TEG. The current of the serial TTEG is same for the top and bottom stages, while the current of the parallel two-stage TEG is independent for each of the stages. The insulating ceramic piece is inserted between the two layers, it has good thermal conductivity. The model of the two-stage thermoelectric generator is based on the materials of the medium-temperature skutterudite (P/N,$(Zn_{0.9975}Ge_{0.0025})Sb_3$ [24] /$Ba_{0.4}In_{0.4}Co_4Sb_{12}$ [25]) and the low-temperature bismuth telluride (Bi_2Te_3) [26] using the exhaust gas of internal combustion engine as the heat source. Bi_2Te_3 can be used in the material of HZ-20. These materials have higher ZT value in the range of the middle and low temperatures than others.