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Thermoelectric Power Generation for Heat Recovery in Automotive Industries

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Abstract

Researches on integrating thermoelectric power generator into various vehicle platform have witness a surge in solid demand of improving thermal efficiency and CO₂ emission reduction from automotive industries. Many prototypes were built and tested in different segments of the car. Position at exhaust gas recirculation valve and downstream of catalyst are preferred by car manufacturers as easiness of installation. Up to 4% improvement of fuel economy has been claimed under an ideal road driving cycle. Much focuses on the lightweighting of the thermoelectric power generator whilst producing stable electric power output under an intermittent working load. However, major barriers to real application still exist due to low conversion efficiency of thermoelectric material and poor heat exchanger system design. Although heat source can be high up to 800 K, actual temperature at thermoelectric legs are much less than that. Thermal losses are inevitable through the heat exchanger route and effectiveness of heat transfer become the key to system development in future. Thermoelectric material working in higher temperature could be a breakthrough and game changer for waste heat recovery in automotive industries.

Keywords: heat enhancement, exhaust heat recovery, heat pipe, thermoelectric power generation, automotive

1. Introduction

Transport represents over a quarter of Europe's greenhouse gas emissions and is the leading cause of air pollution in cities. It has not seen the same gradual decline in emissions as other sectors. According to the research, only 30% of the energy which is generated by the fuel combustion converts into mechanical power and nearly 35% of the energy expels to the ambient through the automotive exhaust system. Stricter emission regulations position automotive

industry as primary sector to improve the propulsion efficiency, and the development of exhaust heat recovery system become imminent, especially for massive light-weight vehicle on roads. The thermoelectric power generation (TEG) technology emerges as an alternative solution to the challenge of CO₂ emission reduction in this area. However, much effort on conversion efficiency and thermal design of the TEG heat exchangers are eagerly needed, and it is essential that recover this part of waste heat effectively to contribute a higher thermal efficiency of automotive engine and better fuel economy and emission. Therefore, this chapter mainly focus on the introduction of recent TEG systems, which are developed by major car manufacturers. In addition, the discussions are introduced for longstanding problems of the heat exchanger design hindering the full integration efforts.

2. Thermoelectric generator in the automotive

In transportation, TEG system turns thermal losses in the exhaust pipe into useful electric energy. This is usually the place where thermoelectric power generator can be installed. The technology can be used either on a hybrid vehicle or a conventional one wherever parasite heat loss from internal combustion engine (ICE) can be utilised properly. And it is targeted to produce electric energy either for batteries charging or for alternator starting so far. Last decades, many pioneering projects have seen such rapid developments from lab prototype to industrial demonstrators. However, it is still too early to conclude that the technology will be adopted by car manufacturers in near future. Moreover, such technology development is also shadowed by the government regulations and strategies of full electrification in this sector over next 15–20 years. Nevertheless, there is still space for innovation and development of thermoelectric materials to take advantage of their solid-state nature, scalability and environmental friendliness in the automotive industry.

2.1. Major players in automotive TEG application

During the last decade, plenty of automotive manufacturers have invested their money on the research of waste heat recovery by using TEG systems. In this section, the TEG systems presented by some leading automotive manufacturers and component supplier will be discussed including Ford, BMW, General Motors, Faurecia, FAW China.

Ford has presented a 350 W-rated power TEG system with the central bypass functionality aiming to control the temperature on its Lincoln MKT platform with 3.0 L V-6 engine. Under US06 driving cycle, the average power output is 180 W [1], according to the test data. In addition to the experimental investigation, Ford engineers also conducted 1-D performance simulation for an existing 2.5 L gas-electric hybrid vehicle. The system simulation predicted that the potential power output for this hybrid vehicle is 300–400 W under US Environmental Protection Agency (EPA) highway driving cycle. The aim of Ford is to improve the structure of the heat exchanger to enhance the heat transfer and reduce the increment of backpressure at the same time (**Figure 1**).

After 2009, most of BMW's waste heat recovery research work focused on integrating a thermoelectric generator inside the exhaust gas recirculation (EGR) cooler system. This technology could harness up to 250 W of energy [1], which is half the on-board energy need of a 5 series

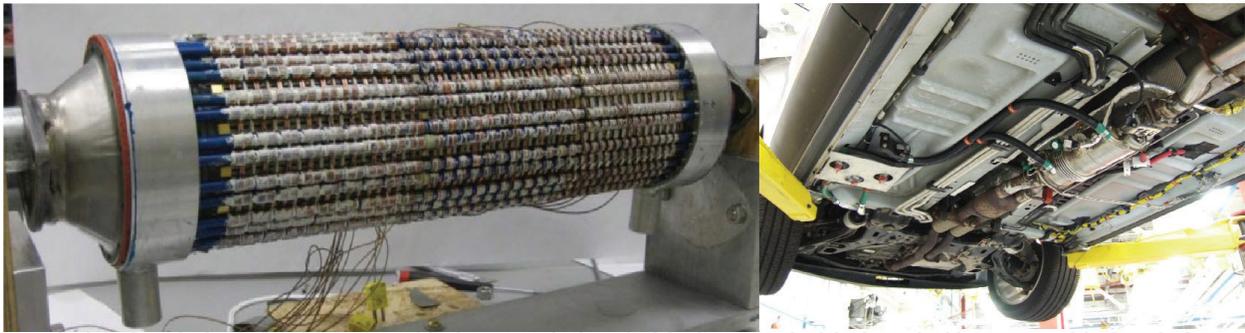


Figure 1. A prototype of Ford's thermoelectric power generator with 350 W power output [1].

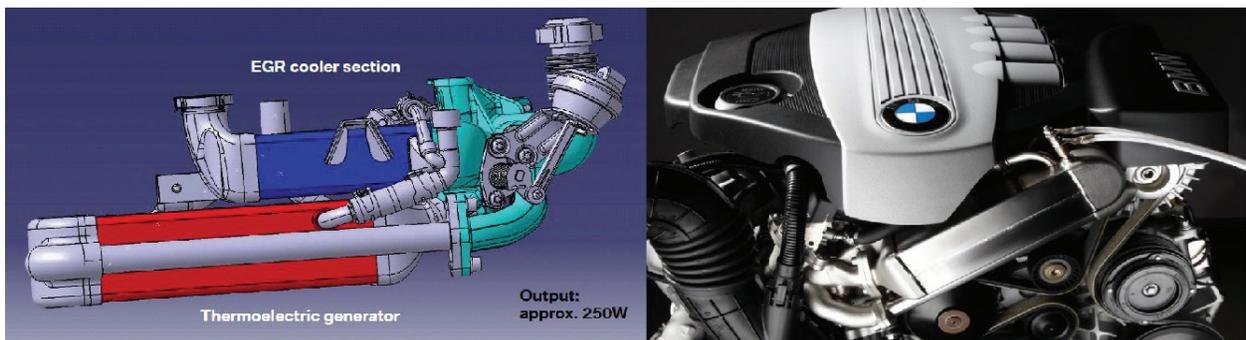


Figure 2. Thermoelectric power generator integrated with EGR cooler system.

in the 4.0 L V8 diesel engine. In terms of fuel economy, this equates to about a 2% savings in gas fuel consumption. This technology was inspired by the Radioisotope Thermoelectric Generator (RTG), which was first used in the 1960s on spacecraft by NASA (**Figure 2**).

In the past decade, General Motors has completed numerous investigation about TEG system for automobile on TE materials, system-level thermal management, efficient TEG heat exchanger design and modelling. One of the most successful achievements is the skutterudite TEMs with the figure of merit, $ZT = 1.6$ at 850 K [2]. This kind of TEM has a multiple filled p-n skutterudites TE materials which have been synthesised by the GM-TE material research group. A prototype of the Skutterudite-based TEG system was assembled and the experimental test was carried out on test rig. A maximum power output of 300 W was achieved under FTP city driving cycle and 5% of fuel economy improvement is expected from this TEG system under FTP-75 driving cycle (**Figure 3**).

The feature in lightweight and highly integration is definitely welcomed by customers. A 3 kg compact TEG system was claimed by Faurecia, which made the system can be easily installed close to the engine for extreme waste heat recovery. The Faurecia TEG system claimed to be competitive among other existing systems because of faster warm-up and increased usage of the electric mode. The system can reduce the fuel consumption up to 7% as claimed. Additionally, the technology is eligible for CO₂ off-cycle credits of 1.5 g/mile in US [3].

Furthermore, this TEG system was based on a hybrid vehicle platform, Faurecia equipped the all-new Hyundai IONIQ Hybrid and plug-in Hybrid with this TEG system, offering up to 3% fuel savings, as measured on U.S. EPA Federal Test Procedure (FTP20) (**Figure 4**).



Figure 3. Skutterudite based TEG system with a rated power output of 330 W for FTP city drive cycle.



Figure 4. Faurecia offers a compact TEG system with 3 kg weight.

China First Automobile Works (FAW), as the leading vehicle manufacturer in China, has also made great effort in the waste heat recovery technologies to keep pace with the research status worldwide. FAW has proposed a novel structured concentric cylindrical TEG system, which used annular shaped TEM and combined heat pipes to enhance the heat transfer in radial direction and total filling ratio of the whole system. According to some simulation results, the peak power output can be as high as 1.2 kW under New Europe Driving Cycle (NEDC), in the same time, the power density is 800 W/m [4]. The concentric cylindrical TEG system takes the advantages of heat pipes and acquires the uniformity with the shape of exhaust pipe to make the system much easier in matching with different platform of vehicles (**Figure 5**).

2.2. The problems of scaling up

Conventional single TEG module is usually simple in a square/rectangular shape with positive/negative leads soldering on the cold side copper interconnectors. Although the common structure of thermoelectric module is rather simple, it is very difficult to configure the small modules into a large assembly. The assembling processes usually determine the working condition, the electric and thermal contacts and the final performance of the TEG. These also include the number of total TEG modules, the electric interconnections through them (series, paralleled or hybrid), the direction of arrangement against the exhaust, the clamping method and the coolant tightness.

Usually, an electric assembly with proper sized cables is carefully designed before the structural system design. This is because that the proper electric insulation to TEG assembly is under risk of short-circuit by surrounding coolants, which may drain all the electric energy

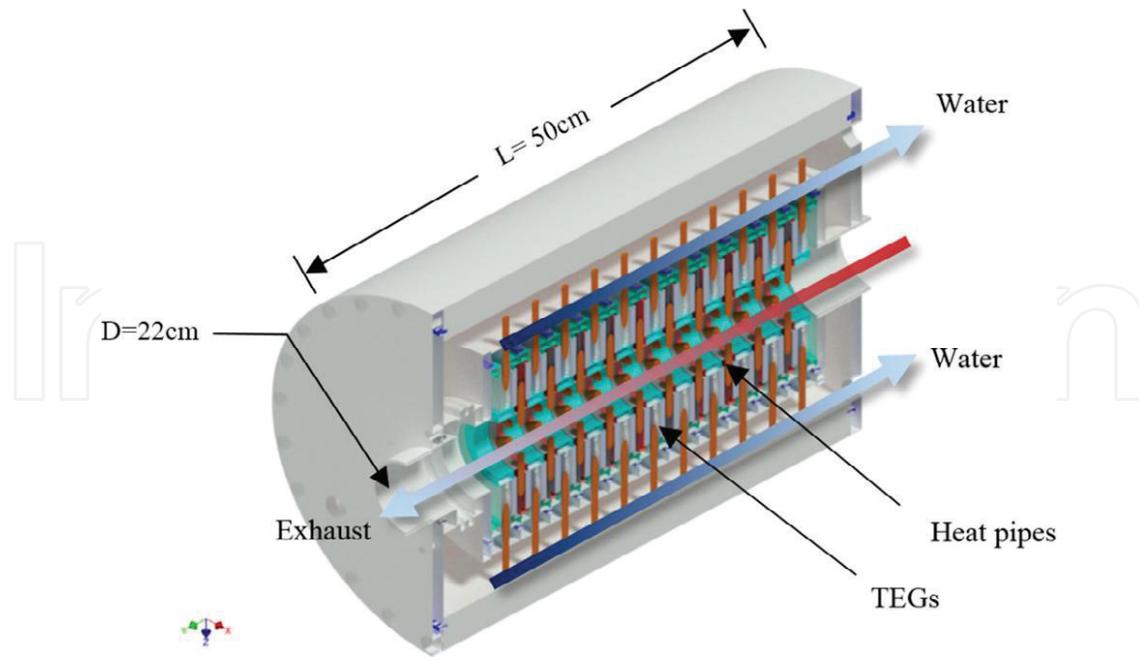


Figure 5. A heat pipe assisted and modulated TEG system offered by FAW China.

accidentally. Therefore, TEG modules should be thermally contacted other components but electrically insulated. All these issues should be carefully considered since sealing an assembly make the configuration process irreversible in most cases.

What makes the scaling up problematic is from not only TEG modules, but also the heat/cold source in the vehicle. They add extra difficulties to the final design process. As known, intermittent heat source from ICE makes heatsink temperature fluctuate. Moreover, in a typical exhaust heat recovery system, heat sink/source temperature also varies along the flow direction. Different thermoelectric materials along the exhaust flow direction may be applied in order to match each material's optimum operating temperature. The optimum operating temperature probably can be achieved by structural optimization in heatsink design. However, if the temperature varies significantly within the exhaust flow, the different types of materials should be applied to obtained higher efficiency. Additionally, sufficient thermal insulation within the whole system should be employed. Otherwise, heat leakage from the exhaust gas to the coolant will cause efficiency decline.

For example, Gao et al. [5] assessed a flat TE module with an air space in-between, which is commercially available in the market. As shown in **Figure 6**, commonly a TEM consists of several positive-type (P-type) and negative-type (N-type) that are connected by conducting strips in serials to increase the total voltage, combined with the cold and hot ceramic plates. The space between the hot and cold ceramic plates is filled by air. This air space will cause a heat loss within the TEM, as there will be heat radiation from the thermoelectric legs to the air space, which is non-negligible, even though the heat radiation is rare in TEMs. However, when it comes to the system level, a series of TEMs scaled up together, this part of radiation will cause a considerable heat loss from the hot side to cold side. As a result, the design optimization of TEM should be deliberated before the assembly of TEM.

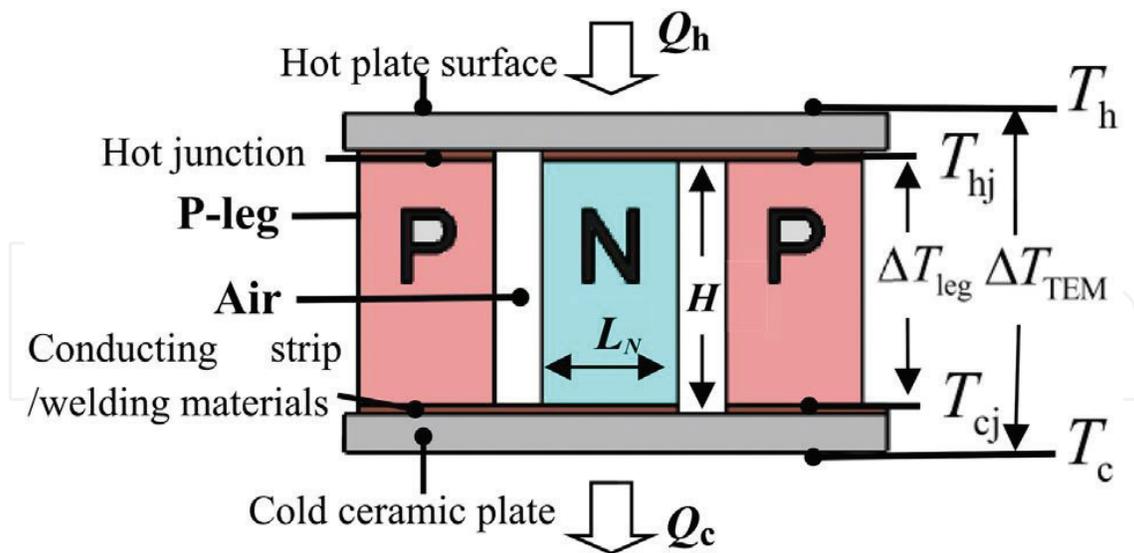


Figure 6. Mathematical models of thermoelectric module regarding the heat transfer.

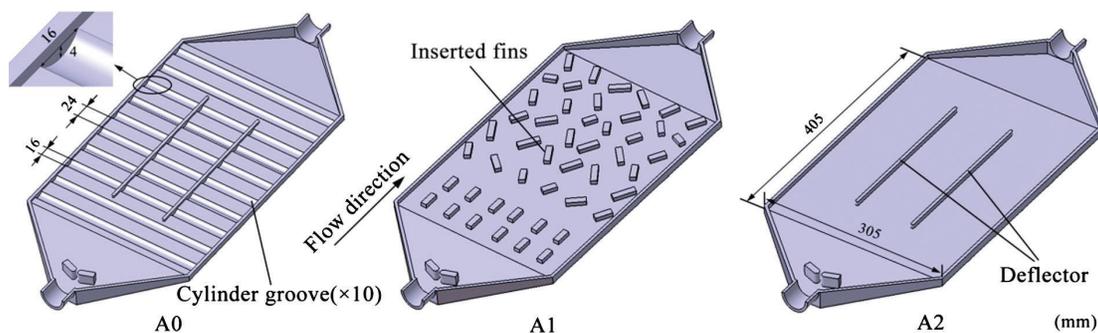


Figure 7. Topology of exhaust heat exchanger with different heat enhancement methods.

As previous researches discovered that the power output of TEG system was influenced by temperature gradient and temperature uniformity of the system significantly. Furthermore, the power output and efficiency could be improved by increasing the convection heat transfer coefficient of the high-temperature-side, but it was pricey due to the limited installation space and back pressure increment of the exhaust. Therefore, a well-designed heat exchanger will contribute to the improvement of the performance of TEG system effectively. Wang et al. [6] from Wuhan University of Technology have completed a number of investigation on the heat transfer enhancement in flat heat exchanger for TEG system [6]. The studies consisted a series of different structured heat exchanger with fins, deflectors or grooves. According to the results, by inserting fins, the heat transfer in heat exchanger could be enhanced. However it would also result in a large unwanted back pressure increment which went against to the efficiency of the engine. A heat exchanger containing cylindrical grooves on the interior surface of heat exchanger could increase the heat transfer area and enhance the turbulence intensity, meanwhile there was no additional inserts in the fluid to block the flow. Compared to flat surface, cylindrical grooves in exchanger could decrease the thermal resistance and enhance the power generation of TEG with nearly the same back pressure. Fins could greatly enhance the heat transfer and power generation of TEG, but the additional pressure loss was also great (Figure 7).

2.3. The potential integration of TEG system with mufflers or catalytic converters

Since the economics of thermoelectric power generation depends on the nature of the heat source, there is an increasing awareness of deep integration among undergoing research projects. Moving thermoelectric power assembly closer to the ICE will certainly enhance the TEG performance. Inevitably, stricter requirements of TEG have to match working condition both muffler and thermoelectric power generators when such integration happens. One apparent advantage of such integration is the cost reduction of manufacturing.

Mufflers are used for noise reduction emitted by the exhaust of an internal combustion engine. It usually consists of several perforated tubes inside the shell. The structure of muffler is similar to the common shell and tube heat exchanger. In that case, it inspire a natural thinking of integrating two separated components into one functional device. Therefore, the integration can be achieved by redesign the muffler structure with added TEG modules on the inner surface of the shell. Double layered shell may accommodate coolant loop to cool the TEG modules. Nonetheless, both noise reduction and TEG assembly performance have to be re-evaluated under such circumstances.

At present, most of the TEGs installed in the exhaust pipe system are located after the catalyst converter. The simple reason is that the exhaust emission treatment is prior to energy recovery process. However, the high temperature will decrease roughly by 100 K through the catalyst converter. If TEG developer would like to harness higher-grade heat from exhaust, the integration with catalyst converter is sensible but difficult. Inside catalyst converter, there are two functional components including reduction and oxidation process. Both components are coated perforated structures with 600 mesh number or higher. Therefore, fundamental changes in combined structure are needed and effects of harmful gas on the TEG modules need investigation in future work.

3. Heat transfer enhancement options in vehicle

Unlike common circumstances, thermoelectric power generator in the vehicle has to work under a constant moving condition. Even if thermoelectric materials with high ZT are developed, there are still many system-level challenges to implement them into automotive applications. Especially, only ambient air is available as the eventual cold source for the thermoelectric power generator no matter what intermediate coolant adopted. Thermal systematic design is the key to match optimum heat flux between heatsinks and thermoelectric modules. Key innovations are urgently needed from not only material development but also the holistic system design. In this section, we discuss heat transfer related issues in thermoelectric modules and systems in the context of automotive applications.

3.1. Heat transfer in thermoelectric device

Layers in thermoelectric modules are thermal resistances such as interconnectors, solders and electric insulators. Considerations of minimising them without losing mechanical and electronic performance will benefit the overall system design. In exhaust pipeline, exhaust temperature ranges from 150 K to over 800 K, the added thermal protection from thermoelectric layers

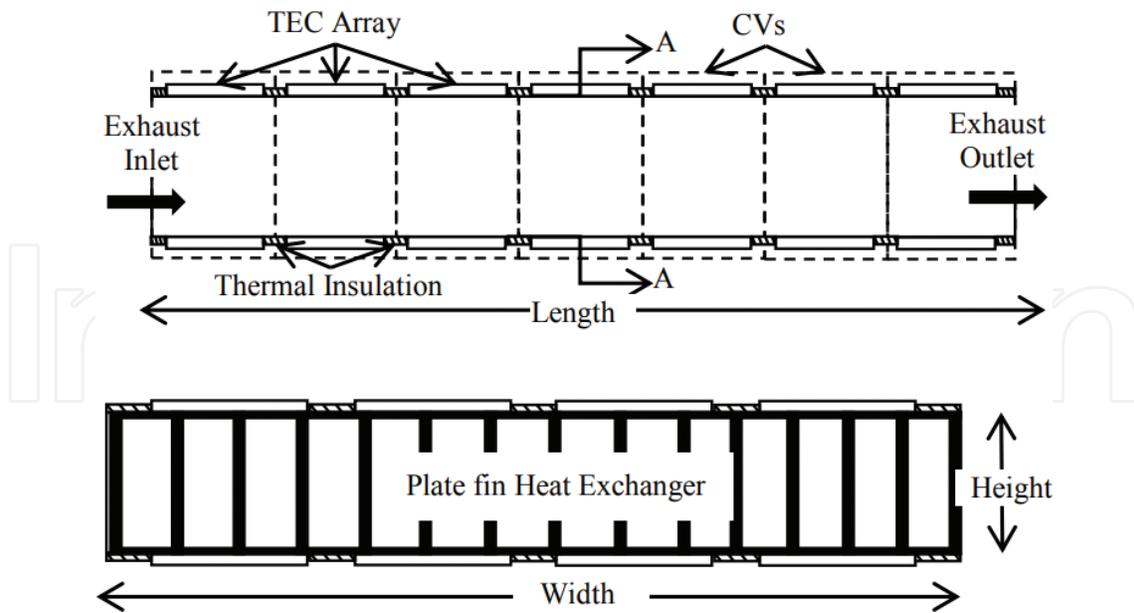


Figure 8. Schematic of TEG device configuration with plate fin heat exchanger.

inevitably become the source of parasitic loss, which leads to reduced system power output and conversion efficiency. High temperature durability for thermal layers is the key to position thermoelectric modules closer to the engine.

Kumar et al. [7] have investigated the overall heat transferred, the electrical power output, and the associated pressure drop for given inlet conditions of the exhaust gas and the available TEG volume by using a rectangular configuration TEG system. In this system each TEM is mounted on the top and the bottom surface and arranged uniformly over 80% of total surface area. The remaining 20% area and the lateral walls are thermally insulated to minimise heat leakage. As shown in figure, the plate-fin heat exchanger is applied in the TEG system and there are several transverse fins distribute along the hot channel of heat exchanger. Moreover, the inlet and outlet of the hot channel of heat exchanger are connected to the engine exhaust pipe. According to the results, TEG power output is observed to have strong relation with the mass flow rate and inlet exhaust temperature. It was found that, at the average inlet conditions, up to 64% of the inlet energy can be transferred through the thermoelectric modules, resulting in a power output of 552 W, approximately 3.33% of the inlet power (**Figure 8**).

Zhou et al. [8] proposed a newly designed TEG with cylindrical shell and straight fins to overcome the common defects of conventional TEG system. They established a two-dimensional heat transfer numerical model under steady-state conditions and utilised this model to predict the performance of the TEG system in different working conditions. As shown in figure, the newly designed TEG system is compact in structure and can be arranged between catalytic converter and the muffler to make it effective in the recovery of waste heat. The TEMs and heat transfer fins are in direct contact, avoiding the exhaust tube structural transformation, and it will not cause any influence on the engine exhaust back pressure. The cooling tubes are branches of the engine cooling system, and the engine coolant flows into the tubes to cool down the cold sides of TEM (**Figure 9**).

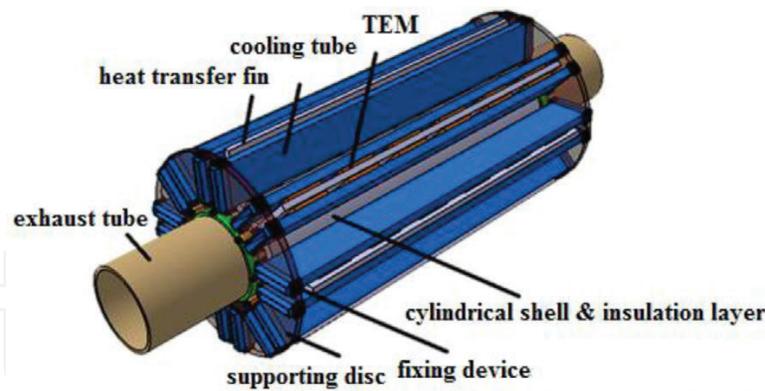


Figure 9. Radial TEG arrangements for exhaust heat recovery.

In order to enhance heat transfer between the exhaust gas and the hot side of TEM, Li et al. [9] have applied foam metal to fill in the space of the exhaust pipe. By filling foam metal within the exhaust pipe, the convective heat-transfer coefficient is increased by 4 times, meanwhile, the back pressure of the exhaust system do not boost significantly (Figure 10).

Another innovation may come from polymer with function of flexibility. The pipeline shape and exhaust assembly method make such demands speciously since car manufacturers are reluctant to fundamentally change the overall looking of the pipe, and it may involve the adjustment of chassis to accommodate irregular thermoelectric modules.

3.2. Heat transfer in vehicle system

When considering the installation of thermoelectric modules to the vehicle, the complexities of material configuration, clamping methods, heat sink structures, installation positions, flow resistance to the backpressure and overall cost make major car manufacturers hesitant to fully embrace this heat recovery technology. All these issues are related to the heat transfer in a powertrain system, a major research area that system specialist make enormous efforts to solve. To make use of scalable feature for large energy demands in the vehicle, careful system design are required including technical and cost considerations.

When developing a thermoelectric system including heat exchangers, heat flux through the thermoelements should be large enough to maintain the appropriate temperature difference. The general heat flux through thermoelectric legs is 100 kW/m^2 , assuming that the height of thermoelectric leg is 1 mm, then the temperature gradient should be 100°C .

It could be achievable that we can deliver this level of heat flux by concentrating the heat at hot and cold side of TEM with fins or any other heat transfer enhancement methods. Therefore, the structural optimisation of TEM and heat exchanger is critical and both of them should be developed to match the high density of heat flux.

In addition to the previous work, Kumar et al. [10] have completed more investigation on the influence of heat exchanger and thermoelectric module configurations to achieve optimization of the TEG system. As shown in figure, they presented four different structured heat sinks to compare the performance between them. The topologies having a rectangular

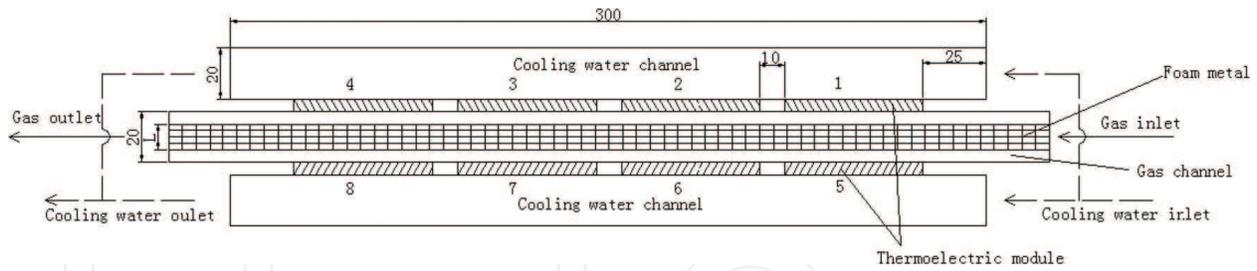


Figure 10. Heat enhancement method by filled metal foam into exhaust pipe.

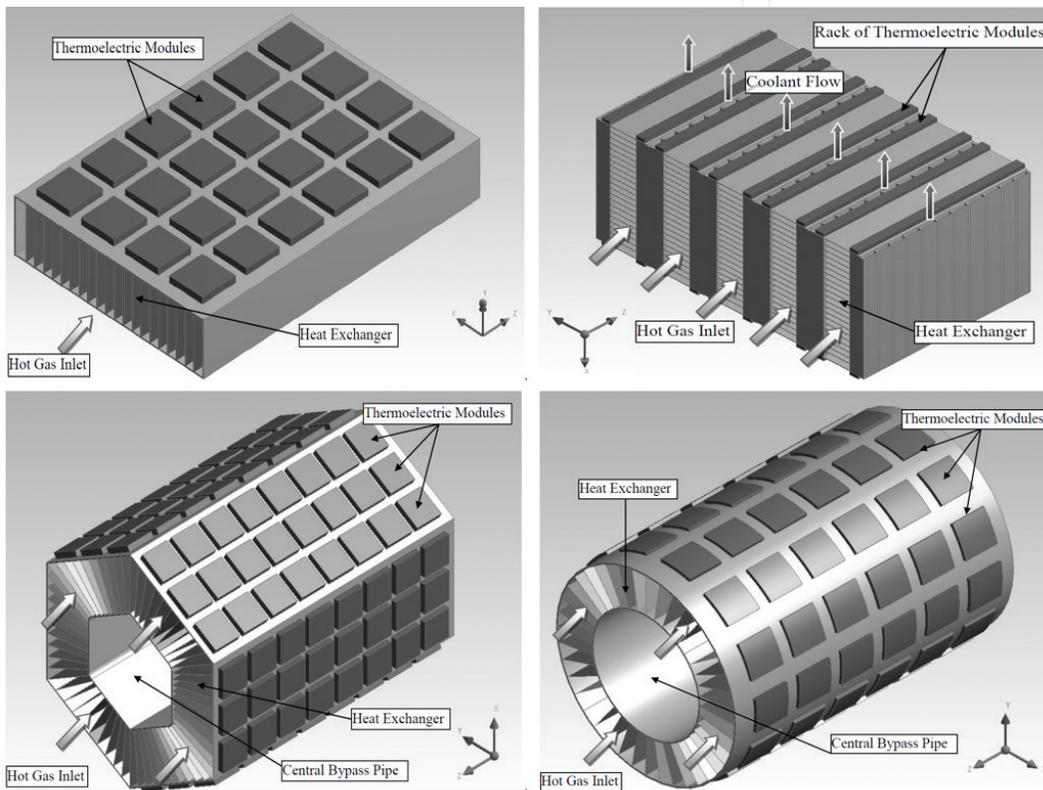


Figure 11. Various Heat exchanger structures for exhaust pipe adjustment.

box-like shape are grouped as rectangular topology. The names of the model—longitudinal and transverse—are derived from the way the TEMs are placed with respect to the exhaust flow direction. Two types of circular configuration: regular hexagon and cylinder are also presented for comparison. These models are similar to the longitudinal model except the cross-section is hexagonal or cylindrical (Figure 11).

All topologies behave somewhat similarly at lower numbers of TEMs in terms of electrical generation. However, the performance of the hexagonal and cylindrical topologies suffers when the number of TEMs exceeds 40 owing to large pressure drops. Overall, the transverse design shows better results in the heat enhancement and power output comparing with longitudinal designs. Furthermore, if the width of the transverse heat exchanger equals to the

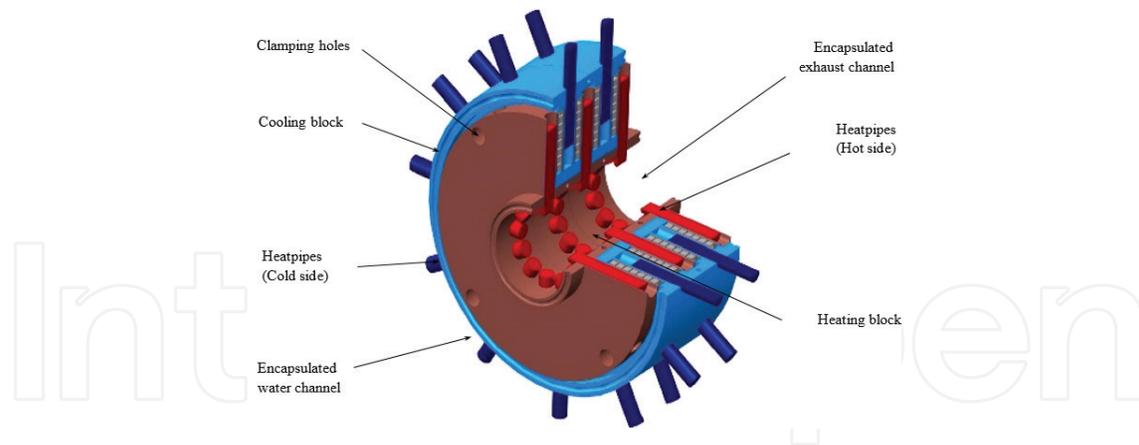


Figure 12. Simplified heat pipe assisted exhaust heat recovery system for concentric TEG device.

length of a single TEM, the TEG system will obtain the highest electrical power output with lower pressure drop among other designs.

Heat pipe-assisted heat enhancement method is approved to be an effective way to improve the TEG performance. Encapsulated heat pipes arrays in the radial direction of the exhaust pipe help to enhance heat effectively from an external fluid stream. The features of heat pipes such as temperature flattening, temperature control and thermal diode, may help TEG modules for autonomous, maintenance-free operation under fluctuating heating sources in the future. The spatial distribution of the temperature rise is considerably responsive by the variation of heating condition from exhaust streams.

In order to get a better filling ratio, Bo et al. [11] from University of Nottingham have presented a concentric cylindrical TEG system consists of a series of repeat units that are conjugated along the exhaust stream to shape of the exhaust pipe. As shown in the figure, the repeat unit is made up of four concentric TEMs, three hot plates and two cooling plates including 12 heat pipes. The exhaust stream interacts with heat pipes and transfers the heat into the TEG in the radial direction of the exhaust stream. Comparing with some commonly used TEG system, the concentric cylindrical TEG system gain a better filling ratio by such configuration. Furthermore, in this system, a compact and lightweight heat sink which is assisted by heat pipes is introduced. The merits of utilising heat pipes in the system are explored regarding the improvement of heat transfer in radial direction and the simplicity of system integration. Besides, the combination of heat pipes reduce the weight of the TEG system as well, consequently improving the fuel economy (**Figure 12**).

Lu et al. [12] investigated the effect of distribution consistency of the interceptor on the performance of heat transfer enhancement for the TEG system. The results showed the non-uniform configuration of the interceptor can lead to approximately doubled power output than smooth channel heat exchanger. However, the pressure drop which governs the pumping power of heat exchanger need to be concerned carefully (**Figure 13**).

Liu et al. [13] built a test bench for examining the performance of TEG system which is assembled into a prototype vehicle. Through the revolving drum test bench, the characteristics of

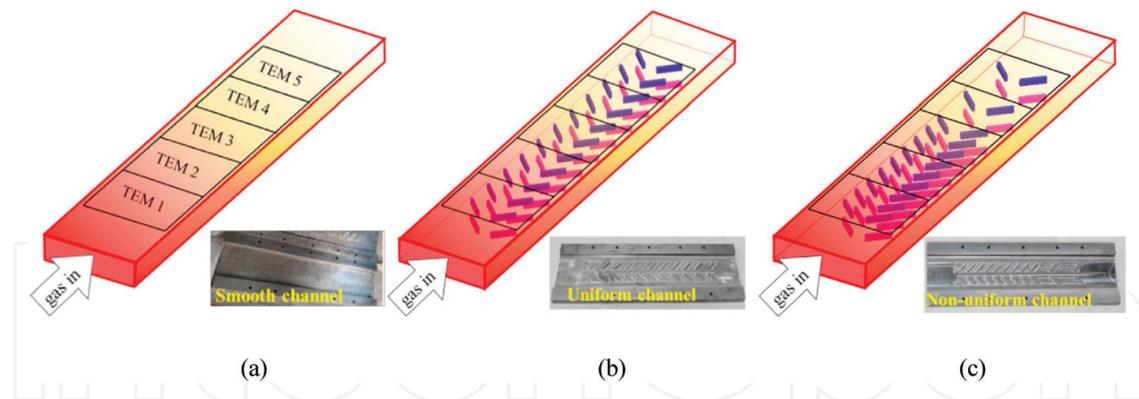


Figure 13. Fin arrangement studies for heat transfer enhancement in TEG heat exchanger.

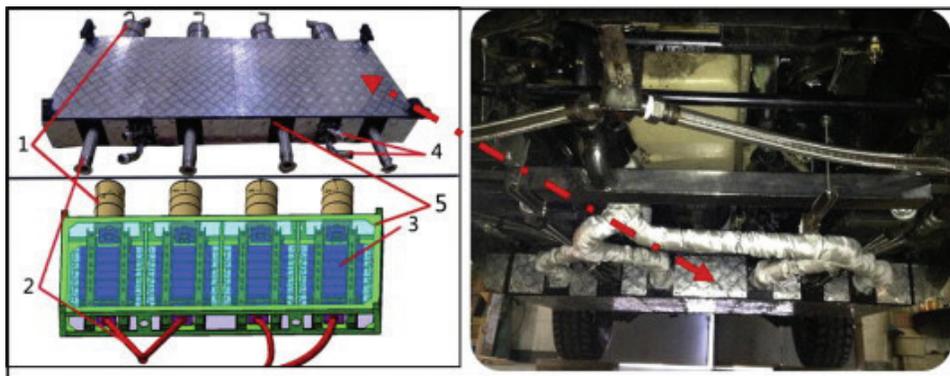


Figure 14. Multi cross flow arrangements for TEG heat exchanger.

the TEG system can be measured, and a maximum power output of 944 W was obtained, which can fulfil the power for some accessories in automotive application (Figure 14).

4. Challenges

High ZT pursued by TE community is not the only case for real automotive application. A high ZT with a limited temperature range is not favoured since varying heat source temperature results in low efficiency in most of time. In addition, conversion efficiency may not sit in the centre of the concern, high power density is the main factor in automotive application same as request for traction battery. Here we organised three main factors for consideration of TE selections including the limited space under chassis, the low power density and the real reliability under an all-weather condition.

4.1. Limited space

Although TEG technology is favoured in the lightweight vehicle, it is still challenge to spare a space for it. Changing the exhaust piping system is usually subject to the chassis design, which involves weight balancing, powertrain system structure and brake force distribution, etc.

Unfortunately, it is not the option for most of car manufacturers. Moreover, the TEG heat recovery system should be ideally designed in a cylindrical shape as much same as the exhaust pipe.

In order to minimising the extra coolant loop or heat sink, extra coolant pumping power should be considered when routing the loop in/out of the TEG system. A proportional electric gas valve is usually integrated with TEG system in order to adjust the bypass flow of the exhaust. In some cases, a DC-DC converter or a DC-AC converter has to be positioned close to the TEG system with extra electric cabling and connection work.

Inevitably, all the added up functional components mentioned here occupy significant space. To squeeze such TEG system into a highly-packed and harsh environment is not always an easy task for the system designers.

4.2. Power density

Power density is usually the main concerns that car manufacturers focus on. Every car manufacturer pursues highest power output in a certain weight. At present, the threshold of power output in automotive market is 1 kW per unit. In other way, the thermoelectric have to obtain at least 10 kW heat energy from the exhaust given that most of current system efficiency are less than 10%. It is a dilemma for TE material scientist and thermal system designer. To maintain such power density, system designer have to find ways to deliver sufficient heat to the TE material. Material scientist have to tune the TE into best power output capacity within a defined space.

4.3. Reliability

The lifespan of a common passenger car can reach over 25 years or more. Although no moving parts in the TEG system, TEG system exposes to an extremely varying thermal cycling condition. Tiny cracks between soldering layers and metalized layer will decrease the efficiency and cause mismatched resistive load. In addition, the clamping is prone to failure under a shock or vibration. Unfortunately, there is little research in this area but it should be included in any road test in future.

Nonetheless, considering major services in certain intervals and payback time for the customer, it is crucial for TEG developer to define the business model for selling this technology in term of installation cost and repair cost.

5. Conclusion

In this chapter, the latest progress on TEG exhaust heat recovery is introduced. The technology is still the favourite solution for lightweight vehicles until final phase-out of fuel-powered combustion engine in the middle of the twenty-first century. It is worth mentioning that automotive engineering is a process of system engineering, all the potential applicable technology should be evaluated in the context of specific vehicle platform. There is no exception for the TEG technology. Due to the nature of internal combustion engine, the heat source varies from

exhaust temperature, torque load and even climate condition. The energy demands in passenger car is very different with heavy-duty truck in respect of fuel economy. To help the decision making of go/no-go in automotive, further material researches on higher power density and economic TE material are necessary. For TEG heat recovery system, heat exchanger designers should focus on the heat enhancement to match the heat flux through TE materials.

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