The role of thermoelectric generator in the efficient operation of vehicles

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The Role of Thermoelectric Generator in the Efficient Operation of Vehicles

by

Song Lan

A Doctoral Thesis

Submitted in partial fulfilment of the requirements for the award of

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I
Abstract

In the face of the internationally tightened requirements and regulations for CO$_2$ emissions from the transportation sector, waste heat recovery using a thermoelectric generator (TEG) has become the most significant research interest. A vehicular TEG, converting otherwise wasted thermal energy from engines to electricity directly for use in the vehicle systems, is a promising approach for vehicle original equipment manufacturers (OEMs) to reduce fuel consumption and lower CO$_2$ emissions.

This thesis aims to explore the main challenges to be faced in the commercialisation of TEGs. Based on a review of the literature, four research gaps have been identified, which are respectively:

- Translating the material improvements into TEG Performance,
- Transient behaviours of vehicular TEGs under driving cycles,
- Fuel saving percentage and cost-benefit estimation of TEG,
- Bidirectional characteristic of TEM and bifunctional vehicular TEG.

To directly address these research gaps, a quasi-static TEM model, a dynamic TEG model, a semi-empirical vehicular TEG model, and a dual-model TEM model have been respectively developed and validated through experiments on both TEM test rigs and TEG engine test benches. These developed models are used as tools to investigate the performance of TEG, parameters sensitivity, and integration effects. Model-based TEG control, TEG cost benefit ratio and feasibility of a bifunctional TEG are also explored based on the developed models.

The simulation results show that TEG power generation is highly sensitive to the heat
transfer coefficient of hot side heat exchanger and thermal contact resistance. The TEG installation position is identified as the most important integration effect. It has been found by the simulation result that the fuel saving with TEG installed upstream of the three-way catalyst (TWC) is 50% higher than the fuel saving with TEG installed downstream of the TWC. The fuel saving percentage for a skutterudite vehicular TEG, which can generate around 400-600W in constant speed 120km/h, is 0.5-3.6% depending on the integration position in the exhaust line. A 3-minute faster warm-up effect of engine oil can be obtained when the bifunctional TEG works in engine warm-up mode with electrical current applied.

Keywords:

thermoelectric generator, waste heat recovery, dynamic model, fuel economy, engine warm-up
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Chapter 1

Introduction

This chapter provides an overview for the global CO\textsubscript{2} legislation and vehicle electrification. The potential of using waste heat recovery systems in vehicles has been analysed. The various techniques, including the thermoelectric generator, employed in the design of a waste heat recovery system for vehicles are discussed. The comparison of these waste heat recovery methods emphasizes the aims and objectives of the thesis. The outline of the thesis and the interconnection between chapters are presented at the end of this chapter.
1.1 Research Background

1.1.1 CO\textsubscript{2} Legislation

Based on the global greenhouse gas (GHG) emissions report of 2014 from the United States Environmental Protection Agency (EPA) [1], if the GHG emissions continue to increase at the present rate, earth’s surface temperature could exceed historical values as early as 2047, with potentially harmful effects on ecosystems, biodiversity and the livelihoods of people worldwide. The 2014 report on climate change from the Intergovernmental Panel Protection Convention (IPPC) [2] investigated the GHG emissions by different sectors, which can be seen in Figure 1.1. The transportation was one of the sectors that contributed 23% of the GHG emissions, which was the second largest sector. The majority of the transportation sector emissions were generated by cars (light-duty and heavy-duty vehicles). The light-duty vehicle was the largest source of CO\textsubscript{2} emission within the transportation sector and accounted for 40% of the total GHG emissions in transportation sector. These estimates are likely to increase even more under the pressure of the increasing global population and expanding vehicle fleet [3]. One of the main reasons for the large amount of CO\textsubscript{2} emissions from the transportation sector is the use of inefficient internal combustion engines (ICEs) in the vehicles [4]. Because of these, in the past few years, governments around the world have published a series of CO\textsubscript{2} regulations for vehicles.
Table 1.1: Fuel economy and GHG standards for vehicles around the world [3]

<table>
<thead>
<tr>
<th>Country/region</th>
<th>Test Cycle</th>
<th>Measure</th>
<th>Year</th>
<th>Target</th>
<th>Penalties</th>
</tr>
</thead>
<tbody>
<tr>
<td>United States</td>
<td>U.S CAFE</td>
<td>Fuel</td>
<td>2016</td>
<td>36.2mpg</td>
<td>Economical fines &amp; Sales restriction</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>2025</td>
<td>56.2mpg</td>
<td></td>
</tr>
<tr>
<td>European Union</td>
<td>EU NEDC</td>
<td>CO₂</td>
<td>2015</td>
<td>130g/km</td>
<td>Economical fines</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>2020</td>
<td>95g/km</td>
<td></td>
</tr>
<tr>
<td>Japan</td>
<td>Japan 10-15</td>
<td>Fuel</td>
<td>2015</td>
<td>16.8km/L</td>
<td>Economical fines</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>2020</td>
<td>20.3km/L</td>
<td>&amp; Public proclamation</td>
</tr>
<tr>
<td>China</td>
<td>EU NEDC</td>
<td>Fuel</td>
<td>2015</td>
<td>6.9L/100-km</td>
<td>Economical fines</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>2020</td>
<td>5L/100-km</td>
<td>&amp; Public proclamation</td>
</tr>
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In 2013, over 70% of the global market for passenger cars was subject to automotive CO₂ regulations [3]. It has been proved in many regions and countries that increasing the fuel economy standards for vehicles is one of the most effective tools in controlling GHG emissions from the transportation sector [5]. Table 1.1 provides a detailed overview of countries and regions that have proposed vehicle fuel economy or GHG emission standards for passenger cars. In the EU, the law requires that by 2020, the fleet average to be achieved by all new cars is 95 grams of CO₂ per kilometre. In the US, the Environment Protection Agency (EPA) and National Highway Traffic Safety Administration (NHTSA) raised the requirement for fuel economy of new passenger vehicles to 54.5 miles per gallon for the years 2017-2025. In Japan, the Top Runner program set 20.3km per liter of fuel as the fuel efficiency target of passenger cars for 2020. China introduced fuel economy standards for light duty passenger vehicles targeting a fuel consumption of 5L/100km by 2020. When comparing automotive CO₂ regulations across countries and regions, different test cycles, penalties, time frames, fleet target, and calculation method have been proposed. Although there is not a uniform global approach to regulate the automotive CO₂ emissions, the CO₂ emissions standard and fuel economy requisitions are becoming increasingly stringent around the world.

To meet these tightening regulations, car original equipment manufacturers (OEMs) are currently emphasising the efficiency of the conventional internal combustion engines (ICEs) and drivetrain while exploring for alternative powertrains that will ultimately replace the conventional ICEs. Many new technologies have been rapidly developed and introduced in
the market such as hybrid vehicle, electric vehicle, dual clutch transmission, variable valve timing, starts-stop system, gasoline direct injection. Despite these improvements, a great proportion of the waste heat from ICEs is still lost. Compared with already widely optimized engine control and mechanical drivetrain, the exhaust gas still offers a high potential for waste heat recovery (WHR). Waste heat recovery is recognized as a future technology potentially relevant to reaching the fuel economy and CO₂ emission goals [6]. The potential of vehicular WHR and its methods that are currently applied in vehicles are both presented in Section 1.2 Research Motivation.

1.1.2 Increased Electrification in Vehicles

A key trend in development of vehicle systems is the increased electrification [4], which can be seen in Figure 1.2. The electrification does not necessarily mean solely battery electric vehicles, but it also includes the electric power needs driven by conventional ICE vehicles for enhanced driving experience, safety and efficiency. This includes the introduction of
automatic transmission, electric power steering, electronic fuel injection, electro-mechanical brakes, electronic stability control and navigation system. For the conventional ICE vehicles, the increased electric power requirements are beyond the capabilities of the current alternator and require supplemental electrical generation [8]. In addition, the efficiency of converting fossil fuels into electric power is relatively low. The efficiency of fuel energy conversion into mechanical energy is around 25-27%. The efficiency of mechanical energy conversion (alternator) into electricity is about 60%. This means that the efficiency of transformation of fossil fuels into electrical energy is around 15-16% [9]. Therefore, the increased electric power output from alternator is contrary to the ever more urgent demands for cuts in CO₂ emissions. One potential solution to this problem is the recuperation of energy from exhaust gas using WHR methods to support the on-board vehicle electric system. For conventional ICE vehicles, the regenerated electric power can be used to relieve the load of alternator or to support electrical auxiliaries.

The UK government announced that new diesel and petrol cars and vans would be banned in 2040 in a bid to tackle air pollution [10]. This announcement will shrink the market share for the conventional ICE vehicles and accelerate the shift towards full and hybrid electric vehicles. Hybrid electric vehicles can also use the regenerated electric power to directly assist with vehicle propulsion. Study has shown that although the average electric power recovery in conventional ICE vehicle is higher than hybrid ones, the hybrids has the greatest fuel economy improvements by using WHR technology because of its effective use of the recovered energy [11]. Therefore, the increased electrification in vehicle system makes the electric recovery from WHR more useful and attractive for both conventional ICE vehicles and hybrid vehicles.

1.2 Research Motivation

1.2.1 Waste Heat Recovery Potential in Vehicles

To investigate the potential of WHR, it is important to understand how the chemical energy of the fuel is distributed at first. Figure 1.3 shows a typical energy flow path of an ICE [12]. Only about 25% of the fuel combustion can be converted to useful shaft work, whereas 70%
of the energy is either discharged in the exhaust gas or in the coolant. This is partly a consequence of gas exchange process in the internal combustion engine, which needs to be initiated when there is still substantial energy content in the products of combustion. Due to the large percentage of energy in exhaust flow path, being able to turn even a small amount of waste energy into useful energy would be a big step in the right direction of improving engine fuel economy and meeting CO₂ reduction target.

Due to irreversibility and ambient condition, not all the exhaust thermal energy can be recovered and only a percentage of the exhaust thermal energy is available for utilization. The term available energy refers to the available energy for work production, which can be estimated by specific exergy. The specific exergy can be used to predict the maximum theoretical work which can be obtained when a system of interest interacts with a reference environment to equilibrium. The notions of specific exergy are well established and developed in the references [13, 14]. The specific exergy of exhaust gas in a given instant is simply defined as follow [14]:

\[ e = c_{exh} [(T_i - T_o) - T_o \ln(T_i/T_o)] \quad [J/kg] \]  

(1.1)
$T_i$ and $T_o$ are respectively the exhaust gas temperature and environment temperature. $c_{exh}$ is the specific heat of exhaust gas. The instantaneous exergy rate of exhaust gas $E$ can be computed by multiplying the exhaust mass flow $\dot{m}_{exh}$:

$$E = \dot{e}_{exh} = \dot{m}_{exh} c_{exh} \left[ (T_i - T_o) - T_o \ln(T_i/T_o) \right] \text{ [W]} \quad (1.2)$$

To further quantify this available thermal energy that could actually be converted to useful work in the exhaust flow and analyse the potential of WHR in vehicles, an exergy analysis is done based on the exhaust data for a gasoline and a diesel engine of light-duty vehicles [8, 14, 15].

Figures 1.4 and 1.6 respectively present the exhaust temperature profile of gasoline and diesel engines of BMW 3-series at steady-state of full load and part load operating conditions [8]. As can be seen from Figures 1.4 and 1.6, the exhaust temperature varies at different positions of exhaust system. The exhaust gas temperature of the gasoline engine is usually higher than that of the diesel engine. However, the exhaust mass flow rate of gasoline engine tends to be lower than diesel engine. Based on the temperature profiles and mass flow rates, the instantaneous exergy rates of exhaust gas $E$ at environment temperature $T_0 = 20^\circ C$ are calculated and plotted in Figures 1.5 and 1.7. These figures show the available thermal energy at different positions of exhaust system when the gasoline and diesel engine is running at full load and part load. The available thermal energy in the gasoline and diesel exhaust system are respectively in the range of 0.2-15 kW and 1.1-18 kW, which depends on the locations of exhaust system and engine load. The available thermal energy for both engines are relatively higher when they are located closer to the exhaust manifold at full engine load.

Since the big differences of available thermal energy at steady-state of full engine load and part engine load, the instantaneous exergy of the exhaust gas with frequent variations at dynamic driving cycles has also been calculated. Figures 1.8 and 1.10 respectively present the exhaust temperature and mass flow rate of the two engines running a New European Driving Cycle (NEDC). The speed profile of the NEDC can be seen in Appendix A. The instantaneous exergy rates of exhaust gas at environment temperature $T_0 = 20^\circ C$ are calculated and plotted in Figures 1.9 and 1.11. The figures show that the available energy fluxes in the exhaust system of a gasoline engine and a diesel engine respectively lie in the range
Figure 1.4: BMW 3-series exhaust temperature profiles of a gasoline engine at steady-state [8]

Figure 1.5: Available exhaust thermal energy at the gasoline engine exhaust system of BMW 3-series at steady-state [8]
Figure 1.6: BMW 3-series exhaust temperature profiles of a diesel engine at steady-state [8]

Figure 1.7: Available exhaust thermal energy at the diesel engine exhaust system of BMW 3-series at steady-state [8]
Figure 1.8: Exhaust temperature and mass flow rate downstream of the three way catalyst for a 3L-BMW-gasoline engine [14]

of 2-10 kW and 1-8 kW for light duty vehicles running NEDC. The exergy fluxes of both engines are characterized by wide scatter, mainly induced by the highly transient variation in exhaust gas flow and the heating and cooling effect of the engine. The average available energy has also be calculated. During the urban drive, the average available exhaust exergy fluxes in the gasoline and diesel engine are respectively at 0.8 kW and 0.3 kW. They increase to respectively 2.8 kW and 1.6 kW over the extra-urban cycle. The reason for these differences is that during the urban cycle, engines operate mostly at idle speed and low load conditions, therefore the corresponding exhaust exergy is relative lower. However, when it comes to the extra-urban cycle, engines operate mostly at high load or even full load conditions, the waste thermal energy is significantly higher.

The calculation of the available thermal energy in the exhaust gas of both gasoline and diesel engines leads to a conclusion that the available thermal energy varies at different positions of the exhaust systems. The operating conditions of the engines have significant influence on the potential of WHR. The potential of WHR is greater when the engine works at high speed and full load condition.
Figure 1.9: Available exhaust thermal energy at the outlet of three way catalyst for a 3L-BMW-gasoline engine

Figure 1.10: Exhaust temperature and mass flow rate between the diesel oxidation catalyst and diesel particulate filter for a 2L-Nissan-diesel engine [15]
Figure 1.11: Available exhaust thermal energy between the diesel oxidation catalyst and diesel particulate filter for a 2L-Nissan-diesel engine.

1.2.2 Overview of the Waste Heat Recovery Methods

Due to the great potential of WHR in vehicles and emission legislations, many efforts have been made in this field during the last few years. Several effective methods have been found, which include turbo-compounding (TC), Rankine cycles (RC), thermoelectric generators (TEG), Stirling engine and thermochemical recuperation (TCR). The basic principle of all these WHR technologies is to recover the waste heat from ICEs by exchanging the energy with other materials or fluids or by converting to another form of energy. This section gives a short description of the working principles as well as an overview of the current development of these WHR methods.

Turbo-Compounding (TC)

Turbo-compounding (TC) technology is a commercially-ready technology for the vehicular WHR [16], which reduces the fuel consumption of ICEs by recovering waste energy in the exhaust gas. The recovered energy by the power turbine can be transmitted either to the engine or to an electrical generator. Based on this difference, the turbo-compounding is divided
into two types: mechanical turbo-compounding (MTC) and electrical turbo-compounding (ETC). Previous studies revealed an average of 5% fuel economy improvement for a driving cycle and a maximum of 9-10% fuel economy improvement can be expected when using high efficiency turbocharger components [16]. The main disadvantage of TC is the increased back pressure on the engine as the expansion ratio of the power turbine increases.

Figure 1.12 shows a scheme of a turbo-compounding device. A power turbine (PT) is positioned downstream of the main turbocharger to recovery the exhaust gas energy. For the MTC, at low engine speeds, the PT can take energy from the engine to accelerate the turbo shaft, while at high engine speeds, the PT can recover the exhaust thermal energy and give it to the engine. For the ETC, when the power produced by the turbine (T) exceeds the power requirement of the compressor (C), PT converts the exceed energy into electricity by a generator, when the power requirement of the compressor cannot be met, the electrical generator runs the PT to meet the requirement. The efficiency of the ETC is usually higher than that of the MTC, since the exhaust thermal energy can be stored and then re-used.

**Rankine Cycles (RC)**

Rankine cycle (RC), using the expansion of vaporized working fluid to push the expander
Figure 1.13: schematic representation of a Rankine cycle [19]

To produce mechanical or electrical power, has been identified as a suitable approach for the conversion of waste heat into usable power [17]. Conventional RCs use water steam as the working fluid. The organic Rankine cycle (ORC) uses some organic fluids (e.g., siloxanes, hydrocarbons or fluorocarbons) as working fluids, which can phase change at a lower temperature than the water-steam. Generally, a 10-15% fuel efficiency improvement is reported for Rankine cycles on the diesel engine truck applications [18]. The main disadvantage of RC is its high volume and heavy weight.

In Figure 1.13, a schematic representation of Rankine cycle with a reciprocating expander is shown. A basic Rankine cycle is usually made up by four main components: a pump, an evaporator, an expander and a condenser. The working principle of Rankine cycle is similar to a steam power plants and can be divided into four steps as follows:

- Compression of the working fluid in a pump.
- Vaporization of the working fluid in an evaporator.
- Expansion of the working fluid through an expander to generate mechanical or elec-
Thermoelectric Generators (TEG)

Thermoelectric generators (TEGs) have been identified as a reliable solid state technology for power generation [20]. TEG can convert otherwise wasted thermal energy of the exhaust gas into electricity. Thermoelectric devices can also be used in cooling applications to pump heat. The working principle of TEG is based on the Seebeck effect and the Peltier effect. The Seebeck effect is the generation of electricity when there are different temperatures between the hot side and cold side of thermoelectric material. The Peltier effect is the inverse where an imposed electrical current results in a heat transfer from a cool junction to a hot junction. The typical efficiency of the TEG made up by the state-of-art commercial Bismuth Telluride modules is 5% [21] and the claimed fuel consumption reduction is 3% [22].

One of the barriers to the successful application of TEG is its lower conversion efficiency. It can be seen from Figure 1.14 that a complete TEG usually consists of a heat source, a heat sink, heat exchangers, thermoelectric modules (TEMs), and connecting wires. The heat source is connected to the exhaust path and the temperature of the heat sink is maintained by the engine coolant. The heat exchangers extract the exhaust heat flow from the heat.
source and through the TEMs to the heat sink. The TEMs normally consists of an array N and P type semiconductors, which are joined thermally in parallel and electrically in series. When there is a temperature gradient across the TEMs, the negatively charged electrons in n-type semiconductors and the positively charged holes in p-type semiconductors move from the heat source to the heat sink and conduct heat to the cold end. Consequently, a current flow is resulted from the initially uniform charge carrier distribution. The connecting wires connect these TEMs electrically in series with a battery or a motor.

**Stirling Engine**

Stirling engines are able to transfer heat to mechanical or electrical work by forming Stirling cycle between a heat source and a heat sink. The principle of Stirling cycle is that the working gas is generally compressed in the colder portion of the engine and expanded in the hotter portion. Repeated heating and cooling will cause a reciprocating movement of the piston which can be converted to rotary motion using a conventional connecting rod and a crankshaft with a flywheel [23]. Stirling engines have a high efficiency compared to ICEs [24] being able to reach 40% of thermal efficiency. The main disadvantages of Stirling engine are its large size and heavy weight.

Distinguished by the way of working gas moving between the hot and cold areas, the Stirling
engines usually has three types: alpha, beta, and gamma [24], which can be seen in Figure 1.15. The alpha configuration is typically in a V-formation. It has two power pistons, one in a hot cylinder, one in a cold cylinder, and the gas is driven between the two by the pistons. The beta configuration has only one cylinder which is heated at one end and cooled at the other. The gamma configuration has two cylinders and the power piston is not mounted coaxially with the displacer piston but in a separate cylinder. Each of these three configurations utilize a heat source, a heat sink, heat exchangers, a regenerator and a displacer. The exhaust gas can be used as the heat source and engine coolant is used as heat sink to maintain the temperature difference. The hot side heat exchanger transfers the heat from heat source to heat up the working gas, while the cold side heat exchanger transfers the heat from engine to the coolant and cool down the working gas. The regenerator is an internal heat exchanger and temporary heat store placed between the hot and cold space. The displacer is a special-purpose piston to move the working gas back and forth between the hot and cold heat exchangers.

**Thermochemical Recuperation (TCR)**

Thermochemical recuperation (TCR) is a promising technology to recuperate the energy contained in exhaust gases of ICES [25]. TCR provides a method for recycling exhaust thermal energy in a chemical form.

Figure 1.16 shows a scheme of a thermochemical recuperation. It uses the energy contained in exhaust gases to promote the reforming of hydrocarbon fuels into hydrogen, carbon diox-
ide, steam and carbon monoxide. These reforming products are then re-burned in the engine. Because these reforming products have a relatively higher enthalpy, more heat can be generated when burning them in the engine and the engine efficiency is increased. However, the problems of uncontrolled combustion, catalyst deactivation, cold start and engine maximal power loss remained unsolved. Thus, TCR is not yet popular amongst the automotive community.

**Comparison of Waste Heat Recovery Technologies**

The development of WHR technologies are closely related to factors such as: complexity, size and weight, cost, fuel economy and controllability. The characteristics and development for these five WHR technology are collected and summarized in Table 1.2.

It can be clearly seen that these five WHR systems all have their own advantages and also face different challenges. In general, the turbo-compounding has low cost and relatively simple structure, but it usually brings a large pressure drop and has limited operating conditions. For the Rankine cycle, it has high efficiency of energy recovery, but its big size and complicated configuration still need to be improved. The TEG has the advantages of low maintenance, silent operation, high reliability and compactness, and stability, while the high cost of thermoelectric materials and the low recovery efficiency restrict the application. Stirling engine has the characteristics of high efficiency, quiet operation, low maintenance, and smooth torque delivery, but its main limitations are its long start-up time at cold starting and its size and weight. For the TCR, it has low cost and lightweight, but technology still need to be improved to deal with reformate management to avoid pre-ignition, backfire, knock and coke formation.

In summary, in order to enable the potential and commercial feasibility of these WHR technologies in vehicular application, future development work needs to be focused on the following aspects:

- WHR efficiency improvement
- System reliability enhancement
- Weight and size reduction
- Cost-effective solution exploration.
Table 1.2: Comparison of WHR systems; adapted from [? , 16, 17, 20, 25]

<table>
<thead>
<tr>
<th>WHR</th>
<th>Typical Fuel saving</th>
<th>Maturity</th>
<th>Complexity</th>
<th>Cost</th>
<th>Size &amp; Weight</th>
<th>Main challenges</th>
</tr>
</thead>
<tbody>
<tr>
<td>TC</td>
<td>3-10%</td>
<td>Commercially ready</td>
<td>+</td>
<td>+</td>
<td>++</td>
<td>1. Back-pressure</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>2. Limited operating conditions</td>
</tr>
<tr>
<td>RC</td>
<td>10-15%</td>
<td>Prototypes</td>
<td>+++</td>
<td>++</td>
<td>+++</td>
<td>1. Size and weight</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>2. Cost</td>
</tr>
<tr>
<td>TEG</td>
<td>3-5%</td>
<td>Prototypes</td>
<td>+</td>
<td>++</td>
<td>+</td>
<td>1. Low efficiency</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>2. Cost</td>
</tr>
<tr>
<td>Stirling</td>
<td>3-12%</td>
<td>Commercialized as standalone devices</td>
<td>++</td>
<td>+++</td>
<td>+++</td>
<td>1. Size and weight</td>
</tr>
<tr>
<td>engine</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>2. Cost</td>
</tr>
<tr>
<td>TCR</td>
<td>-</td>
<td>Concepts</td>
<td>+++</td>
<td>+++</td>
<td>+</td>
<td>1. Reformate management</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>2. Cost</td>
</tr>
</tbody>
</table>

These four aspects will also be the major success factors in competition among the listed four WHR technologies.

1.3 Research Aims

From the previous sections, it can be seen that interest in using WHR technologies to recover the exhaust thermal energy and lower the fuel consumption has flourished in recent years. This thesis focuses on thermoelectric generator (TEG) applied for WHR. Compared with other WHR technologies such as organic Rankine cycle and turbo-compounding, TEG has the advantages of low maintenance, silent operation, stability, compactness and bidirectional characteristics. All of these advantages, in addition to the increasingly demanding CO₂ emissions requirements for passenger cars, make the TEG an attractive option for conventional light-duty vehicles. Nevertheless, considerable technical challenges for TEG integration remain. The three main challenges include:

- Low conversion efficiency and low maximum operating temperature dictated by the properties of the chosen thermoelectric materials,
- Integration effects arising from increased mass, increased exhaust backpressure, and
installation complexity,

- High cost of many thermoelectric materials, which leads to a commercialization challenge to the TEG technology.

The research aim of this thesis is to investigate methods and solutions that help address the three listed challenges. By using a modular design approach, the vehicular TEG system is subdivided into a series of smaller parts, which are created and modelled independently then can be used as discrete scalable and reusable modules in different systems. The developed quasi-static TEM model, dynamic TEG model and semi-empirical vehicular TEG model, accommodating different type and number of TEMs, heat exchanger properties, vehicle parameters, and TEG integration scenarios, are used as a useful tool to run comprehensive assessments and analysis for different vehicular TEG systems.

The following objectives were set to fulfil the research aim:

- Developing a quasi-static thermoelectric module (TEM) model,
- Developing a dynamic TEG model,
- Applying a dynamic TEG model for the parameters sensitivity identification and model-based control strategy development,
- Developing a semi-empirical vehicular TEG model,
- Applying a semi-empirical vehicular TEG model for fuel saving potential estimation, TEG integrations effects analysis and TEG economic analysis,
- Developing a dual-mode TEM model,
- Exploring the bidirectional characteristics of TEG applied for engine warm-up.

1.4 Thesis Outline

The overall thesis organisation and its interconnection between chapters can be seen in Figure 1.17. A brief description of the thesis organization is given below.

Chapter 2: Literature Review
This chapter gives a literature review on the development of thermoelectric materials, modules and vehicular TEG prototypes. Based on the literature review, the research gaps for the development of vehicular TEG system is analysed.

Chapter 3: Quasi-static TEM Model

This chapter explains the development of quasi-static TEM Model. Both a Bi$_2$Te$_3$ and a skutterudite TEMs are modelled and tested on a power generation test rig. The validation results shows that both the Bi$_2$Te$_3$ and skutterudite TEM models have strong consistencies with the experiment results.

Chapter 4: Dynamic TEG Model

This chapter presents the development of dynamic TEG model. Both a Bi$_2$Te$_3$ and a skutterudite TEG models have been developed based on the developed TEM model in Chapter 3. The validation of the Bi$_2$Te$_3$ and skutterudite TEG models are respectively done on a diesel engine test bench and a gasoline engine test bench. Validation results shows that both models can predict the dynamics with good accuracy.

Chapter 5 Applications of Dynamic TEG Model

This chapter presents the applications of dynamic TEG model for a Bi$_2$Te$_3$ TEG integrated with a heavy-duty diesel engine. The validated Bi$_2$Te$_3$ TEG model in Chapter 4 is used as
a useful tool to develop the model-based temperature control strategy, estimate the TEG power output and analyse the parameter sensitivity.

Chapter 6 Semi-empirical Vehicular TEG Model

A semi-empirical vehicular TEG model is developed based on the scenarios of the skutterudite TEG integrated in different positions of a conventional light-duty gasoline vehicle. The semi-empirical vehicular TEG model includes a quasi-static vehicle model, a dynamic exhaust model, a dynamic coolant model, and a dynamic skutterudite TEG model. Both experimental and published data are used to tune and validate the models.

Chapter 7 Applications of Semi-empirical Vehicular Model

In this chapter, the applications of the semi-empirical vehicular TEG model developed in Chapter 6 are presented. By using the semi-empirical vehicular TEG model, the fuel saving percentage of TEG is estimated by taking the integration effects of added weight, added electrical pump, exhaust backpressure and energy loss in DC-DC converter into account. Then these four integration effects on the fuel saving are studied individually and possibilities to increase the fuel saving potential are also investigated. An economic analysis is conducted to estimate the benefit cost ratio of the vehicular TEG.

Chapter 8 Upgrade a Single-model TEM Model to a Dual-model TEM Model

The quasi-static TEM model developed in Chapter 3, which can only model the power generation mode, has been upgraded to a dual-model TEM model. A heating-cooling test rig has been setup to validate the performance of TEM operating in heating-cooling mode. A four-quadrant operation diagram of TEM is developed to present the cooling, heating and power generation curves of a TEM.

Chapter 9 Feasibility Study of a Bifunctional Vehicular TEG

A feasibility of applying a bifunctional TEG to a 2l-diesel engine light-duty vehicle is carried out based on the developed and validated dual-mode TEM model. The performance of bifunctional TEG in terms of WHR and engine oil warm-up are both evaluated. The feasibility and effectiveness for the proposed bifunctional TEG is demonstrated by comparing with the vehicular TEG only used for WHR.
Chapter 2

Literature Review

This chapter is focused on reviewing the evolution and advancements over the last three decades concerning the use of vehicular TEG for WHR. There are three main research aspects for the development of vehicular TEG:

- Thermoelectric materials
- Thermoelectric modules (TEMs)
- Vehicular TEG system

A broad literature review, which describes the most recent and important research efforts on the listed three aspects, is given to understand the theory base and current developments of vehicular TEG. Then, based on the literature review, the research gaps in the existing research are identified and presented. The aim of the thesis is to fill these research gaps.
2.1 Thermoelectric Materials Research

2.1.1 Material Properties

The performance of thermoelectric devices strongly depends on the efficiency of the thermoelectric materials. The dimensionless figure of merit (ZT) \([27]\), is used to evaluate the efficiency of thermoelectric materials:

\[
ZT = \frac{\alpha^2 \sigma T}{k}
\]  

(2.1)

where \(\alpha\) is the Seebeck coefficient, \(\sigma\) is the electrical conductivity, \(k\) is the thermal conductivity, and \(T\) is the absolute temperature. Based on equation (2.1), in order to increase the ZT value high Seebeck coefficient, high electrical conductivity, low thermal conductivity and high operating temperature have to be achieved in the same material simultaneously.
However, the Seebeck coefficient, electrical conductivity and thermal conductivity are interrelated and it is very difficult to change one parameter independently without influencing others.

Figure 2.1 presents different materials and their relationships to figure of merit (Z) [26]. It can be seen that the Seebeck coefficient, electrical conductivity and thermal conductivity values are all dependent on the free carrier concentration. For the metals, the electrical and thermal conductivity are directly related and they are both high while the Seebeck coefficient is quite low. Insulators, on the other hand, have high Seebeck coefficient and low thermal conductivity but are poor electrical conductors. In comparison, semiconductors are the ideal thermoelectric materials because of the trade-off among electrical and thermal conductivity and Seebeck coefficient. Based on the dominant carrier concentrations in a semiconductor, semiconductors can be divided into two types: p-type and n-type. N-type semiconductors have a larger electron concentration than hole concentration. The term n-type comes from the negative charge of the electron [28]. As opposed to n-type semiconductors, p-type semiconductors have a larger hole concentration than electron concentration. The term p-type refers to positive charge of hole [28]. The p-type and n-type semiconductors are usually combined in pairs in the use of thermoelectric modules (see Chapter 2.2.1).

2.1.2 Recent Development of Materials

From 1960s to 1990s, the achievement in thermoelectric materials was very low. After the mid-1990s, due to the development of nanostructural engineering, modern synthesis and characterization techniques, a wide variety of different thermoelectric materials were developed. Different thermoelectric materials operate at their maximum ZT values at specific temperatures. Based on their operating temperature range, thermoelectric materials can be classified into three groups: low temperature materials (below 300°C), medium temperature materials (300-800°C), and high temperature materials (above 800°C). Figure 2.2 and Table 2.1 summarize recent achievement of thermoelectric materials in these three temperature ranges.
Table 2.1: Recent achievements in thermoelectric materials and their ZT values [29–38]

<table>
<thead>
<tr>
<th>Temperature range</th>
<th>Materials category</th>
<th>Materials name</th>
<th>Type</th>
<th>ZT&lt;sub&gt;max&lt;/sub&gt;</th>
<th>Ref</th>
</tr>
</thead>
<tbody>
<tr>
<td>Low (Below 573K)</td>
<td>Bi&lt;sub&gt;2&lt;/sub&gt;Tc&lt;sub&gt;3&lt;/sub&gt;</td>
<td>Bi&lt;sub&gt;0.55&lt;/sub&gt;Sb&lt;sub&gt;1.5&lt;/sub&gt;Tc&lt;sub&gt;3&lt;/sub&gt;</td>
<td>p-type</td>
<td>1.4 (373 K)</td>
<td>[29]</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Bi&lt;sub&gt;0.52&lt;/sub&gt;Sb&lt;sub&gt;1.48&lt;/sub&gt;Tc&lt;sub&gt;3&lt;/sub&gt;</td>
<td>p-type</td>
<td>1.56 (300K)</td>
<td>[29]</td>
</tr>
<tr>
<td></td>
<td>Skutterudites</td>
<td>In&lt;sub&gt;x&lt;/sub&gt;Cr&lt;sub&gt;y&lt;/sub&gt;Co&lt;sub&gt;4&lt;/sub&gt;Sb&lt;sub&gt;1&lt;/sub&gt;</td>
<td>n-type</td>
<td>1.43 (800K)</td>
<td>[30]</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Ce&lt;sub&gt;0.5&lt;/sub&gt;Yb&lt;sub&gt;0.5&lt;/sub&gt;Fe&lt;sub&gt;3.25&lt;/sub&gt;Ce&lt;sub&gt;0.75&lt;/sub&gt;Sb&lt;sub&gt;12&lt;/sub&gt;</td>
<td>p-type</td>
<td>0.93 (800K)</td>
<td>[30]</td>
</tr>
<tr>
<td></td>
<td></td>
<td>CoSb&lt;sub&gt;2.75&lt;/sub&gt;Sb&lt;sub&gt;0.05&lt;/sub&gt;Tc&lt;sub&gt;0.20&lt;/sub&gt;</td>
<td>n-type</td>
<td>1.13 (700K)</td>
<td>[31]</td>
</tr>
<tr>
<td>Medium (573- 1073K)</td>
<td>Clathrates</td>
<td>Yb&lt;sub&gt;2&lt;/sub&gt;Ba&lt;sub&gt;8&lt;/sub&gt;Ga&lt;sub&gt;4&lt;/sub&gt;Ge&lt;sub&gt;30&lt;/sub&gt;</td>
<td>n-type</td>
<td>1.1 (950K)</td>
<td>[31]</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Ba&lt;sub&gt;8&lt;/sub&gt;Ga&lt;sub&gt;16&lt;/sub&gt;Ge&lt;sub&gt;30&lt;/sub&gt;</td>
<td>n-type</td>
<td>1.35 (900K)</td>
<td>[31]</td>
</tr>
<tr>
<td></td>
<td>Half-Heusler</td>
<td>Hf&lt;sub&gt;0.75&lt;/sub&gt;Zr&lt;sub&gt;0.25&lt;/sub&gt;NiSn&lt;sub&gt;0.99&lt;/sub&gt;Sb&lt;sub&gt;0.01&lt;/sub&gt;</td>
<td>n-type</td>
<td>1.0 (900K)</td>
<td>[32]</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Hf&lt;sub&gt;0.6&lt;/sub&gt;Zr&lt;sub&gt;0.4&lt;/sub&gt;NiSn&lt;sub&gt;0.975&lt;/sub&gt;Sb&lt;sub&gt;0.025&lt;/sub&gt;</td>
<td>n-type</td>
<td>1.0 (1073)</td>
<td>[33]</td>
</tr>
<tr>
<td></td>
<td>Silicides</td>
<td>Mg&lt;sub&gt;2&lt;/sub&gt;Si&lt;sub&gt;0.6&lt;/sub&gt;Sn&lt;sub&gt;0.4&lt;/sub&gt;</td>
<td>n-type</td>
<td>1.1 (700K)</td>
<td>[34]</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Sb-doped Mg&lt;sub&gt;2&lt;/sub&gt;Si&lt;sub&gt;0.6&lt;/sub&gt;Sn&lt;sub&gt;0.4&lt;/sub&gt;</td>
<td>n-type</td>
<td>1.11 (860K)</td>
<td>[39]</td>
</tr>
<tr>
<td>High (Above 1073K)</td>
<td>SiGe</td>
<td>Si&lt;sub&gt;60&lt;/sub&gt;Ge&lt;sub&gt;20&lt;/sub&gt;P&lt;sub&gt;2&lt;/sub&gt;</td>
<td>n-type</td>
<td>1.3 (1200K)</td>
<td>[35]</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Si&lt;sub&gt;80&lt;/sub&gt;Ge&lt;sub&gt;20&lt;/sub&gt;</td>
<td>p-type</td>
<td>0.95 (1073K)</td>
<td>[36]</td>
</tr>
<tr>
<td></td>
<td>Oxides</td>
<td>Ca&lt;sub&gt;1.2&lt;/sub&gt;Ag&lt;sub&gt;0.8&lt;/sub&gt;Co&lt;sub&gt;4&lt;/sub&gt;O&lt;sub&gt;9+δ&lt;/sub&gt;</td>
<td>p-type</td>
<td>0.23 (973K)</td>
<td>[37]</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Zn&lt;sub&gt;0.96&lt;/sub&gt;Al&lt;sub&gt;0.02&lt;/sub&gt;Ga&lt;sub&gt;0.02&lt;/sub&gt;O</td>
<td>n-type</td>
<td>0.65 (1247K)</td>
<td>[38]</td>
</tr>
</tbody>
</table>
2.1.2.1 Low Temperature Materials

Low temperature materials are usually used in the applications of refrigeration, temperature regulation of scientific instrumentation and recovery of low quality waste heat from combustion processes or electronic device. Bi$_2$Te$_3$ is the most common commercially used thermoelectric materials at low temperature range because of their relatively high ZT values (around 1) at room temperature. Bi$_2$Te$_3$ has been studied extensively since 1954 [40] and are now state-of-the-art thermoelectric materials. Hi-Z Technology Inc. [41] and European Thermodynamics [42] both have their mass production of Bi$_2$Te$_3$ thermoelectric modules. Poudel et al. [29] fabricated a p-type Bi$_{0.5}$Sb$_{1.5}$Te$_3$ bulk by introducing nanoscale crystalline. The value of ZT started at 1.2 at room temperature, peaked to 1.4 at 100°C, and decreased to 0.8 at 250°C. Xie et al. [43] developed a melt spinning technique combined with a subsequent spark plasma sintering process to form bulk nanostructural p-type Bi$_{0.52}$Sb$_{1.48}$Te$_3$. This p-type bulk material had a ZT value of 1.56 at temperature 300 K.
2.1.2.2 Medium Temperature Materials

Since the temperature regime for most typical waste heat energy sources is between 300 – 800°C, exploring medium temperature thermoelectric materials has become a hot research topic and many medium temperature thermoelectric materials have been developed for the last decade. The most prominent representatives of medium temperature materials are Skutterudite, Half-Heusler, Clathrates and Silicides.

Skutterudite is a naturally-occurring mineral of chemical formulation MX₃ (M=Fe, Co, Rh, Ir, Ni and X=P, As, Sb) [44]. Skutterudite has crystal structure which has a hollow in the centre of the body and can be used to be filled with additional elements to manipulate the properties of the material. Filling the hollow in the centre with atoms could possibly depress the lattice thermal conductivity dramatically and modify the electronic properties to enhance the figure of merit [45]. Li et al. [30] used the a meltquench method to fabricate a n-type skutterudite InₓCeᵧCo₄Sb₁₂, for which a peak ZT of 1.43 was obtained at 800 K. University of Reading [31] successfully synthesized CoSb₄.₇₅Sn₀.₀₅Te₀.₂₀ (n-type material) and Ce₀.₅Yb₀.₅Fe₃.₂₅Co₀.₇₅Sb₁₂ (p-type material). These synthesized materials were appropriate for medium temperature range application, with maximum ZT of 1.13 at 405°C for the n-type material and 0.93 at 550°C for the p-type material.

The general formula for Clathrate is AₓBᵧC₄₆₋ₓ, where B and C are tetrahedrally bonded atoms (Al, Ga, Si, Ge, or Sn). These tetrahedrally bonded atoms form a framework of cages that enclose guest metallic atoms [46]. The metal atoms in the voids will act as barriers to phonon transport through the materials thus yielding a very low thermal conductivity. Tang et al. [47] discovered a n-type Clathrate (YbₓBa₈Ga₁₆Ge₃₀) to be employed in medium temperature applications having the maximum ZT value of 1.1 at 950 K. Saramat et al. [48] reported a n-type Clathrate Ba₈Ga₁₆Ge₃₀ fabricated by using the Czochralski method. The ZT value for this n-type Clathrate was found to increase from 0.08 at room temperature to 1.35 at temperature 900K.

Half-Heusler compounds are crystallized in the ABX structure, where A and B are transition metals and X is a main group element. Half-Heusler compounds usually have relatively high Seebeck coefficient and electrical conductivity, but the thermal conductivity is also quite high. Thus, the main challenge for this compound is the reduction of the thermal...
conductivity. Joshi et al. [32] adopted the nanocomposite approach, and a ZT value of 1.0 was attained in a n-type Hf$_{0.75}$Zr$_{0.25}$NiSn$_{0.99}$Sb$_{0.01}$ sample at 600°C to 700°C. Yu et al. [33] made a n-type Half-Heusler thermoelectric material Hf$_{0.6}$Zr$_{0.4}$NiSn$_{0.975}$Sb$_{0.025}$ by levitation melting and spark plasma sintering. A ZT value of 1.0 was achieved at 1073 K. Silicides as thermoelectric materials were firstly proposed by E.N. Nikitin’s paper in 1958 [49]. Silicides represent a group of promising thermoelectric materials, which not only show good thermoelectric properties, but also are cost-efficient and environmentally friendly. They are especially attractive for WHR in the medium temperature range (400 K to 800 K) where they exhibit the peak ZT. Zaitsev et al. [34] studied n-type Mg$_2$Si$_{0.6}$Sn$_{0.4}$ in broad range of compositions and electron concentration. ZT$_{max}$=1.1 was obtained at temperature 700K. Liu et al. [39] fabricated Sb-doped n-type Mg$_2$Si$_{0.6}$Sn$_{0.4}$ compounds. Small concentrations of Sb considerably enhanced the ZT values and the highest ZT value of 1.11 was reached at 860 K. Lead telluride is a compound of lead and tellurium (PbTe) and its operation temperature is between 600K and 900K. However, because of the toxicity of Pb, which has been identified as one of the restricted-hazardous substance in the EU [50], PbTe is gradually replaced by other thermoelectric materials. Therefore, the literature review only focuses on exploring Pb free thermoelectric materials.

2.1.2.3 High Temperature Materials

Thermoelectric materials working at a temperature range above 800°C are of particular interest for power generation in the space exploration.

Silicon-germanium (SiGe) have been used for converting heat into power in spacecraft designed for deep-space NASA missions since 1976 [51]. The ZT value of n-type silicon germanium bulk alloy has remained at about one at 900-950°C for a few decades. Wang et al. [35] reported that a peak ZT of 1.3 at 900°C in n-type nanostructured dense bulk Si$_{80}$Ge$_{20}$P$_2$ by using a nanostructure approach. Compared with n-type, the ZT value of p-type silicon germanium is relatively lower. In recent years, efforts have been made to improve the ZT value of p-type Silicon-germanium. Joshi et al. [36] fabricated a p-type nanostructured bulk Si$_{80}$Ge$_{20}$ with ZT=0.95 at 800°C, which is about 90% higher than what is currently used.
in space flight missions.

Oxides are another material can be used in the high temperature range. The extremely low electrical conductivity of the oxides has resulted in them being almost entirely ignored for their potential utilization in thermoelectric field. Although the ZT value of oxides is still low compared with the current state-of-the-art thermoelectric materials, the characteristics of high thermal stability and oxidization resistance enable oxides to be as a promising thermoelectric material used in high temperature range. Zhang et al. [37] investigated p-type Ca$_{3-x}$Ag$_x$Co$_4$O$_9$+$\delta$ (x = 0, 0.01, 0.03, 0.05) oxide samples and reported that x = 0.03 sample had the highest ZT value with ZT = 0.23 at 973 K. Ohtaki [38] fabricated a n-type Zn$_{0.96}$Al$_{0.02}$Ga$_{0.02}$O by employing a third element as a co-dopant with Al. Due to the dual doping of ZnO with Al and Ga, it was observed that ZT value increased from 0.47 at 1000 K to 0.65 at 1247 K.

2.2 Thermoelectric Modules Research

2.2.1 Module Principles

Figure 2.3 shows the typical structure of a thermoelectric module (TEM), which is normally the shape of a rectangular parallelepiped. A TEM consists of thermoelectric elements, conductive tabs, and ceramic plates. The thermoelectric elements include negative-type (n-type) thermoelectric elements made by n-type semiconductor materials and positive-type (p-type) thermoelectric elements made by p-type semiconductor materials. A p-type element and a n-type element combined electrically in series to make up a thermocouple. A TEM can contain one to several hundred thermocouples. All the thermoelectric elements are connected by the conductive tabs electrically in series and thermally in parallel between two ceramic plates. The conductive tabs have good thermal conductance to provide heat transfer with minimal thermal resistance. The ceramic plates are thermally conductive and electrically insulating.

Based on either the Peltier effect or the Seebeck effect, the TEMs can be used in two basic modes: heating-cooling or power generation. When a temperature difference (dT) is applied to a TEM, the mobile charge carriers at the hot end tend to diffuse to the cold end, producing
Figure 2.3: Typical structure of a thermoelectric module

Figure 2.4: Schematic illustrations of a thermoelectric module for (a) power generation (Seebeck effect) and (b) thermoelectric cooling (Peltier effect)
an electrostatic potential. This characteristic, known as the Seebeck effect, is the basis of TEM power generation, as shown in Figure 2.4(a). Conversely, when a voltage is applied to a TEM, the module absorbs heat on one side of the device and releases heat on the other, an effect known as the Peltier effect, as shown in Figure 2.4(b). The Seebeck effect and Peltier effect are reversible so that a TEM can act as a cooler, a heater or a generator. However, the TEM suppliers fabricate two different modules: heating-cooling modules used for heating or cooling and power generation modules used for generating electricity. In this way, the heating-cooling modules and power generation modules have been specifically optimised for different temperature ranges, with heating-cooling modules most effective at temperatures closer to room temperature, as usually found in cooler or heater applications, while power generation modules are optimised for higher temperatures and used for energy recovery [52].

For the power generation module, efficiency is the key parameter for power generation. A theoretical expression is frequently used to calculate the maximum efficiency of a single thermoelectric module [53]:

\[ \eta_{\text{max}} = \frac{P}{Q_h} = \frac{T_h - T_c}{T_h} \frac{\sqrt{1 + ZT} - 1}{\sqrt{1 + ZT} + \frac{T_c}{T_h}} \]  

(2.2)

where \( \bar{T} = \frac{(T_h + T_c)}{2} \); \( T_h \) and \( T_c \) are respectively the temperatures on hot side and cold side; \( P \) is the output power and \( Q_h \) is the total quantity of heat at the hot side.

For the heating-cooling modules, the general measure of efficiency is based on the amount of heat \( Q_c \) that it removes at cold side compared to the amount of electrical work \( P \) that it requires. This value is referred to as maximum coefficient of performance \( (\text{COP}_{\text{max}}) \), which also can be expressed as a function of the temperatures on hot side \( (T_h) \) and cold side \( (T_c) \) as [53]:

\[ \text{COP}_{\text{max}} = \frac{Q_c}{P} = \frac{T_c}{T_h - T_c} \frac{\sqrt{1 + ZT} - \frac{T_h}{T_c}}{\sqrt{1 + ZT} + 1} \]  

(2.3)

It can be seen from the equations above that \( \eta_{\text{max}} \) and \( \text{COP}_{\text{max}} \) can be used as convenient indicators for evaluating the potential performance of the TEMs. Figures 2.5 and 2.6 respectively show \( \eta_{\text{max}} \) and \( \text{COP}_{\text{max}} \) as temperature and ZT are varied. The ZT value of materials is proportional to the performance of both generator and heating-cooling modules. However,
Figure 2.5: Response of $\eta_{\text{max}}$ for varied ZT and varied $T_h$

Figure 2.6: Response of $COP_{\text{max}}$ for varied ZT and varied $T_c$
the influence of temperature difference on the two modules are different. For the power generation modules, a large temperature gradient across the TEM could yield a high-efficiency outcome. While for the heating-cooling modules, a small temperature gradient across the TEM could give higher \( \text{COP}_{\text{max}} \) values. Thus, optimization operating conditions for the thermoelectric power generation system and the thermoelectric heating-cooling system are also different (See Chapter 9).

### 2.2.2 Module Design Considerations

It can be seen from previous sections that thermoelectric material properties are critical requirements for the design of better-performing TEMs. However, there are significant parasitic losses when the materials are integrated to form a complete thermoelectric module. The most notable influences are contact resistance and module geometry. Due to these influences, the module’s performance could be below the values (\( \eta_{\text{max}} \) or \( \text{COP}_{\text{max}} \)) predicted on the basis of the ZT of the component materials [54]. Much research has been done to reduce contact resistance and optimize the geometrical parameters of the TEMs, so as to achieve better-performing modules.
2.2.2.1 Contact Resistance

Due to the machining limitations, two solid surfaces will never form a perfect contact when they are pressed together. Even if the surfaces look perfectly smooth, tiny air gaps will always exist between the two contacting surfaces due to roughness. Figure 2.7 presents the locations of thermal and electrical contact resistances [55]. The contact resistances within a TEM include the electrical resistances on both sides of thermoelectric elements, the thermal resistances between the conductive tabs and the ceramic plates and the thermal contact resistance between the thermoelectric elements and the conductive tabs. The influence of contact resistance on the TEMs’ performance can be seen in many experimental TEMs tests [56–60]. Wang et al. [56] found that increasing loading pressure can lead to a decrease in the thermal contact resistance and an increase in both the actual temperature difference across the module and the output power. Sakamoto et al. [57] used CoSi$_2$ as electrodes for the Mg$_2$Si module. 35 % decrease in electrical contact resistance and 27 % increase in output powers were observed.

Based on abundant module test results, both electrical and thermal contact resistances were taken into account when calculating the efficiency of the TEMs. Min and Rowe [61] gave a new expression for the maximum efficiency of a thermoelectric generator modules, in the presence of both an electrical and thermal contact resistance.

$$\eta_{\text{max}} = \frac{T_h - T_c}{T_h - T_c} \frac{1}{1 + 2 R_{c,T} T_h} \left(2 - \frac{1}{2} \frac{T_h - T_c}{T_h} + \frac{4}{Z T_h} \frac{1 + 2 R_{c,T}}{R_{l,T}} \right)$$

(2.4)

where $R_{c,T}$, $R_{c,e}$ are respectively thermal and electrical contact resistance of the TEM. $R_{l,e}$ and $R_{l,T}$ are respectively electrical or thermal resistance of the thermoelectric elements. Björk et al. [62] also built an analytical model with enough accuracy to calculate the influence of electrical and thermal contact resistance on the efficiency of a TEM. In Björk’s model, the influence of thermal contact resistance was modelled as a factor controlling the temperature span across the thermocouples ($T_{h,\text{leg}}$ and $T_{c,\text{leg}}$). The electrical contact resistance was modelled as a single external electrical resistance.

Many efforts have also been put into decreasing the magnitude of the contact resistance. Wang et al. [56] found that increasing loading pressure and application of the thermal grease
to the contact interface can lead to a decrease in the thermal contact resistance. Tanji et al. [63] proved that the use of the metallic paste forming bond between thermoelectric material and electrode is an effective way to achieve low thermal and electric contact resistance. Nemoto et al. [60] used a Ag-based brazing alloy to join the thermoelectric elements and Ni terminals so as to reduce the electrical and thermal contact resistance of the module. Funahashi et al. [64] constructed thermoelectric elements using Ag paste containing p-type and n-type oxide powders for the connection between thermoelectric elements and Ag electrodes. The incorporation of oxide powders in Ag paste was showed to be effective to reduce the contact resistance.

### 2.2.2.2 Module Geometry

Except for the contact resistance, module geometry is another important factor that needs to be considered when designing a TEM. The main geometrical parameters for a TEM include the width, length, and height of the thermoelectric elements and ceramic plates and the occupancy rate of the thermoelectric elements in a module (fill factor). Figure 2.8 shows an example of the geometrical design parameters for a TEM [65].

Investigations found that the geometric structure has remarkable effects on the performance of modules [61,66–69]. Min and Rowe [66] found that the optimum length of thermoelectric
elements (leg length) to obtain maximum power output differed from that for the maximum conversion efficiency. A compromise had to be made between the requirements for maximum power output and maximum conversion efficiency when optimizing the leg length. Meng et al. [67] adopted a multi-objective and multi-parameter optimization approach to design the optimal structure of a module. Three geometric parameters, number of thermocouples, length thermoelectric element, and occupancy rate of the thermoelectric elements in a module, were taken as searching variables, which are optimized simultaneously. By setting a weight factor, the power output and efficiency of the module were both improved simultaneously. Huang et al. [68] built a complete three-dimensional model for a heating-cooling module and used a simplified conjugate-gradient method to optimize geometric structure of the heating-cooling module. The effects of applied current and temperature difference on the optimal geometry had been found out. The optimization results proved that small current and high temperature difference could lead to an increase in the optimum number for the thermocouples. Meydbray et al. [69] investigated the module geometry experimentally by testing modules with different surface area. It found out that the output power showed a significant dependence on module surface area.

Achieving better performance of modules cannot be the only target for module geometrical optimization. The TEMs also need to be cost effective. Thus, there is also a need for module geometrical parameters to be designed based on cost-performance trade-off analyses. Min and Rowe [66] proposed that the module geometry should also be optimized to minimise the cost of the generated electricity. Based on this principle, an optimisation procedure for the module geometry was reported by using an economic factor (£/kWh). Xuan et al. [70] optimized the design parameters for a heating-cooling module to minimize the total cost, which included both the module and supplied electricity costs. Based on a thermal network model, a general expression for the total cost and an optimization procedure to minimize the total cost were described. Yee et al. [71, 72] developed an analytical framework to quantify the tradeoff between performance and cost in a system level. A new cost-performance metric ($ per W) was developed to optimize the fill factor and leg length to minimizes the ratio of cost to performance.
2.3 Vehicular TEG System Research

A typical vehicular TEG system comprises four components: a hot side heat exchanger, a cold side heat exchanger, TEMs and electrical connecting wires. The hot side and cold side heat exchanges (HXRs) are respectively connected to the engine exhaust path and coolant circuit. The TEMs are usually sandwiched between the hot side and cold side HXRs. For the electrical connecting, a DC-DC converter is commonly electrical connected to the TEG, which converts the voltage supplied by the TEG to reach the voltage levels required by the electrical system in the car.

The compatibility of TEG with the original vehicle system is one of the key factors for the vehicular TEG to be successfully commercialized. The following subsections receptively presents the designs and developments of TEG integrated with exhaust system, coolant system and electrical system. The experimental results of vehicular TEG prototypes are collected and summarized in the last subsection.
Table 2.2: The exhaust temperatures for these four possible TEG locations

<table>
<thead>
<tr>
<th>Location</th>
<th>Gasoline</th>
<th>Diesel</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>750-1100°C</td>
<td>600-850°C</td>
</tr>
<tr>
<td>2</td>
<td>400-750°C</td>
<td>350-600°C</td>
</tr>
<tr>
<td>3</td>
<td>200-400°C</td>
<td>150-350°C</td>
</tr>
<tr>
<td>4</td>
<td>300-500°C</td>
<td>100-400°C</td>
</tr>
</tbody>
</table>

2.3.1 TEG Integration with Exhaust System

2.3.1.1 Integration Scenarios with Exhaust System

As can be seen in Figure 2.9, there are mainly four possible installing locations for the TEG in the exhaust system of the vehicles:

- Downstream of the exhaust manifold (Number 1 in Figure 2.9)
- Between the exhaust manifold and the catalytic converters (Number 2 in Figure 2.9)
- Downstream of the catalytic converter (Number 3 in Figure 2.9)
- In the exhaust gas recirculation (EGR) path (Number 4 in Figure 2.9)

The exhaust temperatures for these four possible locations for the installation of the TEG are summarized and listed in Table 2.9 [8, 73]. Generally, the exhaust temperature of gasoline engines is much higher than that of diesel engines. And the exhaust temperature raises when it is closer to the exhaust manifold. Higher exhaust temperature usually means more available thermal energy in the exhaust gas.

When integrating the TEG in the exhaust system, the installing position of TEG also has to be selected according to the temperature limits of the thermoelectric modules. A bypass solution is widely used in the integration with exhaust system [74–76]. The bypass can prevent thermal overloading of the TEG and cooling system at very high engine loads and reduce the exhaust gas backpressure [76]. Massaguer et al. [77] proposed using a PID control to regulate the opening and closing of the bypass valve and installing a temperature sensor on the hot side of TEMs to monitor the temperature. Furthermore, placing the TEG upstream
of the catalytic converter can lead to a reduction of temperature previous to the inlet of catalytic converter resulting in an increased pollutant release [73]. Thus, a temperature control for the outlet temperature of TEG is also needed when installing a TEG upstream of the catalytic converter.

2.3.1.2 Hot Side Heat Exchanger Design

An efficient hot side heat exchanger can enhance the heat transfer from the poorly conducting exhaust gas to the TEMs so as to improve the electrical power generation. Historically, hot side heat exchangers with different shapes have been investigated since the first vehicular TEG was built in 1988 [79]. Based on their cross-sectional geometry, the hot side HXRs can be divided into 3 different groups: rectangular HXR, cylinder HXR, and hexagonal HXR, which can be seen in Figure 2.10.

The internal fins of the hot side HXR can effectively increase the contact area between the gas and heat exchanger to raise the turbulence augmenting and the average heat convection coefficient. In addition, an optimized distribution of fins inside the HXR can improve the thermal uniformity of the exhaust gas so as to improve the electricity generation performance of each module. However, the fins are also the obstacles for the exhaust gas and generate a pressure drop in the HXR, which can affect the engine efficiency. Thus, it is critical that the hot side HXR of the TEG provides a high heat transfer performance while maintaining a low pressure drop.

The geometry and distribution of fins inside the HXR are the keys to increase the efficiency
of the HXRs. Bass et al. [80] proposed a hexagonal cylinder shape HXR for Cummins 14L NTC 350 diesel engine. Discontinuous swirl fins were installed on surface of the centre body to break laminar boundary layer and enhance gas turbulence. Su et al. [81] designed two different exhaust gas heat exchangers with different internal structures. By testing their acoustic characteristics, the fish-bone finned internal structure with 12 mm interior thickness was used to increase thermal uniformity of the HXR. Wen et al. [82] investigated flow characteristic in front of a plate-fin heat exchanger, and determined that thermal uniformity and heat transfer could be strengthened by installing punched baffle. Lu et al. [83] designed two exhaust heat exchangers with muffler-like internal structure and the thermal uniformity and pressure drop characteristics of these two HXRs were compared. The symmetrical 1-inlet 2-outlet structure was found to have more uniform flow distribution and less temperature drop than the 2-inlet 2-outlet structure. Lu et al. [84] investigated two types of heat transfer enhancements for a hot side HXR: rectangular offset-strip fins and metal foams. The results showed that an optimal fin transverse spacing and fin thickness existed to maximize the net power output. Liu et al. [85] used a multi-objective optimization method to optimize both the thermal and pressure performances of a plate-shaped heat exchanger. By choosing five fin parameters and four optimization targets, the average temperature increased 4°C and the pressure drop decreased by approximately 20%. Massaguer et al. [77] found out that finned geometry of the hot side HXR had smaller thermal resistance than the holey geometry and lead to the hot side temperature increasing faster and reaching higher values. Vale et al. [86] compared the performance of two different HXR configurations (plain fins and offset strip fins) for a TEG applied in exhaust gas energy recovery in a diesel road freight transportation. The plain fins were found to be better than the offset strip fins, particularly as a result of the pumping power influence.

2.3.2 TEG Integration with Coolant System

2.3.2.1 Cooling Circuit Integration Scenarios

There are two technical routes for the integration of cooling units of the TEG with the vehicles. The schematic of these two integrations are shown in Figure 2.11.

- The first one is that the cooling units are connected to the original engine cooling
Integrated with the engine cooling system

Integrated with an independent radiator with a fan

Figure 2.11: Two technical routes for the integration of cooling units of the TEG [87]

- The second one is that the cooling units are connected to an independent radiator with a fan.

Compared with adding another independent radiator, integrating a TEG cooling units with the original engine cooling system can effectively avoid the problem of having a lack of space. However, the exhaust rejected to the engine coolant can increase the cooling load of the engine-cooling system, which leads to an increase in coolant temperature and a decrease in the power generated by the TEG. Deng et al. [88] investigated the compatibility of engine-cooling system when a TEG cooling units were integrated. Based on both simulation and experimental data, it was found out that the temperature of the integrated cooling system was 10 °C more than that of the primary engine cooling system under the low vehicle speed and high engine power. Thacher et al. [89] tested a TEG system in a General Motors Sierra pick-up truck. Considering the thermostat valve would prevent coolant from flowing to the TEG, a pre-cooling heat exchanger had to be placed upstream of the TEG to reduce
the TEG coolant inlet temperature to levels. To further optimize the integration of TEG cooling units with the engine coolant circuit, using the heat rejected to coolant from TEG to warm up the engine or the gearbox had been proposed. Rosenberger et al. [76] proposed an integration scenario of TEG cooling units which could distribute the heat introduced between engine, gearbox and vehicle interior as needed. Consequently the CO₂ emission could be further reduced by warming up the gearbox and engine. Gentherm [90] integrated TEG cooling units with the engine coolant system and intended to warm up of the engine-oil by using an engine-oil/coolant HXR to extract the heat from TEG cooling units. The test results showed that the warming up effect was not obvious and deactivating coolant pump was proved to be more effective than to rely on TEG to provide oil preheating.

Adding an independent radiator with a fan for the cooling units of TEG can effectively take away the heat from the TEG system and provide adequate cooling for the TEG. Therefore, temperature difference across the TEMs can be maintained at high values and high power output can be achieved. Since two separate loops are used for cooling TEG and engine, there is no need to worry about the effects of the coolant temperature increase led by the TEG system. However, more space for integration and more power to support the fan are needed and also more costly. This integration of scenario of TEG cooling units were widely used in the vehicular TEG prototypes [74, 77, 79, 80, 91–94]. Gentherm [90] replaced the original radiator of F350 with new radiator, which includes two split loops. The top radiator with same cooling capacity as original radiator and second radiator sized to provide adequate cooling to TEG system. An electric water pump circuits the coolant in the second radiator with average 25 W power consumption. To reduce the power consumption of the added fan, Jiang et al. [87] designed an added TEG radiator, which used the air flow below the car chassis to cool the TEG radiator and also acted as a spoiler to optimize the flow field around the car chassis and even reduce the aerodynamic drag.

2.3.2.2 Cold Side Heat Exchanger Design

Like the hot side HXRs, most of the research for the cold side HXRs mainly focus on the configuration and inner structure to increase cooling performance. Wijewardane [95] found that the overall performance of a TEG increased when the coolant of the cold side HXR was directly exposed to TEMs due to the significant reduction of thermal resistance. Rezania
et al. [96] designed a parallel-plate cold side HXR to a TEG and explored the effective pumping power required for the TEGs cooling at five different temperatures of the hot and cold sides of the TEG. The experimental result indicated that a unique coolant flow rate gives maximum net-power in the system at the each temperature difference. Su et al. [97] built a computational fluid dynamics model and analysed the performance of three different types of cold side HXRs (plate-shape, stripe-shape, and diamond-shape). It was discovered that stripe-shaped cold side HXR offers the best performance. He et al. [98] compared maximum power output of TEG using four types of cooling methods and found out the coflow and counterflow methods had a small difference in the water cooling performance. Qiang et al. [99] proposed a multi-objective optimization method to optimize the inner structure of the cooling units. Five independent geometrical variables were considered and heat transfer coefficient, friction loss coefficient, and temperature difference between the inlet and outlet were regarded as performance parameters.

2.3.3 TEG Integration with Electrical System

2.3.3.1 Integration Scenarios with Electrical System

TEG can be successfully applied in vehicles fitted with both conventional and hybrid powertrains [102]. Based on different types of vehicles, there are two feasible ways of integrating the generated electricity by TEG into the automotive electrical system. The two different integration scenarios for the conventional vehicles and hybrid vehicles are respectively presented in Figures 2.12 and 2.13.

For the conventional internal combustion engine vehicles, the electrical power from the TEG is used to relieve the alternator, which can be seen in Figure 2.12. Weilguni et al. [103] investigated the feasibility of replacing the alternator of a passenger car with a TEG. The results showed that this was practically not feasible to replace the alternator, for the electrical load of the vehicle could not always be met. LaGrandeur et al. [15] proposed a straightforward control strategy for the usage of electrical power in conventional vehicles. When the TEG cannot supply all the electrical power needed by the vehicle, the alternator provided electrical bus voltage regulation. In conditions where the TEG was able to supply all the electrical power needed by the vehicle, the alternator shut off. Deng et al. [100]
Figure 2.12: TEG integration with electrical system in conventional vehicles [100]

Figure 2.13: TEG integration with electrical system in hybrid vehicles [101]
analysed and compared two feasible ways of integrating the generated electricity into the conventional heavy-duty vehicle. One was that the original alternator worked only under certain conditions while the other was that a smaller alternator was adopted and worked together with the TEG. The results showed that both methods could improve the fuel economy, but the former provided slightly better results.

For the hybrid vehicles, the electrical power can not only be used for the electrical load but also directly for propulsion, which can be seen in Figure 2.13. Deng et al. [101] built a hybrid vehicle model of the Honda Insight with a TEG directly supplying the integrated starter and generator (ISG) and charging the batteries. The simulation results indicated that the TEG charged the battery SOC smoothly and cut down the needs for engine torque to enable the engine to work. Vijayagopal et al. [11] conducted a simulation analysis for the benefits of TEG varied with the type of vehicle: a conventional vehicle, a mild hybrid and a full hybrid. This study demonstrated that although the average power of TEG in conventional vehicle was higher than both two hybrid vehicles, the mild hybrid vehicle had the greatest fuel economy improvements because of its effective use of the recovered energy. Fang et al. [104] designed an ISG weak hybrid power system structure based on thermoelectric conversion. A minimum fuel consumption was used as an objective function and the battery pack’s output current was used as the control variable. Data analysis showed that the fuel economy of the hybrid power system under European Driving Cycle conditions was improved by 14.7%.

2.3.3.2 DC-DC Convector Design

The output voltage and power of TEG are highly temperature dependant. In order to reach the voltage levels required by the electrical system in the car, a DC-DC converter is needed to regulate the output voltage and provide a stable voltage supply. There are two major concerns in the design of DC-DC converters: efficiency and regulation. The impedance matching between the internal resistance of the TEMs and the input resistance of DC-DC converter can lead to a power loss and decrease of efficiency. The issue of regulation is due to the variable output voltage of TEG while the stable requirement of the electrical system in the car. Much research has been done to solve these two issues.

Cao et al. [105] proposed a multiphase multilevel DC-DC conversion network based on a 630
W TEG prototype for automotive applications. The proposed DC-DC conversion network could effectively reduce the power loss in DC-DC converter from 5 % of total TEG power output to about 3 %. Li et al. [106] proposed a multisection multilevel DC-DC conversion network based on a TEG used for automotive applications. Compared with traditional single-stage conversion systems, the proposed network provided higher reliability and higher efficiency. Ni et al. [107] designed a two-cascade boost DC-DC converter for battery charging supplied by TEG. A new control strategy coordinating the operations of input stage and output stage was proposed to achieve lower input current ripple and optimum power efficiency. Experimental results verified the feasibility and effectiveness of the proposed control strategy. Park et al. [108] proposed an analog maximum power point tracking circuit for a thermoelectric generator using peak gain control of boost DC-DC converters. The proposed maximum power point tracking technique provided a simple and useful analog maximum power point tracking solution, without employing digital microcontroller units. Laird [109] presented a novel high step-up DC-DC converter topology operating with a fractional short-circuit maximum power point tracking algorithm. Experimental results were reported to verify the better performance of the short-circuit maximum power point tracking algorithm over the perturb and observe algorithm.

2.3.4 Experimental Results of Vehicular TEG

A significant number of studies, in cooperation with several automotive manufacturers, have performed experimental tests of the TEG prototype mounted on exhaust simulators, engines and vehicles revolving drums, which can be seen in Figure 2.14. The most representative experimental results of vehicular TEG are summarized and presented in the order of time. The comparison of the experimental test conditions, thermoelectric modules types and numbers, power outputs and installing positions are presented in Table 2.3.

In 1988, Birholz et al. [79], in cooperation with Porsche, built the first vehicular TEG, which used FeSi₂ as thermal materials. The TEG was tested on a Porsche 944 engine and was placed just behind the exhaust manifold. It reported that it produced a maximum electrical output power of 58 W.

In the early 1990s, HI-Z Technology [80] designed a TEG for on a 14 litre Cummins NTC
Figure 2.14: Vehicular TEG experimental setup: (a) TEG engine simulator test bench [110], (b) TEG engine test bench [77], (c) TEG vehicle revolving drum test bench [111]
Table 2.3: Overview of representative experimental results of vehicular TEGs

<table>
<thead>
<tr>
<th>Engine</th>
<th>TEG location</th>
<th>HXRs</th>
<th>Cooling</th>
<th>TEMs</th>
<th>Max Power (W)</th>
<th>Ref</th>
</tr>
</thead>
<tbody>
<tr>
<td>Porsche 944</td>
<td>Downstream the exhaust manifold</td>
<td>Rectangular</td>
<td>Cooling water</td>
<td>FeSi</td>
<td>58W (870°C)</td>
<td>[79]</td>
</tr>
<tr>
<td>14L-diesel</td>
<td>Downstream the catalyst converter</td>
<td>Octagonal</td>
<td>Cooling water</td>
<td>72 Bi₂Te₃</td>
<td>1kW (300hp, 1700 rpm)</td>
<td>[80]</td>
</tr>
<tr>
<td>3L-gasoline</td>
<td>Downstream the exhaust manifold</td>
<td>Rectangular</td>
<td>Cooling water</td>
<td>72 Si-Ge</td>
<td>35.6W (60km/h hill climb)</td>
<td>[74]</td>
</tr>
<tr>
<td>3L-gasoline</td>
<td>Downstream the catalyst converter</td>
<td>Rectangular</td>
<td>Cooling water</td>
<td>16 Bi₂Te₃</td>
<td>193W (60km/h hill climb)</td>
<td>[91]</td>
</tr>
<tr>
<td>2L-gasoline</td>
<td>Downstream the exhaust manifold</td>
<td>Rectangular</td>
<td>Cooling water</td>
<td>6 Bi₂Te₃, 2 Bi₂Te₃</td>
<td>266W (60 km/h hill climb)</td>
<td>[112]</td>
</tr>
<tr>
<td>3L-gasoline</td>
<td>Downstream the catalyst converter</td>
<td>Rectangular</td>
<td>Cooling water</td>
<td>16 Bi₂Te₃</td>
<td>255W (112 km/h)</td>
<td>[80]</td>
</tr>
<tr>
<td>Exhaust simulator</td>
<td>Main exhaust pipe</td>
<td>Cylinder</td>
<td>Cooling water</td>
<td>224 Bi₂Te₃</td>
<td>350W (Constant condition)</td>
<td>[110]</td>
</tr>
<tr>
<td>2.0L-diesel</td>
<td>Exhaust gas path</td>
<td>Rectangular</td>
<td>Cooling water</td>
<td>Mg₂SiMnSi</td>
<td>130W (Highway condition)</td>
<td>[113]</td>
</tr>
<tr>
<td>1.3L-diesel</td>
<td>Upstream the muffler</td>
<td>Octagonal</td>
<td>Cooling water</td>
<td>24 Bi₂Te₃, 2 Bi₂Te₃</td>
<td>135.1W (City road condition)</td>
<td>[113]</td>
</tr>
<tr>
<td>2.3L-diesel</td>
<td>Exhaust gas path</td>
<td>Rectangular</td>
<td>Cooling water</td>
<td>504 Bi₂Te₃, 2Bi₂Te₃</td>
<td>200W (WLTP)</td>
<td>[114]</td>
</tr>
<tr>
<td>2L-gasoline</td>
<td>Mid-muffler position</td>
<td>Cartridges</td>
<td>Engine coolant</td>
<td>10 Skutterudite cartriges</td>
<td>130W (US06)</td>
<td>[90]</td>
</tr>
<tr>
<td>6.2L-flex fuel</td>
<td>Downstream the catalyst converter</td>
<td>Cartridges</td>
<td>Engine coolant</td>
<td>20 Skutterudite cartriges</td>
<td>1,160W (US06)</td>
<td>[90]</td>
</tr>
<tr>
<td>Heavy-duty diesel</td>
<td>Upstream the muffler</td>
<td>Multi-rectangular</td>
<td>Cooling water</td>
<td>240 Bi₂Te₃</td>
<td>941W (Revolving drum test)</td>
<td>[111]</td>
</tr>
<tr>
<td>Heavy-duty diesel</td>
<td>EGR path</td>
<td>Multi-rectangular</td>
<td>Cooling water</td>
<td>300 Bi₂Te₃</td>
<td>416W (1000 kg/h, 300°C)</td>
<td>[92,93]</td>
</tr>
<tr>
<td>Heavy-duty diesel</td>
<td>Downstream the catalyst converter</td>
<td>Multi-rectangular</td>
<td>Cooling water</td>
<td>224 Bi₂Te₃</td>
<td>398W (1000 kg/h, 300°C)</td>
<td>[92,93]</td>
</tr>
<tr>
<td>4.0L-diesel</td>
<td>Exhaust gas path</td>
<td>Rectangular</td>
<td>Cooling water</td>
<td>40 Bi₂Te₃</td>
<td>119.1W (2000rpm, 0.6MPa)</td>
<td>[115]</td>
</tr>
<tr>
<td>13L-diesel</td>
<td>Exhaust gas path</td>
<td>Multi-rectangular</td>
<td>Cooling water</td>
<td>400 Half-Heusler</td>
<td>1003W (458g/s, 553°C)</td>
<td>[116]</td>
</tr>
<tr>
<td>1.4L-gasoline</td>
<td>Downstream the catalyst converter</td>
<td>Rectangular</td>
<td>Cooling water</td>
<td>12 PbTe-Bi₂Te₃</td>
<td>111.22W (2000rpm, 85% FTPP)</td>
<td>[77]</td>
</tr>
</tbody>
</table>
350 diesel engine truck using 72 Bi$_2$Te$_3$ modules installed on an octagonal heat exchanger. It obtained 1 kW of output energy when the TEG was coupled directly to the exhaust gas outlet of the engines turbocharger at engine condition of 300 horse power and 1700 rpm.

In 1998, Nissan [74] fabricated Si-Ge modules, which was available to high temperature application, as thermal materials for a TEG on a 3000cc gasoline engine. The TEG was installed just behind the exhaust manifold and a bypass line was used to control the temperature. It reported 72 Si-Ge modules generated 35.6W of electric power when the TEG worked in the condition corresponding to the 60km/h hill climb.

In 1999, Nissan [91] designed a thermoelectric generator used in a 3-litre gasoline engine after the catalyst converter. The hot side heat exchanger had fins with different area ratios, which was used to reduce the temperature distribution and protect the Bi$_2$Te$_3$ modules. When the TEG was working in the conditions corresponding to the vehicle running at 60 km/h hill climb, the electric power generated by the 16 Bi$_2$Te$_3$ modules was 193 W.

In 2002, to maximize the conversion efficiency of the TEG operating in the wider temperature range, Matsubara et al. [112] built new modules segmented with the skutterudite and Bi$_2$Te$_3$. Six segmented modules (Skutterudite/Bi$_2$Te$_3$) and four Bi$_2$Te$_3$ modules constitute the TEG, which was were stacked on the exhaust pipe before the catalyst converter of a 2000cc gasoline engine. The test result showed that 266 W electric power were generated when the engine was running in a speed 60 km/h.

In 2007, Clarkson University [89] in collaboration with General Electric Motor had tested a TEG on a GMC Sierra pick-up truck with a 3-litre gasoline engine in a dynamometer-equipped wind tunnel. 16 Bi$_2$Te$_3$ modules from HI-Z Technology were used and the TEG was installed after the catalytic converter. The experimental results presented that the TEG produced 255 W and achieved 2 % fuel saving at a vehicle speed of 112 km/h.

In 2011, Kim et al. [110] proposed a TEG system with two aluminium wing plates attached symmetrically to the exhaust pipe. Based on the test from the exhaust simulator, a maximum 350 W could be achieved by the TEG consisting of 224 Bi$_2$Te$_3$ TEMs when the hot exhaust gas heated the evaporator surface of the heat pipe to 170°C.

In 2012, Renault Trucks, Volvo, supplier Valeo and academic laboratories worked on the project RENOTER (acronym for waste heat recovery in engine exhaust trough thermoelec-
tricity) [?]. They tested their vehicular TEG prototypes for a diesel passenger car (2.0-litre engine, 150hp) and concluded that a TEG with Mg$_2$SiMnSi materials could generate up to 130W for a passenger car diesel exhaust in highway conditions.

In 2014, Merkisz et al. [113] tested a thermoelectric generator installed upstream of the muffler of a 1.3-litre 66 kW diesel engine in an actual vehicle driving cycle reproduced on a dynamic engine test bed. The TEG consisted of 24 commercial Bi$_2$Te$_3$-Sb$_2$Te$_3$ modules, an octagonal hot side HXR and individual cooler for each module. The test results showed that maximum 135.1 W was achieved in the urban and suburban traffic conditions.

In 2014, FIAT and Chrysler worked on the project HEATRECAR (Reduced energy consumption by massive thermoelectric waste heat recovery in light-duty trucks) [114]. An IVECO equipped with a 2.3-litre diesel engine had been identified as the reference vehicle for the TEG prototype. The TEG prototype included 504 Bi$_2$Te$_3$ modules, 63 hot tubes and 24 cold tubes. The driving cycle tests results showed that on the NEDC the fuel consumption reduced 2.2 % with a peak thermoelectric electric power of 150 W and on the WLTP the fuel consumption reduced 3.9 % with a maximum thermoelectric electric power of 200 W.

In 2015, Gentherm [90] cooperated with BMW and Tenneco designed a novel thermoelectric power generation cartridge, which consisted of internal and external HXRs and skutterudite modules. The TEGs had been designed to integrate in two vehicles: BMW X3 and Ford F350. Maximum 130W electricity had been generated by a 10-cartridge TEG installed in mid muffler position of BMW X3 running the US06 drive cycle. For the Ford F350, 20-cartridge TEG installed immediately after catalytic converters generated maximum 1,160 W electricity in the US06 drive cycle.

In 2015, Liu et al. [111] tested the performance of a Bi$_2$Te$_3$-based TEG system, which included four identical TEGs connected in parallel and contained 240 TEMs. The TEG was assembled upstream the muffler of a prototype vehicle called "Warrior". A maximum power of 944 W was obtained at revolving drum test with engine speed 2600 rpm.

In 2015, Frobenius et al. [92,93] presented two TEG prototypes for a heavy-duty truck: one in the EGR system path (EGR-TEG) and one in the exhaust gas path located after the treatment system (ATS-TEG). 224 and 300 Bi$_2$Te$_3$ modules were respectively installed on
the ATS-TEG with offset-strip-fin multi-plate HXR sand EGR-TEG with rectangular fin multi-plate HXR. The test results from the engine simulator showed that the overall power output reached 800 W during transient measurements of 9 points long haulage cycle.

In 2016, Kim et al. [115] experimentally investigated the performance of a TEG installed a turbocharged six-cylinder diesel engine. Forty Bi$_2$Te$_3$ TEMs were installed on the top and bottom sides of a rectangular hot side HXR in a 4×5 arrangement with 13-mm gaps between adjacent TEMs. The maximum power output of 119 W was measured at 2000 rpm and at a brake mean effective pressure (BMEP) of 0.6 MPa.

In 2016, Meda et al. [116] fabricated a TEG prototype for a diesel engine of a military tank. The TEG included 5 layers of hot side HXRs, 10 layers of Half-Heusler TEMs with 40 modules on each layer, and 6 layers of cold HXR. The TEG system was tested by connecting to a 13-litre, inline 6 cylinder 450hp diesel engine and 1,003 W electrical power was produced at the inlet ow rate of 458 g/s, 553°C exhaust gas temperature.

In 2017, Massaguer et al. [77] designed a TEG which consisted of 12 PbTe and Bi$_2$Te$_3$ thermoelectric modules and a rectangular hot side HXR. In this study the TEG was installed downstream of the three-way catalyst (TWC) of a Golf 1.4 TSI. The test results showed the maximum power output reached 111.22 W at 2000 rpm at 85 % FTP.

2.4 Research Gaps of Vehicular TEG System

2.4.1 Translating the Material Improvements into TEG Performance

As can be seen from the various TEG prototypes and experimental results in the literatures, Bismuth Telluride (Bi$_2$Te$_3$) is the most popular thermoelectric material. However, as a low temperature thermoelectric materials, the maximum operating temperature of Bi$_2$Te$_3$ limits its installing positions in the vehicle. Most of Bi$_2$Te$_3$ TEG prototypes are installed far from the exhaust manifold leading relatively less available thermal exhaust energy can be recovered. Besides, due to the limit of hot side temperature (250°C), a bypass solution was used for most of Bi$_2$Te$_3$ TEG prototypes. Since a lot of thermal energy at high temperature escaped without recovery, the efficiency of the Bi$_2$Te$_3$ TEGs were less than 5 % [80,89,91].
Thus, the most promising and practical materials for vehicular TEGs in WHR would be materials designed to withstand higher temperatures.

Based on previous literatures on recent development of thermoelectric materials, Skutterudite, Half-Heusler, Clathrates and Silicides have shown good potential for high ZT at higher temperature based on a number of recent material test results [30–34, 39, 44, 46–49]. The operating temperature ranges of those materials are better matched to automotive application, especially for gasoline engines. Consequently, an increased TEG efficiency can be expected. Recently, work is beginning to translate those material improvements into TEG performance [31, 90, 116], but still have a long way to go.

2.4.2 Transient Behaviours of Vehicular TEGs under Driving Cycles

Most reported vehicular TEG studies [74, 79, 80, 89, 91, 110, 112, 115] are carried out under steady state engine conditions or driving profile, which cannot represent the real driving conditions. In fact, the transient performance of TEG is important, especially in the application of vehicle WHR. First of all, the exhaust temperature and gas flow rate vary often during a normal operation of the car where start-up, shut-down, and engine load changes are a major concern. Secondly, the highly temperature dependent characteristic of the thermoelectric properties and thermal inertia of the TEG system further underlines the importance of dynamic operation of the TEG system. Thirdly, the temperature of the cold end of the TEG, which is usually integrated with engine coolant is also often changed with the flow rate of cooling unit and operation of radiator.

The effects of transient behaviours of TEG on the power production can be observed in Table 2.3 for a few studies that tested TEGs under transient conditions of a driving cycle such as WLTP or US06. The results indicate under transient driving conditions relatively less power was generated compared with constant conditions. Thus, the dynamic characteristics of a vehicular TEG needs to be further studies so as to find methods to increase its energy recovery performance.
2.4.3 Fuel Saving Percentage and Cost-benefit Estimation of TEG

As can be seen from the experimental results of the vehicular TEG, the electric power output of TEG prototypes are presented in most of the studies. However, the fuel saving percentage by a vehicular TEG in specific driving cycles was missing. Since the TEG represents another component in the exhaust system, its integration presents challenges. The fuel economy benefit could be compromised through a number of integration effects such as added weight, increased cooling load, increased exhaust backpressure and energy loss in DC-DC converter. All of the listed effects above have been studied [88,105,117,118] and it has been proved that they could lead to a significant reduction in the fuel saving potential of a TEG in vehicle application. Thus, there is a need for a comprehensive TEG fuel saving estimation method, which considering all the integration effects.

Recent prototypes of vehicular TEGs have all demonstrated the feasibility of their application in vehicular WHR. The continued development and deployment of vehicular TEGs largely depend on the device cost and fuel saving performance. However, the commercial feasibility analysis for the vehicular TEG has been ignored by most of the studies. The cost of many thermoelectric materials may be prohibitively high, which may lead a commercialization challenge to the TEG technology. In order to investigate the commercial feasibility of vehicular TEG technology, a comprehensive assessment of TEG system is needed urgently. The assessment needs predict TEG performance, fuel saving potential, CO$_2$ reduction benefits by taking the integration effect into account. Then a cost-benefit calculation is conducted in Chapter 7 to identify the ratio of cost of manufacture to the value of the benefits.

2.4.4 Bidirectional Characteristic of TEM and Bifunctional vehicular TEG

Because of the bidirectional characteristic of the TEMs, the same TEM can not only work in power generation mode (Seebeck effect), but also in heating-cooling mode (Peltier effect). However, most of the studies on TEMs choose to only focus on one mode, which the thermoelectric materials are specially optimized for, and neglect the other mode. Therefore, the bidirectional characteristic of the TEMs have been neglected in previous literatures.
With the fast development of materials, the TEMs may able to work effectively in both modes in the future. Therefore, exploring the bidirectional characteristic of the TEM and its corresponding application is necessary.

Because of the bidirectional characteristic of the TEMs, a TEG can not only be used as a power generator, but it can also be used as a heating or cooling device. However, reviewing the published papers in the vehicular TEG field, all the studies focused on applying the vehicular TEGs for the WHR based on Seebeck effect. There are no studies using a TEG as a heating device based on Peltier effect for engine warm-up. Therefore, a feasibility study for a bifunctional thermoelectric generator (TEG) applied in vehicle engines, which can use Seebeck effect for waste heat recovery (WHR) and Peltier effect for engine warm-up, can be a novel research topic for vehicular TEG.
Chapter 3

Quasi-static TEM Model

TEMs are categorized into two operation modes based on the direction of energy conversion: thermoelectric heating-cooling converting electricity to thermal energy and thermoelectric generator (TEG) converting heat into electricity. This chapter focuses on the investigation and validation of a quasi-static TEM model only used for TEG. The extension of the quasi-static TEM used for both TEG and thermoelectric heating-cooling will be presented in Chapter 8.

In this chapter, both a Bi$_2$Te$_3$ TEM and a Skutterudite TEM have been modelled by solving a thermal network and an electrical network simultaneously. A TEM test rig has been setup for the module power generation tests and the experimental results are used for the model validation. Simulation results of both the Bi$_2$Te$_3$ TEM model and the Skutterudite TEM model have shown strong consistencies with the test results. The validated Bi$_2$Te$_3$ and Skutterudite TEM model will be used for the TEG modelling in Chapter 4.
3.1 Important Factors in TEM Modelling

For the development of TEM, a numerical TEM model is essential in the performance prediction, cost-benefit ratio calculation, and optimum design. In the TEM modelling, there are three main factors which have significant effect on the TEM performance:

- High temperature dependence of the material properties of the TEMs
- Inner structure of a TEM
- Influence of thermal and electrical contact resistance

A number of TEM models [78, 119–123] have been proposed by assuming constant materials properties for analysis, design, and optimization of TEMs. However, the assumption of constant material properties made in the analytical thermoelectric model is not realistic in many applications. The performance of the TEM strongly depends on the thermoelectric material properties. The Seebeck coefficient, electric conductivity and the thermal conductivity for most of the thermoelectric materials are all strongly temperature-dependent [124]. Therefore, these TEM models are not sufficient to accurately predict the performance of the TEMs. Meng et al. [124] built a multi-physics, steady-state, and three-dimensional numerical TEG model to investigate how the temperature-dependent materials properties affect the TEG performance. It revealed that the assumption of constant material properties lead to underestimated inner electrical resistance, and overestimated thermal conductance and Seebeck coefficient.

Except for temperature-dependent material properties, the impact of the geometrical parameters of the thermoelectric materials on the module performance also cannot be ignored. The influence of length, numbers and cross-sectional area of the p-type or n-type semiconductor on the module performance are investigated by many researchers [61, 66–68, 125]. Some researchers have already studied the geometric-dependent TEG performance using the thermal resistance model [61, 68, 126], or one-dimensional model [125].

In addition to the temperature-dependent characteristics and physical parameters of materials, the thermal and electrical contact resistance at different material junctions also significantly affects its performance. The thermal and electrical contact resistance exist
at the interface of two different materials and can result in substantial resistance to heat transfer compared with the resistance of the bulk material. Therefore, temperature profile, heat flow, and module performance can be affected [62]. Hogblom et al. [127] compared the results from three dimensional finite element simulations with experiments and found that thermal and electrical contact resistances had a major effect on the simulation performance and should always be included in simulations of modules.

In this chapter, a quasi-static TEM model has been developed. The TEM model is built from thermoelectric materials into a TEM model, and the high temperature dependence of material properties, geometric dimensions and thermal and electrical contact resistances are all considered in the model. The material properties are extracted from the datasheets provided by the TEM manufacturers. The TEM model is created in Matlab/Simulink package and compatible with Matlab/Simulink libraries for further TEG model (Chapter 4), quasi-static vehicle model (Chapter 6), exhaust model (Chapter 6) and coolant model (Chapter 6), which are all built in the Matlab/Simulink block libraries.

### 3.2 TEM Dimension and Properties

Most commercial TEMs are manufactured in planar forms, which are illustrated in Figures 3.1 and 3.2. A TEM consists mainly of thermocouples, ceramic plates and conductive tabs. A positive-type and a negative-type thermoelectric element make up a thermocouple. The
conductive tabs connect all the thermoelectric elements electrically in series and thermally in parallel between two ceramic plates. The ceramic plates are thermally conductive and electrically insulating. For a typical commercial TEM, both p-type and n-type thermoelectric elements are made in the same dimensions but different materials. The thermoelectric elements in most commercial modules are not closely arranged and air gap exists in the module.

Both a Bi$_2$Te$_3$ TEM and a Skutterudite TEM respectively are investigated in this study. The physical form of each module is shown in Figure 3.1. The Bi$_2$Te$_3$ TEM is a commercial module purchased from European Thermodynamics Ltd [42]. The Skutterudite TEM was recently developed by our project group. The manufacture of Skutterudite material had been carried out in the lab of chemistry department in the University of Reading, UK [31]. Then the Skutterudite material was fabricated into Skutterudite TEMs in Cardiff University, UK [31]. The dimension and properties of Bi$_2$Te$_3$ and Skutterudite TEMs are listed in Table 3.1. The date for Bi$_2$Te$_3$ module is from the date-sheet of manufacture [42]. The regression equations for materials properties of the Skutterudite TEMs are the best fit derived from measured material characteristics.
Table 3.1: The dimension and properties of Bi$_2$Te$_3$ and Skutterudite TEMs.

<table>
<thead>
<tr>
<th></th>
<th>Bi$_2$Te$_3$ TEM</th>
<th>Skutterudite TEM</th>
</tr>
</thead>
<tbody>
<tr>
<td>Area of a ceramic plate</td>
<td>$A_{cp}$ ($10^{-6} \cdot m^2$)</td>
<td>62 x 62</td>
</tr>
<tr>
<td>Area of a thermocouple</td>
<td>$A_{tc}$ ($10^{-6} \cdot m^2$)</td>
<td>2.8 x 5.6</td>
</tr>
<tr>
<td>Thickness of a thermocouple</td>
<td>$l_{tc}$ ($10^{-3} \cdot m$)</td>
<td>1</td>
</tr>
<tr>
<td>Thickness of a ceramic plate</td>
<td>$l_{cp}$ ($10^{-3} \cdot m$)</td>
<td>1.5</td>
</tr>
<tr>
<td>Thickness of a TEM</td>
<td>$l_{TEM}$ ($10^{-3} \cdot m$)</td>
<td>4</td>
</tr>
<tr>
<td>Number of thermocouples</td>
<td>$n_{tc}$</td>
<td>127</td>
</tr>
<tr>
<td>Thermal conductivity of the ceramic plate</td>
<td>$k_p$  (=) $3.62T^2 - 2635T + 622162)</td>
<td>$k_p$  (=) $-3.77 \times 10^{-2}T^2 + 160T + 138358)</td>
</tr>
<tr>
<td></td>
<td>$k_n$  (=) $3.35T^2 - 2335T + 560633)</td>
<td>$k_n$  (=) $0.994T^2 - 1107T + 62055)</td>
</tr>
<tr>
<td>Seebeck coefficient of the thermal elements</td>
<td>$S_p$  (=) $-3.63T^2 + 2743T - 296214)</td>
<td>$S_p$  (=) $-2.17 \times 10^{-7}T^2 + 3.66 \times 10^{-4}T + 1.94 \times 10^{-3}T)</td>
</tr>
<tr>
<td></td>
<td>$S_n$  (=) $1.53T^2 - 1080T - 28338)</td>
<td>$S_n$  (=) $7.91 \times 10^{-7}T^2 - 1.08 \times 10^{-3}T + 0.13)</td>
</tr>
<tr>
<td>Electric conductivity of the thermal elements</td>
<td>$\sigma_p$ (=) $1.56T^2 - 1570T + 446638)</td>
<td>$\sigma_p$ (=) $0.1025T^2 - 181.5T + 192825)</td>
</tr>
<tr>
<td></td>
<td>$\sigma_n$ (=) $1.05T^2 - 1016T + 311371)</td>
<td>$\sigma_n$ (=) $0.0981T^2 - 162.74T + 160395)</td>
</tr>
<tr>
<td>Max operation temperature</td>
<td>250 °C</td>
<td>550 °C</td>
</tr>
</tbody>
</table>
The properties of the TEM can be calculated from material properties and geometrical parameters which can be easily obtained from the manufacturers’ datasheet. The Seebeck coefficient $S_{tc}$, thermal conductance $K_{tc}$ and electrical resistance $R_{tc}$ of the thermocouples, thermal conductance of the air gap $K_{gap}$ and ceramic plate $K_{cp}$ are respectively calculated as follows:

$$S_{tc} = n_{tc} (S_p - S_n)$$  

$$K_{tc} = \frac{n_{tc} A_{tc} (k_p + k_n)}{2l_{tc}}$$  

$$R_{tc} = \frac{2n_{tc} l_{tc}}{A_{tc}} \left(\frac{1}{\sigma_p} + \frac{1}{\sigma_n}\right)$$  

$$K_{gap} = \frac{k_{gap} (A_{cp} - n_{tc} A_{tc})}{l_{tc}}$$  

$$K_{cp} = \frac{k_{cp} A_{cp}}{l_{cp}}$$

All of these properties are temperature-dependent and here they are functions of an average temperature of the two sides of the thermocouple.

### 3.3 Model Structure

As can be seen from Figure 3.3, the TEG model can be divided into two networks: a thermal network and an electrical network. The thermal network includes all the thermal resistances of the main components. Based the thermal network, the temperature distribution of the TEM can be solved. The electrical network is made up by the open-circuit voltage generated by the Seebeck effect, the internal resistance of module and load resistance. The output voltage and power output of a TEM can be obtained by solving the electrical network.
3.4 Assumption

The following assumptions are made for the TEM model to simplify the complex problem of modelling.

- Seebeck coefficient, thermal conductivity and electrical resistance of the material changes with the average temperature of the two sides of the thermocouple.
- The Thomson effect in the TEM can be neglected.
- Heat conduction through the conductive tabs is ignored.
3.5 Modelling

3.5.1 Thermal Network

Figure 3.4 depicts the temperature distribution in a TEM and its energy balance. $T_{cp,h}$, $T_{cp,c}$ and $T_{tc,h}$, $T_{tc,c}$ are respectively the temperatures of the hot side and cold side of the ceramic plate and temperatures hot side and cold side of the thermocouples. The three effects that are assumed to happen in the TEM are presented in three different colours: Peltier effect (green), Joule heating effect (blue), and Fourier effect (red). According to Figure 3.4, the energy balance equations for the hot side and cold side of the thermocouples can respectively be expressed as [51]:

$$Q_{hm} = IS_{tc}T_{tc,h} + Q_{tm} - \frac{1}{2}I^2R_{int}$$  \hspace{1cm} (3.6)

$$Q_{cm} = IS_{tc}T_{tc,c} + Q_{tm} + \frac{1}{2}I^2R_{int}$$  \hspace{1cm} (3.7)

$R_{int}$ is the overall electrical resistance of the TEM, which includes the electrical resistance of the thermocouples $R_{tc}$ and electrical contact resistance $R_{ct}$. 

Figure 3.4: Temperature distribution and energy balance in a TEM.
\[ R_{int} = R_{tc} + R_{ct} \] (3.8)

\( Q_{hm} \) and \( Q_{cm} \) are respectively the heat conducted through the hot and cold side of the module. \( Q_{tm} \) includes the heat conducted through the thermocouples and the air gap between the thermocouples. They can be calculated respectively as follows:

\[ Q_{hm} = K_{hm}(T_{cp,h} - T_{tc,h}) \] (3.9)

\[ Q_{cm} = K_{cm}(T_{tc,c} - T_{cp,c}) \] (3.10)

\[ Q_{tm} = (K_{tc} + K_{gap})(T_{tc,h} - T_{tc,c}) \] (3.11)

where \( K_{hm} \) and \( K_{cm} \) are respectively the overall thermal conductance of the hot and cold sides of the module. They can be expressed as follows:

\[ \frac{1}{K_{hm}} = \frac{1}{K_{cp}} + \frac{1}{K_{ct,h}} \] (3.12)

\[ \frac{1}{K_{cm}} = \frac{1}{K_{cp}} + \frac{1}{K_{ct,c}} \] (3.13)

where \( K_{ct,h} \) and \( K_{ct,c} \) are respectively the hot and cold side thermal contact conductance, which include thermal contact conductance inside TEMs and between the TEMs and the aluminium plates.

### 3.5.2 Electrical Network

Figure 3.5 presents the electrical network of a TEM. Based on Seebeck effect, when there is temperature difference across a TEM, an open circuit voltage can be generated.

\[ U_{TEM, ocv} = S_{tc}(T_{tc,h} - T_{tc,c}) \] (3.14)
The current in the closed circuit can be expressed as:

\[ I = \frac{U_{\text{TEM.ocv}}}{R_{\text{int}} + R_{\text{load}}} \]  
(3.15)

The output voltage and power output of a TEM can be respectively expressed as:

\[ U_{\text{TEM.out}} = U_{\text{TEM.ocv}} - IR_{\text{int}} \]  
(3.16)

\[ P_{\text{TEM.out}} = U_{\text{TEM.out}}I \]  
(3.17)

3.6 TEM Test Rig Design

The performance of a TEM is evaluated using a test rig. The scheme of the test rig and its structure are shown in Figures 3.6 and 3.7. The 300 mm² electric heating plate (3), which houses a 2.3 kW flexible heater element, is used as the heat source. The temperature of the heating plate is controlled by a heater control box (11). The heat sink is cooled by a
Figure 3.6: TEM test rig.

Figure 3.7: Test rig structured diagram.
circulated coolant (10). The TEM (6) is sandwiched by two aluminium plates (4,5). The tested TEMs are the Bi$_2$Te$_3$ module and the Skutterudite module. Its properties can be found in Table 1.1. In the middle of each aluminium plate, there are holes (7, 8) to install thermocouple sensors to measure both hot and cold side temperatures of the TEM (T$_{hd}$ and T$_{cd}$). Insulation materials (9) are used to fill the gap between the two aluminium plates and minimize the unwanted heat transfer. The bottle jack (1) makes sure the aluminium plates and TEM are in close contact by applying clamping force F, which can be measured by the load cell (2). An NI Crio-9024 DAQ chassis (12) and a computer (13) make up the data acquisition system, which records the data from the load cell (F), thermocouples sensor (T$_{hd}$ and T$_{cd}$), the output voltage of the TEM (U$_{TEM.out}$) and the current (I) simultaneously. The uncertainty for voltage and current measurements are respectively ± 0.05 A and ± 0.05 V.

3.7 Parameter Estimation and Validation

3.7.1 Parameter Estimation Method

$R_{ct}$ and $K_{ct}$ exist as a result of the fabrication and connection method. Thus, the real tested properties of a TEM in the application can be different from a direct calculation from the materials and geometrical parameters [128, 129]. $R_{ct}$ depends mainly on contact pressure, properties of the contact materials and contact surface characteristics. Constant clamping force and same electrical connecting method are applied in all the tests. Thus, a constant $R_{ct}$ is assumed in the TEM model.

$$R_{ct} = b_{ct.0}$$  \(3.18\)

where $b_{ct.0}$ is the tuning parameter. The primary factors in determining the magnitude of $K_{ct}$ are respectively contact pressure, properties of contact materials, contact surface characteristics, and the mean junction temperature. The same aluminium plates and constant clamping force are used in each test. Thus, $K_{ct.h}$ and $K_{ct.c}$ are respectively expressed as the similar linear functions of temperature, which are presented as follows:
\[ K_{ct.h} = b_{ct.1} + b_{ct.2}T_{hd} \] (3.19)

\[ K_{ct.c} = b_{ct.1} + b_{ct.2}T_{cd} \] (3.20)

\( b_{ct.1} \) and \( b_{ct.2} \) are tuning parameters.

The tuning parameters \( b_{ct.0}, b_{ct.1}, b_{ct.2} \) are determined by solving a least-squares optimization problem that minimizes \( J_1 \), which is defined as:

\[ J_1(b_{ct.0}, b_{ct.1}, b_{ct.2}) = (U_{TEM.out} - U_{TEM.out.meas})^2 \] (3.21)

\( U_{TEM.out} \) is the model output and \( U_{TEM.out.meas} \) is measured data.

Relative errors (Equation 3.22) and mean absolute error (MAE) are calculated and used to evaluate the tuning and the validation of the model.

\[ error(i) = \frac{y_{meas}(i) - y_{mod}(i)}{y_{meas}(i)} \times 100\% \] (3.22)

\[ MAE = \frac{\sum_{i=1}^{N} |error(i)|}{N} \] (3.23)

where \( i \) and \( N \) are respectively an operating point and total number of operating points; \( y_{meas} \) and \( y_{mod} \) are respectively measured data and model output.

### 3.7.2 \( \text{Bi}_2\text{Te}_3 \) TEM Parameter Estimation and Validation

Experiments with two different cold side temperatures \( T_{cd} \) are conducted here for the validation of the \( \text{Bi}_2\text{Te}_3 \) TEM. Each experiment is repeated at least three times to obtain reproducible results. The mean value of the experimental data is used as the final experimental data. Before switching on the electric heating plate, the following operating conditions are set:

- The coolant temperature is set constant as \( T_{cd}=30 \, ^\circ C \) or \( 50 \, ^\circ C \).
Figure 3.8: Experimental data and simulation results of Bi$_2$Te$_3$ TEM test with error bars.

- Using the bottle jack to set the clamping force $F=3000$ N, which is about 0.8 MPa on the module.
- The electric load resistance $R_{load}$ is set as 0.3 $\Omega$.

The experiment is started by switching on the electric heating plate with a target temperature of 250 $^\circ$C. The hot side temperature $T_{hd}$ begins to increase so does the output voltage $U_{TEM.out}$. $T_{hd}$ and $U_{TEM.out}$ are simultaneously recorded by the data acquisition system.

Based on the experimental data of Bi$_2$Te$_3$ TEM, $R_{ct}$, $K_{ct,h}$ and $K_{ct,c}$ can be expressed respectively as follows:

$$R_{ct} = 0.11\Omega$$  \hspace{1cm} (3.24)$$

$$K_{ct,h} = (-0.021 + 0.024T_{hd}) W/K$$ \hspace{1cm} (3.25)$$
\[ K_{ct,c} = (-0.021 + 0.024 T_{cd}) W/K \] (3.26)

The comparison of the simulation results with the experimental data including error bars is presented in Figure 3.8. It can be seen that both simulation results correspond well with the test results. The calculated MAE is about 2\%. This validation shows that both the electrical contact resistance and thermal contact conductances give a good fit for the tested Bi\textsubscript{2}Te\textsubscript{3} TEM.

### 3.7.3 Skutterudite TEM Parameter Estimation and Validation

Experiments with only one cold side temperatures \(T_{cd}\) are conducted here for the validation of the Skutterudite TEM. Both output voltage \(U_{TEM.out}\) and output power \(P_{TEM.out}\) are validated for the Skutterudite TEM. Each experiment is also repeated at least three times and the mean value of the experimental data is used as the final experimental data.

Before switching on the electric heating plate, the following operating conditions are set:

- The coolant temperature is set constant as \(T_{cd}=30^\circ C\).
- Using the bottle jack to set the clamping force \(F=3000\) N, which is about 0.8 MPa on the module.
- The electric load resistance \(R_{load}\) is set as 0.3 \(\Omega\).

The experiment is started by switching on the electric heating plate with a target temperature of 600 \(^\circ C\). As the hot side temperature \(T_{hd}\) begins to increase so does the output voltage \(U_{TEM.out}\). \(T_{hd}, U_{TEM.out}\) and \(I\) are simultaneously recorded by the data acquisition system. \(P_{TEM.out}\) is then calculated from the recorded \(U_{TEM.out}\) and \(I\).

Based on the experimental data of Skutterudite TEM, \(R_{ct}\), \(K_{ct,h}\) and \(K_{ct,c}\) can be expressed respectively as follows:

\[ R_{ct} = 0.03\Omega \] (3.27)
Figure 3.9: Experimental data and simulation results of Skutterudite TEM test with error bars.

\[ K_{ct,h} = (1.04 \times 10^{-4}T_{hd} + 0.392)W/K \]  
\[ K_{ct,c} = (1.04 \times 10^{-4}T_{cd} + 0.392)W/K \]

The validation results and tuning parameters of thermal contact conductances \((K_{ct,h} \text{ and } K_{ct,c})\) and electrical contact resistances \((R_{ct})\) are presented in Figure 3.9. It shows that the TEM model predicts the performance of skutterudite TEM with good accuracy and the mean absolute error for open circuit voltage \((U_{TEM.ocv})\) and power output \((P_{TEM.out})\) are respectively 1% and 5%. This validation shows that both the electrical contact resistance and thermal contact conductances give a good fit for the tested Skutterudite TEM.
3.8 Summary

3.8.1 TEM Model

A quasi-static TEM model has been presented and built in this chapter. By including in the TEM model the temperature dependence of the TE material properties, the model is made more accurate. A TEM test rig has been set up for the module test. Steady-state measurements for both a Bi$_2$Te$_3$ module and a Skutterudite module are carried out on the TEM test rig. Based on these test data, the least-squares optimization strategy is used for the tuning of thermal contact resistance and electrical contact resistance. Simulation results of both the Bi$_2$Te$_3$ TEM model and the Skutterudite TEM model have shown a strong consistency with the test results. It consistency strongly suggests that this TEM modelling and validation method can also be used to model thermoelectric modules made by any other thermoelectric materials.

An important application of this TEM model is to predict the performance of a TEG that include modules of different types. In Chapter 4 of the thesis, the integration of these validated TEM models in a TEG model is described and the results presented.

3.8.2 A Comparison of Bi$_2$Te$_3$ and Skutterudite TEMs

Different thermoelectric materials have different temperatures at which the TEM is able to generate its maximum power and conversion efficiency. This temperature for the Bi$_2$Te$_3$ TEM is lower than that of Skutterudite TEM as illustrated in Figures 3.8 and 3.9. Therefore, the Skutterudite TEM can be installed on a TEG working in a high temperature environment (400-600°C), such as WHR of gasoline engines. In comparison, the melting temperature of Bi$_2$Te$_3$ TEM is only around 250°C. This implies that the Bi$_2$Te$_3$ TEM is relativity less suitable for high temperature gasoline engine WHR application, but can be used in relatively lower temperature diesel engine WHR application. Therefore, in the next chapter a Bi$_2$Te$_3$ TEG prototype and a Skutterudite TEG prototype are respectively tested on a diesel engine test bench and a gasoline engine test bench.
Chapter 4

Dynamic TEG Model

This chapter explains the modelling and validation process of a dynamic TEG model. Both a Bi$_2$Te$_3$ and a Skutterudite TEG model have modelled based on the TEM model described in Chapter 4. Both a TEG diesel engine test bench and a TEG gasoline engine test bench have been set up for the TEG engine tests of the Bi$_2$Te$_3$ TEG prototype and the Skutterudite TEG prototype, respectively. Both the Bi$_2$Te$_3$ and Skutterudite TEGs are validated using steady-state operating points as well as the dynamic engine cycle tests data. Simulation results show that the models can accurately predict the TEG’s dynamic behaviour.
4.1 Importance of Dynamics in TEG Modelling

In the development of TEG for WHR, a number of modelling studies have been carried out to evaluate the performance [130–135] and optimize the design parameters [136–139]. However, only a few of studies [132, 134, 135, 138, 139] took the dynamics of the WHR system into account. In fact, the transient performance of TEG is important, especially in the application of vehicle WHR.

First of all, the exhaust heat flow often changes during a normal operation of the car where start-up, shut-down, and engine load changes are a major concern. Yu et al. [134] developed a dynamic numerical model of TEG WHR model and found that the changing vehicle speed was a critical factor affecting the TEG performance and that the increased vehicle speed led to a fast response and better performance of TEG. He et al. [139] found that increase in exhaust temperature led to an increase in the optimal length and reduction in the optimal width based on a dynamic optimization simulation. Secondly, the highly temperature dependent characteristic of the thermoelectric properties also underlines the importance of understanding dynamic operation of the TEG system. The simulation results presented by Meng et al. [138] showed that the temperature dependence of thermoelectric properties had a significant effect on the power, efficiency and optimal variables of TEG. Thirdly, the temperature of the cold end of the TEG, which is usually integrated with engine coolant is also subject to change according to the flow rate of cooling unit and operation of radiator. Gou et al. [132] investigated the dynamic characteristics of TEG using a theoretical dynamic model and found out that enhancing heat dissipation on the cold side could lead to a greater improvement on TEG performance than enhancing heat transfer on hot side. Meng et al. [135] studied the transient behaviour of the TEG when cold end temperature changed. The response hysteresis of the output power to the cold end temperature was observed. The conversion efficiency of TEG was found to overshoot and undershoot respectively in the decreasing and increasing cases of cold end temperature.

Based on previous studies [132, 134, 135, 138, 139] for the transient behaviour of TEG, more reliable performance prediction and appropriate optimization guidance has emerged. However, an important function for a dynamic TEG model to enable safe operation of the TEG system and effective operation of aftertreatment system has been neglected. The maximum
The temperature limit for the most popular bismuth tellurium module is 250 °C \[140\] while the exhaust temperature of a diesel engine and a gasoline engine can be respectively higher than 400 °C and 800 °C. Besides, when the TEG is integrated upstream of after-treatment system, the outlet temperature of TEG can affect the catalytic conversion \[76\].

Therefore, a dynamic TEG model is needed to capture both the dynamics of the temperatures for the hot end and outlet exhaust and create a basis for developing temperature control strategies. The primary objective of the chapter is to develop a modular dynamic TEG model applied to WHR for engines. In contrast to the previously mentioned dynamic TEG models \[132,134,135,138,139\], an important feature of the model is its ability to capture the dynamics of the temperatures for the hot end and outlet exhaust, which can be used for a model-based temperature control design (Chapter 5).
4.2 TEG Dimension

The configuration of a TEG system with counter flow type HXRs is presented in Figures 4.1 and 4.2. The TEG system is symmetrical about the hot channel. For the purposes of analysis the structure of the TEG system, it is divided into three major regions: hot end, cold end, and central region. Both the hot and cold end are made up of a HXR and an aluminium plate. The hot side HXR can be connected to the exhaust pipe of an engine and cold side HXR is connected to an engine coolant or a separate chiller. The function of the aluminium plates is to even out the temperature distribution along the flow direction and reduce the spreading resistance with their relatively higher thermal conductivity. Although aluminium plates contribute to an increase of thermal resistance, an optimal thickness of aluminium plate can increase the average delta temperature of all TEMs on the HXRs [141]. The central region consists of a number of TEMs and insulation materials. It is assumed that all the TEMs are evenly distributed on the surface of HXR and electrically connected in series. The air gap between the TEMs are filled with insulation materials, which can effectively reduce the possible heat leakage through the air gaps.

Geometric parameters for the plate-fin hot side HXR are shown in Figure 4.3. $L_{h_{xrr}}$ is the length of the heat exchanger. $W_{h_{xrr}}$ is the width of the hot side HXR. $H_{h_{xrr}}$ is the height of the hot side HXR. $\delta_{h_{xrr}}$ is the fin thickness. $B_{h_{xrr}}$ is the space between the fins. $N_{fin}$ is the number of the fins.
The heat transfer area of the plate-fin hot side HXR can be calculated as:

$$A_{hxr} = 2N_{fin}A_{fin} + 2A_{base}$$

(4.1)

Where $A_{fin}$ and $A_{base}$ are respectively the exposed area of one fin and the exposed area of the base plate. They can be calculated as follows:

$$A_{fin} = H_{hxr}L_{hxr}$$

(4.2)

$$A_{base} = L_{hxr}W_{hxr} - N_{fin}\delta_{hxr}L_{hxr}$$

(4.3)

$D_{hxr}$ is the hydraulic diameter of plate-fin hot side HXR. Based on the structure of the plate-fin exchanger, $D_{hxr}$ can be calculated as follow:

$$D_{hxr} = \frac{4(H_{hxr} - \delta_{hxr})(B_{hxr} - \delta_{hxr})}{2(H_{hxr} - \delta_{hxr}) + 2(B_{hxr} - \delta_{hxr})}$$

(4.4)
4.3 Model Structure

The TEG model can be divided into two models: a quasi-stationary TEM model and a dynamic TEG model. The quasi-stationary TEM model converts the thermal energy into electricity based on hot and cold side temperatures of the TEM. A quasi-stationary model is used because of the much faster electric response than thermal response [135]. Since the thermal masses of both sides of the HXRs are significantly larger than the TEMs and dominate the thermal dynamics of the TEG system, energy transfer at the hot and cold end of the TEG system are simulated by dynamic models. The structure and parameters of the model are shown in Figure 4.4.

4.4 Assumption

The following assumptions are made for the TEG model:
• The main heat leakage is the heat flow through the insulation materials. Both radiative and convective heat loss from the TEG system to the surroundings are neglected.

• The flow rates for both exhaust gas and coolant are assumed to stay constant along the flow direction. Both exhaust gas and coolant density variation with temperature change in TEG are sufficiently small to have no practical effect on the predictions.

• Heat conduction along the flow rate direction is ignored in each control volume, as heat conduction perpendicular to the flow direction is dominant. Temperature inside each component is uniformly distributed in each control volume.

• The hot and cold ends of the TEG are assumed to be lumped-capacity systems.

4.5 Modelling

4.5.1 Control Volume Approach

The TEG model is discretized into small control volumes along the length of TEG. In this way, the variation of fluid properties and TEMs’ performance changing with temperature along the flow direction are taken into consideration. Since the TEG is symmetric with respect to its height, only half of the domain is simulated here. As shown in Figure 4.5 the TEG is equally divided into $n_{CV}$ control volumes. The heat transfer area, mass of the HXRs
Figure 4.6: Temperature distribution and energy transfer in \( i \)th control volume.

and aluminium plate for each control volume can be expressed as follow:

\[
A_{hxr.CV} = \frac{A_{hxr}}{n_{CV}} \tag{4.5}
\]

\[
A_{cxt.CV} = \frac{A_{cxt}}{n_{CV}} \tag{4.6}
\]

\[
A_{Ins.CV} = \frac{A_{Ins}}{n_{CV}} \tag{4.7}
\]

\[
M_{hxr.CV} = \frac{M_{hxr}}{2n_{CV}} \tag{4.8}
\]

\[
M_{cxt.CV} = \frac{M_{cxt}}{n_{CV}} \tag{4.9}
\]
Each control volume has its own inlet and outlet exhaust temperature and coolant temperature. The outlet temperatures of a control volume are also the inlet temperatures for the control volume next to it. In each control volume, it is assumed that there is a uniform distribution of TEMs: one TEM in flow direction and \( n_{TEM} \) TEMs perpendicular to the flow direction.

Since all the control volumes have the same structure, here the \( i \)th control volume is chosen as an example. The temperature distribution and energy transfer in the \( i \)th control volume are presented in Figure 4.6. \( T_{exh,i} \), \( T_{exh,i+1} \), \( T_{col,i+1} \), \( T_{col,i} \) are respectively exhaust gas-in temperature, exhaust gas-out temperature, coolant-in temperature, and coolant-out temperature. \( T_{hd,i} \) and \( T_{cd,i} \) are respectively the temperature for the hot and cold end. The temperature drop or increase of the fluid in both sides of the heat exchangers can be modelled by solving a simple partial differential equation [142]. The gas-out temperature \( T_{exh,i+1} \) and coolant-out temperature \( T_{col,i} \) can be respectively expressed as:

\[
T_{exh,i+1} = T_{hd,i} + (T_{zh,i} - T_{hd,i}) e^{-\frac{h_{exh} A_{exh}}{c_{exh} V_{exh}}}
\]

\[
T_{col,i} = T_{cd,i} - (T_{cd,i} - T_{col,i+1}) e^{-\frac{h_{col} A_{col}}{c_{col} V_{col}}}
\]

where \( h_{exh} \) and \( h_{col} \) are respectively the heat transfer coefficient of the hot and cold side XHR.

4.5.2 Modelling of Hot and Cold Ends

By treating both hot and cold ends as lumped-capacity systems and assuming infinitely fast conductivity along the flow direction, the energy equations for hot end and cold end are expressed respectively as:

\[
(M_{hxr, CV} c_{hxr} + M_{ap, CV} c_{ap}) \frac{dT_{hd,i}}{dt} = Q_{hxr,i} - Q_{hm,i} - Q_{ins,i}
\]
\[
(M_{cxr, CV} c_{cxr} + M_{ap, CV} c_{ap} \frac{dT_{cd.i}}{dt}) = Q_{Ins.i} + Q_{cm.i} - Q_{cxr.i}
\] (4.14)

\(Q_{hm.i}\) and \(Q_{cm.i}\) are respectively the heat conducted from the hot end to the central section and the heat conducted from the central section to the cold end. Based on energy conservation and the symmetrical characteristics of the TEG system, the heat absorbed by the hot side HXR \(Q_{hxr.i}\) and the heat dissipated to cold side HXR \(Q_{cxr.i}\) can respectively be expressed as follows:

\[
Q_{hxr.i} = \frac{1}{2} (T_{exh,i} - T_{exh,i+1}) \dot{m}_{exh} c_{exh}
\] (4.15)

\[
Q_{cxr.i} = (T_{col,i} - T_{col,i+1}) \dot{m}_{col} c_{col}
\] (4.16)

\(Q_{Ins.i}\) is the heat conducted through the insulation materials between the TEMs, which can be expressed as:

\[
Q_{Ins.i} = K_{Ins}(T_{hd,i} - T_{cd,i})
\] (4.17)

where \(K_{Ins}\) is the thermal conductance of the insulation materials, which can be calculated by:

\[
K_{Ins} = \frac{k_{Ins} A_{Ins, CV}}{l_{TEM}}
\] (4.18)

**4.5.3 Modelling of Central Region**

Since the hot end and cold end are closely connected to the hot sides and cold sides of the TEMs, the hot end and cold end temperatures \(T_{hd,i}\) and \(T_{cd,i}\) are assumed respectively to be equal to the previous hot side and cold side temperatures of the TEM \(T_{cp.h}\) and \(T_{cp.c}\).

\[
T_{hd,i} = T_{cp.h}
\] (4.19)
\[ T_{cd,i} = T_{cp,c} \quad (4.20) \]

It is assumed that \( T_{hd,i} \) and \( T_{cd,i} \) are distributed uniformly in each control volume. \( Q_{hm,i} \) and \( Q_{cm,i} \), which can then be calculated based on the previous TEM model, are expressed respectively as follows:

\[ Q_{hm,i} = n_{TEM} Q_{hm} \quad (4.21) \]

\[ Q_{cm,i} = n_{TEM} Q_{cm} \quad (4.22) \]

Then, the hot and cold side temperatures of the TEM \( T_{cp,h} \) and \( T_{cp,c} \) can be solved. Based on the previous TEM model, both the output voltage of the TEM \( U_{TEM.out} \) and its power output \( P_{TEM.out} \) can be calculated. Since all the TEMs are connected in series and the TEG system is symmetrical, the overall output voltage \( U_{CV.out} \) and power output \( P_{CV.out} \) in \( ith \ CV \) can be expressed respectively as follows:

\[ U_{CV.out} = 2n_{TEM} U_{TEM.out} \quad (4.23) \]

\[ P_{CV.out} = 2n_{TEM} P_{TEM.out} \quad (4.24) \]

The overall output voltage \( U_{out.TEG} \) and power output \( P_{TEG.out} \) of the TEG system can be expressed respectively as:

\[ U_{TEG.out} = \sum_{i=1}^{n_{CV}} U_{CV.out} \quad (4.25) \]

\[ P_{TEG.out} = \sum_{i=1}^{n_{CV}} P_{CV.out} \quad (4.26) \]
4.6 TEG Engine Test Bench Setup

4.6.1 TEG Diesel Engine Test Bench Setup

The scheme of the TEG diesel engine test bench and its structure are shown in Figures 4.7 and 4.8. The engine used in this study is a CAT C6.6 heavy-duty diesel engine. This is a six cylinder, 6.6 litre engine equipped with a common rail fuel system and its parameters are shown in Table 4.1. This engine is installed in a test bed with a Froude AG400-HS eddy current dynamometer controlled by a CP Engineering Cadet V14 dynamometer control system. The TEG system is mounted on the exhaust gas recirculation (EGR) path of the engine, which has been specially modified for the purposes of the TEG research. The EGR valve is used to control the flow rate and protect the TEG system in high temperatures. Four European Thermodynamics Bi$_2$Te$_3$ modules (GM250-127-28-10) are sandwiched, assembled with two TEMs on each side of the hot side HXR. All the TEMs are electrically connected.
Figure 4.8: The TEG diesel engine test bench and its structure diagram.

Table 4.1: Datasheet of the CAT C6.6 heavy-duty diesel engine

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<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
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<td>Architecture</td>
<td>I6</td>
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<tr>
<td>Fuel</td>
<td>Diesel</td>
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<td>Stroke</td>
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<tr>
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<td>Direct Injection</td>
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<td>Emission control</td>
<td>HP EGR, DOC-DPF</td>
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</tbody>
</table>
in series with $R_{load}$. The same clamping force ($F=3000\text{N}$) is applied, which is measured by a load cell. The cold side of the TEG is maintained using chilled water from a laboratory recirculation chiller. The temperatures are measured by a number of thermocouple sensors, which are respectively installed upstream and downstream of the hot side HXR ($T_{exh.\text{in}}$ and $T_{exh.\text{out}}$), upstream and downstream of the cold side HXR ($T_{col.\text{in}}$ and $T_{col.\text{out}}$), and in the hot and cold side aluminium plates ($T_{hd}$ and $T_{cd}$). Flow meters are used to measure the flow rates of exhaust gas in the EGR path $\dot{m}_{exh}$ and coolant $\dot{m}_{col}$. The data acquisition system used in the experimental work consists of a NI CRIO chassis and a 16bit analog input module. It simultaneously records the data of all the temperatures and voltage $U_{\text{TEG.out}}$ and current $I$. The uncertainty for voltage and current measurements are respectively $\pm 0.05 \text{A}$ and $\pm 0.05 \text{V}$. The maximum uncertainty for measuring the temperature is $\pm 1 \text{°C}$. Then according to the uncertainty analysis theory, the maximum uncertainty of the computed electrical power is about $\pm 5\%$. 

Figure 4.9: The TEG gasoline engine test bench.
Table 4.2: Datasheet of the GTDI 2.0 litre I4 gasoline engine

<table>
<thead>
<tr>
<th>Specification</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Displacement</td>
<td>1.999 litre</td>
</tr>
<tr>
<td>Fuel</td>
<td>Gasoline</td>
</tr>
<tr>
<td>Architecture</td>
<td>I4 Turbocharged direct injection</td>
</tr>
<tr>
<td>Maximum power</td>
<td>176.5 kW 5500 rpm</td>
</tr>
<tr>
<td>Maximum torque</td>
<td>340Nm 1750 rpm</td>
</tr>
<tr>
<td>Bore</td>
<td>86.7mm</td>
</tr>
<tr>
<td>Stroke</td>
<td>83.8mm</td>
</tr>
<tr>
<td>Compression Ratio</td>
<td>9.3:1</td>
</tr>
</tbody>
</table>
4.6.2 TEG Gasoline Engine Test Bench Setup

The scheme of TEG gasoline engine test bench is shown in Figure 4.9. The TEG is installed downstream of the TWC of the gasoline engine. The engine used in this study is a JLR production 2litre, I4 DI boosted gasoline engine. The parameters for the gasoline engine are shown in Table 4.2. The exhaust pipe has been specially modified for the purposes of TEG research and a bypass is added so as to protect TEG from the effects of high temperature. This engine is installed on a test bench with a dynamometer. The dynamometer is the same as the diesel engine test bench, which can be used to simulate different driving cycles. Instead of being integrated with the engine cooling system, the cold side temperature of the prototype TEG is maintained using chilled water from a laboratory recirculation chiller. Due to the limitations on the amount of thermoelectric material available for testing, only 12 skutterudite TEMs are placed on a hot side HXR, which has the same dimensions as the hot side HXR used in TEG diesel engine test bench. In order to balance the energy distribution, a same size ceramic plate is placed on the other side of hot side HXR. While only one channel (a hot side HXR and two cold side HXRs) has been tested. Here it is assumed that the TEG engine test of one channel is representative and the power output can be scaled according to the number of channels. The test data is recorded by the same data acquisition system used in TEG diesel engine test bench. The parameters of the two TEG system are presented in Table 4.3.

4.7 Parameter Estimation and Validation

4.7.1 Parameter Estimation Method

A majority of references [132, 134, 135, 139, 143] point out the heat transfer coefficient of the HXR in the form of Nusselt-Reynolds-Prandtl relations. However, there is a large variations in the expression of Nusselt numbers due to its high variability in the exhaust heat transfer [144]. Thus, the heat transfer coefficient of HXR needs to be tuned based on the tested HXR. The heat transfer coefficients of hot and cold side HXRs $h_{hxr}$ and $h_{cxr}$ can be expressed as Nusselt-Reynolds-Prandtl relations as follows:
<table>
<thead>
<tr>
<th>Variables</th>
<th>Bi$_2$Te$_3$ TEG</th>
<th>Skutterudite TEG</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of control volumes $n_{CV}$</td>
<td>2</td>
<td>3</td>
</tr>
<tr>
<td>Number of TEMs in a control volume $n_{TEM}$</td>
<td>1</td>
<td>4</td>
</tr>
<tr>
<td>Heat transfer area of the hot side HXR $A_{hx}$</td>
<td>0.16m$^2$</td>
<td>0.16m$^2$</td>
</tr>
<tr>
<td>Heat transfer area of the cold side HXR $A_{cx}$</td>
<td>0.024m$^2$</td>
<td>0.024m$^2$</td>
</tr>
<tr>
<td>Area of the overall insulation materials on one side $A_{Ins}$</td>
<td>0.017m$^2$</td>
<td>0.021m$^2$</td>
</tr>
<tr>
<td>Hydraulic diameter of hot side HXR $D_{hx}$</td>
<td>0.013m</td>
<td>0.013m</td>
</tr>
<tr>
<td>Hydraulic diameter of cold side HXR $D_{cx}$</td>
<td>0.007m</td>
<td>0.007m</td>
</tr>
<tr>
<td>Mass of the hot side HXR $M_{hx}$</td>
<td>0.64kg</td>
<td>0.64kg</td>
</tr>
<tr>
<td>Mass of the cold side HXR $M_{cx}$</td>
<td>3kg</td>
<td>3kg</td>
</tr>
<tr>
<td>Mass of an aluminium plate $M_{ap}$</td>
<td>0.05kg</td>
<td>0.05kg</td>
</tr>
<tr>
<td>Specific heat capacity of the hot side HXR $c_{hx}$</td>
<td>500J/(kg.K))</td>
<td>500J/(kg.K))</td>
</tr>
<tr>
<td>Specific heat capacity of the cold side HXR $c_{cx}$</td>
<td>950J/(kg.K))</td>
<td>950J/(kg.K))</td>
</tr>
<tr>
<td>Specific heat capacity of the aluminium $c_{ap}$</td>
<td>900J/(kg.K))</td>
<td>900J/(kg.K))</td>
</tr>
<tr>
<td>Thermal conductivity of insulation materials $k_{Ins}$</td>
<td>0.025W/(m.K)</td>
<td>0.025W/(m.K)</td>
</tr>
</tbody>
</table>
\[
    h_{hXR} = \frac{N_u}{D_{hXR}} k_{exh} = \frac{b_{hXR,0} Re^{b_{hXR,1}} Pr^{b_{hXR,2}}}{D_{hXR}} k_{exh}
\]

(4.27)

\[
    h_{cxr} = \frac{N_u}{D_{cxr}} k_{col} = \frac{b_{cxr,0} Re^{b_{cxr,1}} Pr^{b_{cxr,2}}}{D_{cxr}} k_{col}
\]

(4.28)

where \( D_{hXR} \) and \( D_{cxr} \) are respectively the hydraulic diameters for hot and cold side HXRs. The tuning parameters for the TEG model are \( b_{hXR,0}, b_{hXR,1}, b_{hXR,2} \) for \( h_{hXR} \) and \( b_{cxr,0}, b_{cxr,1}, b_{cxr,2} \) for \( h_{cxr} \).

The tuning and validation of the TEG model is based on a validated TEM model and is conducted in two steps. First of all, measurements of the TEG performance at steady-state engine operating points are used to tune the heat transfer coefficients of both side HXRs. Secondly, measurements of the TEG performance during transient engine cycle test are compared with the model output. This comparison forms the basis for the validation of the model. Since the same clamping force, TEMs, aluminium plates, and electrical connecting method are used, the tuning parameters of the TEM model are assumed to be the same for the TEG model validation. Based on the steady-state data from TEG engine test, the tuning parameters for the TEG model are estimated using a least-squares optimization that minimizes errors both in output voltage and exhaust gas-out temperature.

\[
    \min J_2(h_{hXR,0}, h_{hXR,1}, h_{hXR,2}, b_{cxr,0}, b_{cxr,1}, b_{cxr,2})
\]

(4.29)

\[
    b_{hXR,0}, b_{hXR,1}, b_{hXR,2}, b_{cxr,0}, b_{cxr,1}, b_{cxr,2} \subseteq \text{feasible set of heat transfer coefficients}
\]

where \( J_2 \) is the cost function given by

\[
    J_2 = (U_{TEG, out} - U_{TEG, out, meas})^2 + (T_{exh, out} - T_{exh, out, meas})^2
\]

(4.30)

\( U_{TEG, out} \) and \( T_{exh, out} \) are respectively model output and \( U_{TEG, out, meas} \) and \( T_{exh, out, meas} \) are respectively measured data.
4.7.2 Bi$_2$Te$_3$ TEG Parameter Estimation and Validation

4.7.2.1 Parameter Estimation and Stationary Validation

Ten steady-state TEG engine tests with five different EGR positions and two different engine loads are conducted here. Test data is recorded when it is stable. Each test is repeated at least three times to obtain reproducible results. The mean value of the experimental data is used as the final experimental data. The steady-state data is measured under the specific operating conditions as follows:

- Engine speed is set as constant 1500 rpm.
- $R_{\text{load}}$ is set as constant 10 $\Omega$.
- Coolant temperature and flow rate are set respectively as 10 $^\circ$C and 0.095 kg/s.
- Engine load is set as constant 400 Nm or 500 Nm.
- The EGR value positions are set as 0.1, 0.2, 0.3, 0.4 and 0.5 respectively.

The final tuning results for $h_{hr}$ and $h_{xr}$ are expressed as follows:

$$h_{hr} = \frac{0.99Re^{0.0002}Pr^{0.33}}{D_{hr}}k_{exh} \quad (4.31)$$

$$h_{xr} = \frac{0.023Re^{0.8}Pr^{0.33}}{D_{xr}}k_{col} \quad (4.32)$$

A comparison of the simulation and test results including error bars for $U_{\text{TEG.out}}$ and $T_{\text{exh.out}}$ at different EGR positions are plotted in Figures 4.11 and 4.12. It can be seen that both simulation results correspond well with the test results. The calculated MAE for $U_{\text{TEG.out}}$ and $T_{\text{exh.out}}$ are 3.8 % and 4.6 % respectively. The relatively bigger errors for $T_{\text{exh.out}}$ can be explained as follows: The underestimation of $T_{\text{exh.out}}$ at lower EGR values is due to the measurements of $T_{\text{exh.out}}$ being influenced by the relatively higher temperature of the pipe wall when $\dot{m}_{exh}$ is low. The overestimation at higher EGR values can be explained by neglecting the effects of radiation and convection to the ambient when developing the TEG model.
Figure 4.11: Output voltage at different EGR positions with error bars.

Figure 4.12: Gas-out temperature at different EGR positions with error bars.
Figure 4.13: Experimental data and simulation results of NRTC for $P_{TEG.out}$.

### 4.7.2.2 Dynamic Validation

A non-road transient cycle (NRTC) is conducted in the TEG diesel engine test bench to validate the $Bi_2Te_3$ TEG model. NRTC is the type test cycle specified for non-road applications of heavy duty engines to be sold in the USA and the EU. The NRTC is specified by the EPA [145]. In order to limit the maximum temperature seen by the TEMs to $250 \, ^\circ C$, the NRTC torque profile was scaled to 0.3 of its normal value. The dynamic data is measured under the specific operating conditions as follows:

- Engine is set to run 30 % torque NRTC.
- Coolant temperature and flow rate are set respectively as $10 \, ^\circ C$ and $0.095 \, \text{kg/s}$.
- The EGR value positions is set as 0.5.
- $R_{load}$ is set as constant $0.3 \, \Omega$.
Figure 4.14: Experimental data and simulation results of NRTC for $T_{exh.out}$.

Figure 4.15: Experimental data and simulation results of NRTC for $T_{hd}$.
The comparison between the simulation results and test data for $P_{TEG.out}$ of NRTC is presented in Figure 4.13. It shows an agreement between the simulation and experimental results. The mean difference between measurement and simulation is 0.33 W, which is 7\% regarding average power output of the cycle. The maximum deviation is around 1 W, which occur at operating points of sudden torque change. This can be explained by the uncertainty in heat transfer coefficients and inertia of the test equipment.

Figures 4.14 and 4.15 respectively show comparisons of predicted and measured gas-out temperature ($T_{exh.out}=T_{exh.3}$) and hot end temperature ($T_{hd} = \frac{T_{hd.1}+T_{hd.2}}{2}$). The simulation result shows that the dynamics of both $T_{exh.out}$ and $T_{hd}$ are well captured by the model. In comparison with the measured data, the average absolute error for $T_{exh.out}$ is 10 K and the maximum deviation is 41 K, which happens at time periods with intensive temperature fluctuation caused by sudden torque change. For $T_{hd}$, the average absolute error is 7 K and the maximum error is about 18 K, which occur at the beginning of the test cycle and also at the temperature fluctuation period. The error at the beginning is due to the start up process of the model itself.

4.7.3 Skutterudite TEG Parameter Estimation and Validation

4.7.3.1 Parameter Estimation and Stationary Validation

Ten steady-state TEG engine tests with five different bypass valve positions and two different engine loads are conducted here. Test data is recorded when it is stable. Each test is repeated at least three times to obtain reproducible results. The mean value of the experimental data is used as the final experimental data. The steady-state data is measured under the specific operating conditions as follows:

- Engine speed is set as constant 2000 rpm.
- $R_{load}$ is set as constant 1Ω.
- Coolant temperature and flow rate are set respectively as 10 °C and 0.095 kg/s.
- Engine load is set as constant 100 N.m or 150 N.m.
- The bypass valve positions are set as 0.4, 0.3, 0.2, 0.1 and 0 respectively.
Figure 4.16: Output voltage at different flow rate with error bars.

Figure 4.17: Gas-out temperature at different flow rate with error bars.
Figure 4.18: Validation of the Skutterudite TEG model.

A comparison of the simulation and test results including error bars for $U_{\text{TEG.out}}$ and $T_{\text{exh.out}}$ at different flow rates are plotted in Figures 4.16 and 4.17. It can be seen that both simulation results correspond well with the test results. The calculated MAE for $U_{\text{TEG.out}}$ and $T_{\text{exh.out}}$ are 4.2 % and 2.6 % respectively. The relatively bigger errors for $T_{\text{exh.out}}$ and $U_{\text{TEG.out}}$ both occurred at lower flow rate. This can be explained by the exhaust energy loss through the bypass pipe wall when bypass valve positions is high.

4.7.3.2 Dynamic Validation

A worldwide harmonized light vehicles test procedure (WLTP) is conducted in the TEG gasoline engine test bench to validate the Skutterudite TEG model. WLTP is the new test cycle defining a global harmonized standard for determining the levels of pollutants and CO$_2$ emissions, fuel or energy consumption, and electric range from light-duty vehicles.
The WLTP will replace the current NEDC test procedure for establishing the official Fuel Consumption and CO$_2$ emissions of new cars in the EU. The dynamic data is measured under the specific operating conditions as follows:

- Engine is set to run 100% torque WLTP.
- Coolant temperature and flow rate are set respectively as 5°C and 0.095 kg/s.
- The bypass valve is closed.
- $R_{\text{load}}$ is set as constant 0.3 Ω.

The validation results for the TEG model with 12 Skutterudite TEMs in a WLTP test is presented in Figure 4.18. It can be seen that the simulation results for both exhaust-out temperature ($T_{\text{exh.out}}$) and power output ($P_{\text{TEG.out}}$) correspond well with the measurements. The mean absolute errors are respectively 7.4% and 4.8%. It can be seen that both dynamics for exhaust temperature and power output are well captured. The relatively high error for the temperature prediction at the beginning can be explained by the slow dynamics of the temperature sensor at low temperature. Since the exhaust temperature at high engine load are more concerned, the validation result is acceptable.

### 4.8 Summary

#### 4.8.1 TEG Model

This chapter focuses on the development of a dynamic model of TEG system designed for vehicular WHR, which is made up of counter-flow heat exchangers (HXRs) and commercial thermoelectric modules (TEMs). This dynamic TEG model is based on the developed and validated TEM model in Chapter 3. Based on a control volume approach, the gas properties and heat transfer along the HXR are more precisely described than in previous studies. Thermal inertia of the HXRs is taken into account in the model so that dynamic behaviour of the system is included. Both a Bi$_2$Te$_3$ and a Skutterudite TEG prototype have been respectively installed on the EGR path of a heavy-duty diesel engine and downstream the TWC of a light duty gasoline engine. Based on these test data, the least-squares optimization
strategy is used for the tuning of heat transfer coefficient in hot side and cold side HXRs. Both the Bi$_2$Te$_3$ and Skutterudite TEGs are validated by steady-state operating points as well as the dynamic engine cycle test data. Simulation results show that the dynamic TEG models can predict its dynamics with an acceptable accuracy.

As can be seen from the literature review in Chapter 2, the development of the TEG system has to address a wide range of design issues including thermoelectric material selection, heat exchanger design, and the integration of the TEG into the vehicles. In general, these design problems cannot be studied and solved simultaneously at the development stage, for it is profoundly difficult to evaluate the effect of each design parameter using physical experiments. Therefore, a model-based design approach can be one of the most efficient techniques to reduce the development time and cost while minimizing the requirement of experimental equipment. The validated dynamic TEG model will be further used in the TEG performance prediction, parameter sensitivity analysis, and model-based control system design in Chapter 5.

4.8.2 A Comparison of Bi$_2$Te$_3$ and Skutterudite TEGs

The temperature limitation of the Bi$_2$Te$_3$ TEM prevented the Bi$_2$Te$_3$ TEG prototype being tested in high speed and load conditions of the diesel engine. Even in the relatively lower exhaust temperature of diesel engine, a bypass solution is still needed to protect the Bi$_2$Te$_3$ TEG prototype under high speed and load engine conditions. Therefore, a lot of thermal energy at high temperature escape without recovery in the Bi$_2$Te$_3$ TEG. The control system for the bypass valve needs to be well developed to ensure the safety of the TEG and achieve the maximum energy recovery at the same time.

In comparison, the Skutterudite TEG can withstand higher temperatures and is more suitable to be used in gasoline engine WHR. Larger temperature gradients were achieved in the test of the Skutterudite TEG prototype. As can be seen from the test result, the need for a bypass can be reduced by wisely choosing the installing position of the Skutterudite TEG in the exhaust line of gasoline engine.
Chapter 5

Applications of the Dynamic TEG Model

For the work reported in this thesis, the dynamic TEG model has been used to support three research themes:

- as a basis for the investigation of temperature control strategies,
- for the performance prediction of new TEG designs,
- to support an investigation of the sensitivity of TEG performance to design parameters.

In this chapter, these three applications of the Bi$_2$Te$_3$ TEG model are presented. Three different integration scenarios of a Bi$_2$Te$_3$ TEG with a heavy-duty diesel engine are assumed and modelled in this chapter. By using the Bi$_2$Te$_3$ TEG model, two model-based temperature control systems have been proposed. The power outputs of TEG in the three scenarios are simulated and compared. A sensitivity analysis of TEG parameters to the power output is performed.
Figure 5.1: $\text{Bi}_2\text{Te}_3$ TEG system used for WHR in a heavy-duty diesel engine.

### 5.1 $\text{Bi}_2\text{Te}_3$ TEG Integration with a Heavy-duty Diesel Engine

Figure 5.1 shows the structure and size of this $\text{Bi}_2\text{Te}_3$ TEG system. It can be seen that the TEG has the same structure as the previous modelled TEG in Chapter 4. The TEG is assumed to be 16cm wide by 40cm long, with 10 ($n_{CV}=5$, $n_{TEM}=2$) $\text{Bi}_2\text{Te}_3$ TEMs (GM250-127-28-10) on each side. All 20 TEMs are electrically connected in series with $R_{\text{load}}=6\ \Omega$, which is matched to the internal resistance of the TEG system. The specification for this $\text{Bi}_2\text{Te}_3$ TEG system is presented in Table 5.1.

The TEG is assumed to be integrated in a 6.6 litre heavy-duty diesel engine whose specification is shown in Table 5.2. As can be seen from Table 5.2, a High Pressure (HP) EGR system and Diesel Oxidation Catalyst-Diesel Particulate Filter (DOC-DPF) system are applied for
Table 5.1: Specification for the Bi$_2$Te$_3$ TEG

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dimension of hot side HXR [m]</td>
<td>0.40 × 0.16 × 0.02</td>
</tr>
<tr>
<td>Dimension of cold side HXR [m]</td>
<td>0.40 × 0.16 × 0.02</td>
</tr>
<tr>
<td>Heat transfer area of the hot side HXR $A_{hxr}$ [m$^2$]</td>
<td>1.6</td>
</tr>
<tr>
<td>Heat transfer area of the cold side HXR $A_{cxr}$ [m$^2$]</td>
<td>0.24</td>
</tr>
<tr>
<td>Area of the overall insulation materials on one side $A_{Ins}$ [m$^2$]</td>
<td>0.085</td>
</tr>
<tr>
<td>Total number of TEMs [-]</td>
<td>20</td>
</tr>
<tr>
<td>Hydraulic diameter of hot side HXR $D_{hxr}$ [m]</td>
<td>0.013</td>
</tr>
<tr>
<td>Hydraulic diameter of cold side HXR $D_{cxr}$ [m]</td>
<td>0.007</td>
</tr>
<tr>
<td>Mass of the hot side HXR $M_{hxr}$ [kg]</td>
<td>4</td>
</tr>
<tr>
<td>Mass of the cold side HXR $M_{cxr}$ [kg]</td>
<td>5</td>
</tr>
<tr>
<td>Mass of an aluminium plate $M_{ap}$ [kg]</td>
<td>0.25</td>
</tr>
<tr>
<td>Specific heat capacity of the hot side HXR $c_{hxr}$ [J/(kg.K)]</td>
<td>500</td>
</tr>
<tr>
<td>Specific heat capacity of the cold side HXR $c_{cxr}$ [J/(kg.K)]</td>
<td>950</td>
</tr>
<tr>
<td>Specific heat capacity of the aluminium plate $c_{ap}$ [J/(kg.K)]</td>
<td>900</td>
</tr>
<tr>
<td>Thermal conductivity of insulation materials $k_{Ins}$ [W/(m.K)]</td>
<td>0.025</td>
</tr>
</tbody>
</table>

the purposes of emissions control. In order to fully present these three applications of the developed TEG model, Bi$_2$Te$_3$ TEGs with two different installation positions are assumed here, which can be seen in Figure 5.2. In Scenario 1 the Bi$_2$Te$_3$ TEG is installed in the HP EGR path. For both Scenario 2 and Scenario 3, the Bi$_2$Te$_3$ TEG is located in the low pressure exhaust path just upstream of the DOC-DPF system.

Both Scenarios 1 and 2 use the same (Bi$_2$Te$_3$) TEG. The heat transfer coefficient of hot side HXR $h_{hxr}$, heat transfer coefficient of cold side HXR $h_{cxr}$, electrical contact resistance $R_{ct}$ and thermal contact resistance $K_{ct}$ in Scenario 1 and 2 using the same functions of the validated Bi$_2$Te$_3$ TEG model. Compared to Scenario 1 and 2, Scenario 3 includes several changes. Namely, $h_{hxr}$, $h_{cxr}$, $K_{ct}$ are both 20% higher, whereas $R_{ct}$ is 20% lower. The definition of the three scenarios are presented in Table 5.3.

It is assumed that the cold side of the TEG is supplied with coolant at the normal operating temperature of the engine. Coolant conditions are assumed constant with a temperature of 80 °C and flow rate of 0.2 kg/s. The exhaust conditions of both upstream of the after-
Table 5.2: Datasheet of the 6.6 litre heavy-duty diesel engine

<p>| | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Displacement</strong></td>
<td>6.6 litre</td>
</tr>
<tr>
<td><strong>Fuel</strong></td>
<td>Diesel</td>
</tr>
<tr>
<td><strong>Peak Power</strong></td>
<td>205kW, 2200-2500rpm</td>
</tr>
<tr>
<td><strong>Bore</strong></td>
<td>105mm</td>
</tr>
<tr>
<td><strong>Stroke</strong></td>
<td>127mm</td>
</tr>
<tr>
<td><strong>Compression Ratio</strong></td>
<td>16.2:1</td>
</tr>
<tr>
<td><strong>Aspiration</strong></td>
<td>Turbocharged</td>
</tr>
<tr>
<td><strong>Combustion system</strong></td>
<td>Direct Injection</td>
</tr>
<tr>
<td><strong>Emission control</strong></td>
<td>HP EGR, DOC-DPF</td>
</tr>
</tbody>
</table>

Figure 5.2: Integration positions of Bi$_2$Te$_3$ TEG in a heavy-duty diesel engine.

Table 5.3: Definition of three integration scenarios

<table>
<thead>
<tr>
<th></th>
<th>Scenario 1</th>
<th>Scenario 2</th>
<th>Scenario 3</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>TEG location</strong></td>
<td>HP EGR path</td>
<td>Upstream of DOC-DPF</td>
<td>Upstream of DOC-DPF</td>
</tr>
<tr>
<td><strong>TEG size</strong></td>
<td>$16cm \times 40cm \times 7cm$</td>
<td>$16cm \times 40cm \times 7cm$</td>
<td>$16cm \times 40cm \times 7cm$</td>
</tr>
<tr>
<td><strong>TEMs number</strong></td>
<td>20</td>
<td>20</td>
<td>20</td>
</tr>
<tr>
<td><strong>Cooling</strong></td>
<td>$80^\circ C$, 0.2kg/s</td>
<td>$80^\circ C$, 0.2kg/s</td>
<td>$80^\circ C$, 0.2kg/s</td>
</tr>
<tr>
<td>$h_{hxr}$</td>
<td>105-125W/$m^2K$</td>
<td>105-125W/$m^2K$</td>
<td>130-150W/$m^2K$</td>
</tr>
<tr>
<td>$h_{txr}$</td>
<td>3784W/$m^2K$</td>
<td>3784W/$m^2K$</td>
<td>4730W/$m^2K$</td>
</tr>
<tr>
<td>$R_{ct}$</td>
<td>0.1$\Omega$</td>
<td>0.1$\Omega$</td>
<td>0.08$\Omega$</td>
</tr>
<tr>
<td>$K_{ct}$</td>
<td>10-13W/K</td>
<td>10-13W/K</td>
<td>12-15.6W/K</td>
</tr>
</tbody>
</table>
treatment system and in the EGR path during an NRTC run on the test engine are used as inputs to the model.

5.2 Model-based Temperature Control

Under operating conditions where there is a wide fluctuation in exhaust temperature, overheating of the hot side of Bi$_2$Te$_3$ TEMs is likely to damage the modules. At the same time, the TEG will work in concert with other exhaust system components to manage exhaust gas temperatures ensuring that each component performs according to requirements. Therefore, the temperature control of the TEG system serves two main functions:

- Protecting TEMs from high exhaust temperature,
- Ensuring an effective operation of other exhaust system components.

A bypass line is one of the most popular and effective TEG temperature control methods and has been proposed in many previous literatures [76, 77, 92, 93]. In this section, the dynamic TEG model is used as a basis for the investigation of temperature control strategies of the bypass valve. Based on two different TEG locations (in the EGR path and upstream of the DOC-DPF), two TEG temperature control strategies are presented.

5.2.1 Temperature Control of TEG in the EGR path

For the TEG installed in the EGR path, the two main control objectives for the TEG temperature control are:

- protecting the Bi$_2$Te$_3$ TEMs from high exhaust temperature;
- ensuring the EGR-out temperature is in its optimal range.

The evolution of the hot end temperature in the first control volume is presented in Figure 5.3. $T_{hd.1}$ is below the maximum temperature limit (523 K) of the Bi$_2$Te$_3$ TEMs most of the time. Only in the time from 710s to 820s, $T_{hd.1}$ exceeds 523K, which threatens the integrity of the TEMs. This evolution of hot end temperature is based on assuming the EGR valve is fully open at the entire NRTC. In reality, the EGR valve is not always full open but uses
Figure 5.3: The simulated hot end temperature of Bi$_2$Te$_3$ TEG in the EGR path.

Figure 5.4: The simulated outlet temperature of Bi$_2$Te$_3$ TEG in the EGR path.
Figure 5.5: A HP-EGR systems coupled with the TEG.

Based on the prediction of the hot end and outlet temperatures of the TEG, a HP-EGR systems temperature control coupled with the TEG is proposed and presented in Figure 5.5. The TEG is installed upstream of the EGR cooler, which can recover the waste thermal energy in the EGR gas and lower the temperature of the EGR gas. The EGR valve controls the amount of exhaust gas that flows through the TEG. The map-based control method is widely used in the EGR valve control, which computes the EGR rate in advance as a function of engine speed and load. For the EGR valve lift map, as the engine load or the engine speed increases, the EGR rate usually decreases, which effectively ensures the integrity of the TEG. To further ensure the safety of the TEG, a model-based temperature control algorithm can...
be added to regulate the EGR flow once the estimated hot end temperature (523K) has reached.

The EGR cooler is coupled with a bypass line to avoid overcooling and minimize backpressure generation and cooling loading. A feedback controller is established based on the measured outlet temperature of the TEG. In order to adequately react to sudden changes in heat input, an additional feed-forward controller is implemented based on the model-based outlet temperature prediction. When the outlet temperature of TEG is below 403K, the bypass valve is opened and the valve to the EGR cooler is closed. As a result, the exhaust gas would flow only through the bypass and the backpressure and cooling load can be reduced. When the outlet temperature of TEG exceeds 403K, the bypass valve would only allow the exhaust gas to flow through EGR cooler, Therefore, the exhaust gas in the EGR path can be further cooled in the EGR cooler.

5.2.2 Temperature Control of TEG upstream of the DOC-DPF

For the TEG installed upstream of the DOC-DPF, the two main control objectives for the TEG temperature control are:

- protecting the Bi$_2$Te$_3$ TEMs from high exhaust temperature;
- ensuring the inlet temperature of DOC in its optimal range.

The evolution of the hot end temperature in the first control volume is depicted in Figure 5.6. $T_{hd.1}$ shows a response with a time constant of about 50 s. The results indicate that a hysteresis exists in the response of $T_{exh.in}$ to $T_{hd.1}$. This hysteresis is attributed to the delay of thermal diffusion from the exhaust gas to the ceramic plate. Most of the time, $T_{hd.1}$ is below the maximum temperature limit (523K) of the TEMs. However, at 394s, 560s, 689s, and 852s, $T_{hd.1}$ exceeds 523K, which then threatens the integrity of the TEMs. In order to protect the TEMs, a temperature control is needed to lower the hot end temperature so as to ensure that the maximum temperature limit is not exceeded.

Figure 5.7 shows the outlet temperature from the TEG. The DOC-DPF system applied for after-treatment in non-road diesel engines requires an exhaust temperature management mode to ensure that inlet temperature is kept above the value required for DOC light
Figure 5.6: The simulated hot end temperature of Bi₂Te₃ TEG upstream of the DOC-DPF.

Figure 5.7: The simulated outlet temperature of Bi₂Te₃ TEG upstream of the DOC-DPF.
Figure 5.8: A bypass control system of the Bi$_2$Te$_3$ TEG upstream of the DOC-DPF.

off [149]. Here 548 K is used as a criterion for $T_{exh.out}$ to ensure an effective operation of the after-treatment system. In NRTC, $T_{exh.out}$ is usually above the temperature criterion of after-treatment system. Only at 100s, 200s, 300s, 400s, 480s, and 1280s, does a temperature control strategy need to be adopted to maintain the outlet temperature of the TEG.

Based on the control objectives, a bypass exhaust gas circuit is proposed and presented in Figure 5.5. When the bypass valve is open, the exhaust heat is shunted to the DOC. Protecting the TEG and maintain the minimum temperature of the DOC can both be achieved by adjusting the bypass value position. Both a feedback controller and a feed forward controller act on the bypass value position. The feedback controller establishes a feedback loop based on the measured temperatures of $T_{hd}$ and $T_{exh.out}$. To react adequately to the sudden changes in exhaust path, an additional feed forward controller is implemented. Based on the measured $T_{exh.in}$ and $\dot{m}_{exh}$, a prediction for $T_{hd}$ and $T_{exh.out}$ is made by the dynamic TEG model.

### 5.3 TEG Power Output Predictions

Figure 5.9 shows the evolution of electric power output $P_{TEG.out}$ in all three scenarios together with average values. It can be seen that both TEGs work effectively and show a
quick response, and reach their average power output within 200s. The simulation results show that the Bi$_2$Te$_3$ TEG recovers a significant amount of energy from the NRTC drive cycle when it is positioned in the EGR path and upstream of the DOC-DPF of a heavy duty diesel engine. The power outputs of TEG upstream of the the DOC-DPF (Scenario 2 and Scenario 3) are both higher than the TEG in the EGR path (Scenario 1). This is due to the similar temperature but much higher exhaust flow rate upstream of the DOC-DPF than in the EGR path. The average power output of TEG in the EGR path is only 132W. In comparison, the average power output in the Scenario 3 is 224W, which is 25.8% more than the Scenario 2 (178W). The maximum $P_{TEG,out}$ in Scenario 3 is 280W. 

5.4 Sensitivity Analysis for TEG Power Output

$P_{TEG,out}$ in the Scenario 3 is always higher than the Scenario 2 due to the parameters of $h_{hxr}$, $h_{ext}$, $R_{ct}$ and $K_{ct}$. Their contributions to the improvement of power output are analysed by a sensitivity analysis. This subsections explain the sensitivity analysis methodology and
Sensitivity analysis is used to identify the degree to which each input variable ($h_{cxr}$, $h_{exr}$, $R_{ct}$ and $K_{ct}$) contributes to the identification of the average power output. The core information of this sensitivity analysis is that the input variables are perturbed slightly, and the corresponding change in the outputs is reported as a percentage change in the outputs [150]. Here we have one input variable that is perturbed slightly around its mean with a 20% increase, while all other inputs are fixed at their respective means. The output is computed and recorded as the percentage change above and below the mean of that output channel (Scenario 2). This process is repeated for each and every input variable. As an outcome of this process, a report is generated in Figure 5.10, which summarizes the variation of each output with respect to the variation in each input.

According to the results, it can be seen that the TEG power generation is highly sensitive to thermal contact resistance. It is seen that the improvement of $K_{ct}$ brings a 10.6% average power output increase. The next largest contribution is $h_{exr}$ with a 10.1% average power increase. In comparison, $h_{cxr}$ and $R_{ct}$ have relatively lower influence on the electric power output.
output with respectively 1.6% and 3.3% improvements. Thus, the most efficient way of optimizing TEG power output is increasing $K_{ct}$ and $h_{hxr}$.

In conclusion, the integration of TEMs with the HXRs and the design of hot side HXR are of importance for the overall power outputs. $K_{ct}$ is primarily a function of the pressure on the interface, contact materials, and contact surface characteristics. Thus, increasing clamping force, using better thermal interface materials, and finding better methods of integrating the TEMs onto the HXR surface are effective approaches. For the design of hot side HXR, a structural optimization to increase the turbulence intensity of the exhaust gas is suggested. The sensitivity analysis results give an effective way to optimize the TEG, especially when in some cases the optimization requirements are contradictory.

5.5 Conclusions

Based on the validated Bi$_2$Te$_3$ TEG model in Chapter 4, the developed Bi$_2$Te$_3$ TEG model has been used for modeling TEGs integrated in a heavy-duty diesel engine. Two TEG installation positions (in the EGR path and upstream of DOC-DOF) have been both investigated in this chapter. Based on three different integration scenarios, the Bi$_2$Te$_3$ TEG models have been used for model-based temperature control design, power output prediction and parameters sensitivity analysis. Conclusions can be drawn as follows:

- By analysing the simulated hot end and outlet temperatures of TEGs, the model-based temperature control systems for TEG installing in the EGR path and upstream of the DOC-DOF have been both proposed. This aspect of the model indicates its utility in the design of a control system to protect the TEMs and to ensure effective operation of the other components in the exhaust system.

- The power outputs for TEG located in the EGR path and upstream of the DOC-DOF have been predicted for the NRTC driving cycle. The simulation results of power outputs show a TEG with 20 TEMs can produce average 170-224W electric power upstream of the DOC-DOF and average 132W electric power in the EGR path.

- Sensitivity analysis of the TEG was conducted to identify the most influential factors for the power generation of the TEG. Four parameters, thermal contact resistance,
heat transfer coefficient of hot side HXR $h_{hxr}$, heat transfer coefficient of cold side HXR $h_{cxr}$, electrical contact resistance $R_{ct}$ and thermal contact resistance $K_{ct}$ were used for the study. It was found that TEG power generation is highly sensitive to heat transfer coefficient of hot side HXR and thermal contact resistance. Average power generation by the TEG can be significantly increased by 25.8% by optimizing thermal contact resistance, heat transfer coefficient of hot side HXR $h_{hxr}$, heat transfer coefficient of cold side HXR $h_{cxr}$, electrical contact resistance $R_{ct}$ and thermal contact resistance $K_{ct}$.

- The developed dynamic TEG model in Chapter 4 can be used as a useful tool for TEG model-based control system, performance prediction, and optimization design.
Chapter 6

Semi-empirical Vehicular TEG Model

Based on two scenarios of the skutterudite TEG integrated in different positions of a conventional light-duty vehicle, a semi-empirical vehicular TEG model is developed in this chapter. The semi-empirical vehicular TEG model includes a quasi-static vehicle model, a dynamic exhaust model, a dynamic coolant model and a dynamic TEG model. There are four integration effects in the semi-empirical model: the additional mass, the power consumption of an electric circulation pump, the effect of exhaust back-pressure and the energy loss in the DC-DC converter. Both experimental and published data are used to tune and validate the model. This semi-empirical vehicular TEG model will be used as a tool for investigating and verifying the benefits of a TEG proposal by balancing the benefits with the added complexity of a TEG in Chapter 7.
6.1 Importance of TEG Integration Effects in Vehicular TEG Modelling

Since the TEG represents another component in the exhaust system, its integration presents challenges. The fuel economy benefit could be compromised through a number of integration effects:

- Added mass
- Power consumption of an electric circulation pump
- Increased exhaust backpressure
- Energy loss in DC-DC converter

All of the listed effects above may lead to a significant reduction in the fuel saving potential of a TEG in vehicle application. Rowe et al [117] identified the added weight penalty for a TEG applied in a 1.5L family car. For a 13kg mass TEG, at least 156W electrical power had to be generated in order to compensate for its added weight. Li et al [151] proposed a novel design for a concentric cylindrical TEG system to be used in the automotive exhaust system with a compact and lightweight heat sink. Instead of using a bulky and heavy heat exchanger, this innovative design combined the heat pipes with a heat exchanger, which reduced the weight of the TEG system and the whole vehicle as well, consequently improving the fuel economy. Deng et al [88] investigated the compatibility of an engine-cooling system when a TEG cooling unit was integrated. Based on both simulation and experimental data, it was found out that the temperature of the integrated cooling system is 5°C more than that of the primary engine cooling system. A more powerful water pump and cooling fans were recommended to reduce the effect of the TEG cooling unit. He et al [118] optimized the heat exchanger of TEG by considering engine power loss caused by exhaust backpressure. It was found out that the engine power loss increased linearly with exhaust backpressure and the influence of backpressure could be reduced by optimizing the dimensions of the hot side heat exchanger. Cao al [105] proposed a multiphase multilevel DC-DC conversion networks based on a 630W TEG prototype for automotive applications. The proposed DC-DC conversion networks could effectively reduce the power loss in a DC-DC converter from 5% of total
TEG power output to about 3%.

This view of the literature strongly suggests that integration effects are enough significant that they must be taken into account in evaluating the potential fuel economy improvement. The majority of previous studies on the application of TEG in vehicles [15, 78, 123, 134, 137, 139, 152] neglected the integration effects and only estimated the electrical power output. The prediction of fuel saving was simply missing. Besides, steady-state TEG models were used in most of the previous TEG performance predictions [78, 123, 137, 139, 152]. Neglecting warm-up and dynamic effects tended to cause an overestimate in TEG performance [134]. Therefore, the goal of development of semi-empirical vehicular TEG model is to investigate, for the first time, the fuel saving potential of a skutterudite TEG applied in a light-duty conventional ICE vehicle. The four listed aspects of vehicle integration effects are taken into account and the fuel saving percentages are estimated by using a dynamic TEG model based on driving cycles.

6.2 Skutterudite TEG Integration into a Light-duty Vehicle

6.2.1 TEG Integration Scenarios

A higher degree of electrification is being driven by conventional ICE vehicles for enhanced driving experience, safety and efficiency, making electric recovery more useful [153]. Besides, compared with other WHR technologies such as organic Rankine cycle and turbo-compounding, TEG has the advantages of low maintenance, silent operation, stability, and compactness. All of these advantages, in addition to the increasingly demanding CO₂ emissions requirements for passenger cars [154], make the TEG an attractive option for conventional light-duty vehicles.

New technology is usually adopted first in high-end cars and then gradually becomes integrated in standard cars. Consequently, for the purposes of this study, the TEG is assumed to be integrated in a 2l-gasoline and D-segment passenger car whose specification is shown in Table 6.1. The TEG integrated into the exhaust system converts part of the exhaust
Figure 6.1: Integration scenarios of TEG in the exhaust line.

Figure 6.2: Integration scenarios of TEG in the cooling circuit.
energy into electricity and through the DC-DC converter the regenerated electrical power is converted to fit the electric system of the car (Figure 6.2). Therefore, the load on the alternator is relieved and engine torque dragging the alternator is reduced, which consequently reduces the fuel consumption. The method of calculating the quantify of this fuel consumption reduction will be detailed later in Chapter 7.

There are a few possible installation positions for the TEG in the exhaust line, such as upstream of the three-way catalytic (TWC), downstream of the TWC, and downstream of the muffler. Considering the optimal efficiency of the skutterudite materials in its temperature range, by positioning the skutterudite TEG downstream the muffler significantly reduces the available exhaust gas temperature and conversion efficiency. Thus, with a typical gasoline engine exhaust system featuring a close-coupled catalyst (CCC) and a main TWC, there are two conceivable TEG installation positions: between the CCC and the main TWC (Scenario 1) and downstream of the main TWC (Scenario 2). Figure 6.1 shows the integration scenarios of TEG in the exhaust line.

Apart from the integration of TEG in the exhaust line, the TEG also needs to be integrated with the vehicular cooling circuit, which absorbs the heat drawn from the exhaust gas. The lower the coolant intake temperature of TEG, the higher the electric power output of the TEG. Thus, maintaining the cold side temperature of TEG with cold coolant from

---

### Table 6.1: Specification for reference car

<table>
<thead>
<tr>
<th>Specification</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total mass of the vehicle [kg]</td>
<td>1520</td>
</tr>
<tr>
<td>Frontal area [m]</td>
<td>2.26</td>
</tr>
<tr>
<td>Tyre radius [m]</td>
<td>0.326</td>
</tr>
<tr>
<td>Drag coefficient [-]</td>
<td>0.29</td>
</tr>
<tr>
<td>Transmission ratio 1st to 5th gear [-]</td>
<td>3.66/2.05/1.42/1.06/0.85</td>
</tr>
<tr>
<td>Differential gear [-]</td>
<td>3.75</td>
</tr>
<tr>
<td>Engine type</td>
<td>Gasoline</td>
</tr>
<tr>
<td>Displacement [L]</td>
<td>1.984</td>
</tr>
<tr>
<td>Engine maximum power [kW]</td>
<td>150</td>
</tr>
<tr>
<td>Engine maximum torque [Nm]</td>
<td>282</td>
</tr>
</tbody>
</table>

---

118
the radiator outlet is set as the integration scenario for both Scenario 1 and Scenario 2. The operation of thermostat valve can prevent coolant from flowing to the TEG. Thus, an electrical water pump is added to form an independent coolant circuit. As can be seen from Figure 6.2, the added electrical water pump circulates the coolant through the cold side of TEG and the radiator. The heat from the engine and the TEG are both rejected to the ambient air through the radiator.

6.2.2 TEG System Parameters

A typical TEG system comprises three components: a hot side heat exchanger, a cold side heat exchanger and thermoelectric modules (TEMs). The hot side and cold side heat exchanges (HXRs) are respectively connected to the exhaust path and coolant circuit. The TEMs are compressed in certain pressure between the hot side and cold side HXRs to ensures a stable thermal contact and reduce thermal contact resistance. The TEG can be designed in different shapes (shaped as a rectangle, hexagon, cylindrical etc.) and different size with a number of heat exchanger channels and TEMs [73]. Identifying the ideal size and
Table 6.2: Specification for TEG

<table>
<thead>
<tr>
<th>Specification</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>TEG weight [kg]</td>
<td>20kg</td>
</tr>
<tr>
<td>Number of hot side HXRs [-]</td>
<td>2</td>
</tr>
<tr>
<td>Dimension of hot side HXR [cm]</td>
<td>$24 \times 17 \times 1.6$</td>
</tr>
<tr>
<td>Number of cold side HXRs [-]</td>
<td>3</td>
</tr>
<tr>
<td>Dimension of cold side HXR [cm]</td>
<td>$24 \times 17 \times 1.6$</td>
</tr>
<tr>
<td>Number of fins in a HXR [-]</td>
<td>75</td>
</tr>
<tr>
<td>Fin thickness [cm]</td>
<td>0.032</td>
</tr>
<tr>
<td>Totally number of TEMs [-]</td>
<td>400</td>
</tr>
<tr>
<td>Dimension of a TEM [cm]</td>
<td>$1.6 \times 1.3 \times 0.4$</td>
</tr>
<tr>
<td>Hydraulic diameter of hot side HXR [cm]</td>
<td>0.13</td>
</tr>
</tbody>
</table>

The shape of TEG needs a system-level optimization maximizing the power output while also considering the system costs [72]. Here the fuel saving prediction is the main target and the structural optimization is not considered. By simply restricting the TEG to 'shoe-box size', an unoptimized TEG with two channels of parallel counter-flow HXRs is proposed in this chapter.

Figure 6.3 shows the structure of the TEG system and its parameters are shown in Table 6.2. As can be seen from Figure 6.3, the TEG is mainly made up of counter-flow heat HXRs and in total 400 skutterudite TEMs. The TEG can be divided into two channels with four layers of TEMs, two hot side HXRs and three cold side HXRs. The size of TEG is constrained to $24 \, \text{cm} \times 17 \, \text{cm} \times 9.5 \, \text{cm}$ with $10 \times 10$ TEMs on each layer. It is assumed all the TEMs in a layer are connected serially to form a section and all the four sections are connected in parallel. The skutterudite materials used here is recently developed by University of Reading. The maximum ZT of this material is 1.13 at 405 °C for the n-type material and 0.93 at 550 °C for the p-type material. These skutterudite materials are then fabricated into thermoelectric modules with dimensions $1.6 \, \text{cm} \times 1.3 \, \text{cm} \times 0.4 \, \text{cm}$ by Cardiff University. More details of skutterudite materials and modules can be seen in reference [31].
### 6.3 Model Structure

Since a vehicle equipped with a TEG was not available, a semi-empirical model is developed according to the integration scenarios. Both experimental and published data are used to tune and validate the model. The semi-empirical model of TEG in passenger vehicle is made up by four sub-models: a quasi-static vehicle model \[155\], a dynamic exhaust model \[142\], a dynamic coolant model \[156\] and a dynamic TEG model \[75\]. The model structure and variables are shown in Figure 6.4. The quasi-static vehicle model is used to calculate the engine’s load and speed and fuel consumption based on the chosen driving cycle. The exhaust model, coolant model and the TEG model are modelled dynamically. The exhaust mass flow rate \(\dot{m}_{TEG,exh}\) and temperature \(T_{exh,in}\) and coolant mass flow rate \(\dot{m}_{TEG,col}\) and temperature \(T_{col,in}\) are computed at the dynamic exhaust and coolant model based on the mass flow rate of fuel consumption \(\dot{m}_{fuel}\), engine speed \(\omega_{ic}\) and torque \(T_{qic}\). The TEG model predicts the energy transfer from exhaust gas into electrical power \(P_{TEG,out}\). The development and validation of the three sub-modes are described in sections 6.4.
6.4 Experimental Setup

In order to tune and validate the semi-empirical vehicular TEG model, some experimental tests have been set up. Both the TEM test rig presented in Chapter 3 (Figure 3.6) and TEG gasoline engine test bench shown in Chapter 4 (Figure 4.7) are used to tune and validate the dynamic TEG model. The thermocouple sensors and flow meter on the gasoline engine test bench can measure the exhaust temperature and flow rate of the 2L-gasoline engine running different driving cycles. And the data acquisition system of TEG gasoline engine test bench can record the exhaust data. Therefore, the dynamic exhaust model can be also validated on the TEG gasoline engine test bench. Figure 6.5 shows the control desk of the gasoline engine test bench. For the quasi-static vehicle model and dynamic coolant model, published data for the reference vehicle running NEDC [157,158] are used for their model validation.

Figure 6.5: Control desk of the gasoline engine test bench.
6.5 Modelling and Validation of Semi-empirical Vehicular TEG

6.5.1 Quasi-static Vehicle Model

The modelling of the reference passenger car is carried out using the Quasi Static Simulation (QSS) toolkit [155], which is based on a library of Simulink blocks. The model structure is presented in Figure 6.6 and the parameters for the reference cars are listed in Table 6.1. It can be seen from Figure 6.6 that there are 5 sub-systems for this quasi-static vehicle model: the driving cycle subsystem, vehicle subsystem, the transmission subsystem, the combustion engine subsystem, and the fuel tank subsystem.
The quasi-static vehicle model is based on a backward methodology. One of the main objectives of the quasi-static vehicle models is to estimate the engine fuel consumption. It can be seen from Figure 6.6 that based on a given driving cycle profile, the vehicle speed can be readily converted into wheel revolution speed ($\omega_w$) and traction torque ($T_{q_w}$) and then propagated back to the transmission block. By assuming values for the final drive ratio and efficiency, the rotational speed ($\omega_{ic}$) and torque ($T_{q_{ic}}$) of the engine are calculated. Once both $\omega_{ic}$ and $T_{q_{ic}}$ have been determined, an engine fuel consumption map can be used to find the instantaneous fuel consumption rate ($\dot{m}_{fuel}$). Finally, $\dot{m}_{fuel}$ is integrated over the driving cycle to obtain the cumulative fuel consumption of the driving cycle ($E_{fuel}$).

More details of this quasi-static vehicle model can be seen in references [159, 160]. This quasi-static approach has been demonstrated to give a reasonable accuracy for the fuel consumption [161]. The validation of the quasi-static vehicle model was conducted and it was found that the prediction for fuel consumption from the model was within the 2% of the published data for the NEDC [158]. Because the backward simulation method does not employ iteration, the quasi-static vehicle model runs relatively quickly. However, since the engine map is usually based on steady-state real world testing results, the vehicle model does not include engine and driveline dynamic effects. Because of their relatively small effect on the fuel economy estimation, such effects can be neglected for the overall assessment of fuel economy.

### 6.5.2 Dynamic Exhaust Model

The exhaust model is used to predict the inlet exhaust temperature $T_{exh.in}$ and exhaust flow rate $m_{TEG.exh}$ of the TEG system. Since no bypass route is adopted, the exhaust flow rate of TEG $m_{TEG.exh}$ equals to the exhaust flow rate of the exhaust system $\dot{m}_{exh}$, which can be estimated based on $\dot{m}_{fuel}$ from the vehicle model:

$$\dot{m}_{TEG.exh} = \dot{m}_{exh} = (1 + \lambda)\dot{m}_{fuel}$$  \hspace{1cm} (6.1)

where $\lambda$ is the air-fuel ratio.

$T_{cly}$ is the temperature of fluid delivered by the cylinder to the exhaust manifold. From
experimental data is has been seen that a linear model in many cases is a sufficient approximation for the temperature variations of the gases that goes from the cylinder into the exhaust manifold [142]. The expression for the $T_{cly}$ can be expressed as [142]:

$$T_{cly} = k_{exh.0} + \dot{m}_{exh}k_{exh.1}$$  \hspace{1cm} (6.2)

where $k_{exh.0}$ and $k_{exh.1}$ are tuning constants.

The sketch of the heat transfer in the exhaust pipe is shown in Figure 6.7. It can be seen that the heat transfer from the exhaust gas ($T_{cly}$) to the pipe wall and ambient decreases the outlet temperature of exhaust gas ($T_{exh.in}$). By assuming that the exhaust flow through a straight pipe with constant surrounding temperature, $T_{exh.in}$ can be determined by solving a simple differential equation for the temperature drop of a fluid in a straight pipe [142].

$$T_{exh.in} = T_{wal} + (T_{cly} - T_{wal})e^{-\frac{h_{pip.exh}A_{pip.exh}}{\dot{m}_{exh}c_{exh}}}$$  \hspace{1cm} (6.3)

where $c_{exh}$, $h_{pip.exh}$, $A_{pip.exh}$ and $T_{wal}$, are respectively the specific heat of the exhaust gas, heat transfer coefficient, heat transfer area and wall temperature of exhaust pipe.

The thermal inertia of the exhaust pipe is taken into consideration in the calculation of $T_{wal}$ by using an ordinary differential equation [142]:
Figure 6.8: Validation of dynamic exhaust model.

\[
\frac{dT_{\text{wal}}}{dt} m_{\text{wal}} c_{\text{wal}} = \dot{Q}_i(T_{\text{cly}}, T_{\text{wal}}) - \dot{Q}_e(T_{\text{wal}}, T_{\text{eng}}, T_{\text{amb}}) \tag{6.4}
\]

where \( m_{\text{wal}} \) and \( c_{\text{wal}} \) are respectively the mass and specific heat of the pipe wall. \( T_{\text{eng}} \) and \( T_{\text{amb}} \) are respectively the engine temperature and ambient temperature. \( \dot{Q}_i \) and \( \dot{Q}_e \) are respectively the heat transferred from the exhaust to the wall and heat transferred from the wall to the ambient and engine and they can be expressed as follows [142]:

\[
\dot{Q}_i = h_{g,i} A_{\text{pip.exh}} (T_{\text{cly}} - T_{\text{wal}}) \tag{6.5}
\]

\[
\dot{Q}_e = A_{\text{pip.exh}} [h_{cv,e}(T_{\text{wal}} - T_{\text{amb}}) + h_{cd,e}(T_{\text{wal}} - T_{\text{eng}}) + F_v \epsilon \sigma (T_{\text{wal}}^4 - T_{\text{amb}}^4)] \tag{6.6}
\]

where \( h_{g,i}, h_{cd,e} \) and \( h_{cv,e} \) are respectively internal heat transfer coefficient, conductive heat transfer into the engine block, and convective heat transfer into the engine block. \( F_v \) is the gray body view factor, \( \epsilon \) is the emissivity, and \( \sigma \) is the Stefan-Boltzmann constant.
The gasoline engine test bench setup in Chapter 4 is used to provide experimental data for the validation of the dynamic exhaust model. Measurements for the exhaust data downstream of the TWC from the reference engine running the NEDC based on the referenced vehicle are used to tune and validate the exhaust model. A comparison of the modelled and measured $\dot{m}_{\text{exh}}$ and $T_{\text{exh.in}}$ are respectively shown in Figure 6.8. It can be seen that both $\dot{m}_{\text{exh}}$ and $T_{\text{exh.in}}$ correspond well with the test results, with a mean absolute error around 8.4% and 5.1% respectively. $\dot{m}_{\text{exh}}$ has a minor influence on the power output of the TEG [162]. Therefore, the exhaust model can be considered validated and is used to provide accurate inputs for the dynamic TEG model.
6.5.3 Dynamic Coolant Model

Unlike the exhaust path, the engine coolant circuit is a closed circuit. Thus, the heat dissipated from the TEG can influence the cooling system. Before modelling the engine coolant, it is assumed that the heat rejected from the TEG system to the coolant circuit can be fully compensated by the added electrical water pump. Thus, the inlet temperature of the radiator is decided by the original engine coolant circuit.

According to the integration scenarios, the added electrical pump circulates the coolant through the radiator and TEG. The coolant flow rate of TEG $\dot{m}_{\text{TEG, col}}$ is assumed to be determined by the power output of the added electrical water pump ($P_{\text{pump}}$).

$$\dot{m}_{\text{TEG, col}} = P_{\text{pump}} k_{\text{pump}}$$  \hspace{1cm} (6.7)

where $k_{\text{pump}}$ is the tuning constant.

The sketch of the heat transfer in the engine coolant circuit is shown in Figure 6.9. $T_{\text{col}}$ is the engine coolant temperature at the inlet of the radiator and it can be modelled based on the coolant temperature model presented in reference [156]:

$$\dot{Q}_{\text{rej, col}} - \dot{Q}_{\text{amb, col}} - \dot{Q}_{\text{rad, col}} = dT_{\text{col}}/dt M_{\text{col}} c_{\text{col}}$$  \hspace{1cm} (6.8)

where $M_{\text{col}}$ and $c_{\text{col}}$ are respectively the effective coolant mass and specific heat capacity of coolant. $\dot{Q}_{\text{rej, col}}$, $\dot{Q}_{\text{amb, col}}$ and $\dot{Q}_{\text{rad, col}}$ are respectively heat rejection to the coolant from engine, heat loss to the ambient and heat dissipation at the radiator.

The heat rejection to the coolant from engine $\dot{Q}_{\text{rej, col}}$ can be approximated as a function of fuel flow rate $\dot{m}_{\text{fuel}}$:

$$\dot{Q}_{\text{rej, col}} = \eta \dot{m}_{\text{fuel}} Q_{\text{LHV}}$$  \hspace{1cm} (6.9)

where $Q_{\text{LHV}}$ is fuel lower heating value and $\eta$ is the heat rejection coefficient to the engine coolant, which can be simplified as a linear function of calculated mass airflow in this modelling process [156].
The heat loss from the coolant to the ambient $\dot{Q}_{\text{amb.col}}$ can be expressed as:

$$\dot{Q}_{\text{amb.col}} = h_{\text{amb.col}} A_{\text{amb.col}} (T_{\text{col}} - T_{\text{amb}}) \quad (6.10)$$

where $A_{\text{amb.col}}$ and $T_{\text{amb}}$ are respectively the surface area of an engine coolant and ambient temperature. $h_{\text{amb.col}}$ is the convection heat transfer coefficient, which is dependent on both vehicle speed and cooling fan operation status. Here $h_{\text{amb.col}}$ is simplified and described only as a function of cooling fan-operating, since vehicle speed has a minimal impact [156].

The heat dissipation at the radiator $\dot{Q}_{\text{rad.col}}$ can be expressed as:

$$\dot{Q}_{\text{rad.col}} = h_{\text{rad.col}} A_{\text{rad.col}} (T_{\text{col}} - T_{\text{amb}}) \quad (6.11)$$

$A_{\text{rad.col}}$ is the surface area of the radiator. $h_{\text{rad.col}}$ is the radiator heat transfer coefficient, which is dependent on the vehicle speed, cooling fan operating status and coolant flow rate at radiator [156].

The outlet coolant temperature of radiator $T_{\text{col.in}}$, which is also the inlet coolant temperature of the TEG can then be expressed as:

$$T_{\text{col.in}} = T_{\text{col}} - \frac{A_{\text{rad.col}} h_{\text{rad.col}}}{\dot{m}_{\text{rad.col}} c_{\text{col}}} (T_{\text{col}} - T_{\text{amb}}) \quad (6.12)$$

$\dot{m}_{\text{rad.col}}$ is coolant flow rate at the radiator, which is primarily dependent upon the engine speed and the operation of thermostat. $\dot{m}_{\text{rad.col}}$ can be formulated as:

$$\dot{m}_{\text{rad.col}} = k_{cg} A_{\text{thermostat}} \omega_{ic} \quad (6.13)$$

where $k_{cg}$ and $\omega_{ic}$ are respectively the tuning constant and engine speed. $A_{\text{thermostat}}$ is thermostat opening area coefficient and can be simplified to a linear relationship between the thermostat opening coolant temperature $T_{\text{stat.min}}$ and temperature causing the thermostat opening at its maximum $T_{\text{stat.max}}$. 

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Figure 6.10: Validation of dynamic coolant model.

\[
A_{\text{thermostat}} = \begin{cases} 
0 & \text{if } T_{\text{col}} < T_{\text{stat.min}} \\
1 & \text{if } T_{\text{col}} > T_{\text{stat.max}} \\
\frac{T_{\text{col}} - T_{\text{stat.min}}}{T_{\text{stat.max}} - T_{\text{stat.min}}} & \text{if } T_{\text{stat.min}} \leq T_{\text{col}} \leq T_{\text{stat.max}}
\end{cases}
\] (6.14)

Since \(T_{\text{col}}\) are not available in the engine test bench. The NEDC test data for \(T_{\text{col}}\) from a Jaguar S-type vehicle [157], which is comparable to the reference vehicle, is used to tune and validate the coolant model. A comparison of the modelled and measured \(T_{\text{col}}\) is shown in Figure 6.10. The average absolute error for \(T_{\text{col}}\) is 4.2%, which is sufficiently good to use as input for the TEG model.

6.5.4 Dynamic Skutterudite TEG Model

The dynamic skutterudite TEG model developed in Chapter 4 is used here as a sub-model for the semi-empirical vehicular TEG model. Both the skutterudite TEM model and skut-
The skutterudite TEG model have been validated in Chapter 3 and Chapter 4. The validation results and tuning parameters of thermal contact conductances ($K_{ct,h}$ and $K_{ct,c}$) and electrical contact resistances ($R_{ct}$) are presented in Figure 3.9. It shows that the TEM model predicts the performance of skutterudite TEM with good accuracy and the mean absolute error for open circuit voltage ($U_{TEM.ocv}$) and power output ($P_{TEM.out}$) are respectively 1% and 5%.

The validation results for the TEG model with 12 TEMs in a WLTP test is presented in Figure 4.18. It can be seen that the simulation results for both exhaust-out temperature ($T_{exh.out}$) and power output ($P_{TEG.out}$) correspond well with the measurements. The mean absolute errors are respectively 6.4% and 4.8%.

The TEG model for the integration scenario with 400 TEMs could not be fully validated in the engine test programme; for only 12 TEMs were available for testing and were assembled on a single heat exchange channel. With only a subset of the modules tested, a number of assumptions have to be made in order to predict the full TEG performance. Here it is assumed that the TEG engine test of one channel is representative and the power output can be scalable according to the number of channels. In order to predict the TEG output in the case that 400 TEMs were installed, it is assumed that the $h_{hx}$ and $h_{cx}$ are the same as the validated TEG model with 12 TEMs. It is also assumed that both $\dot{m}_{exh}$ and $\dot{m}_{col}$ are evenly distributed in the two channels resulting in the same power output for both two channels.

### 6.6 TEG Integration Effects Modelling

The integration effects of TEG on the vehicle performance are modelled in this section. Four interaction factors (added weight, added electrical water pump, increased exhaust backpressure and energy loss in DC-DC converter) are considered. In the following subsections these factors are analysed and modelled in turn.

#### 6.6.1 Added Weight

The effect of added weight can be easily included in the quasi-static vehicle model by increasing the vehicle mass in the vehicle block. Torque $T_{q_{\text{wTEG}}}$ is added to the original
Figure 6.11: Graph of power of water pump against flow rate of water [163].

engine torque $T_{q_e}$ due the increased mass $m_{TEG}$. Here it is assumed that the total mass of an aluminium TEG system [153] is

$$m_{TEG} = 20\text{kg}$$  \hspace{1cm} (6.15)

### 6.6.2 Added Electrical Water Pump

As can be seen from Figure 6.2, an electrical water pump is integrated in the coolant loop of TEG. It circulates the coolant through the cold side of TEG and radiator. Based the data gathered from the reference [163], 15W output from an electrical water pump can provide around 0.24kg/s coolant flow rate, which can be seen from Figure 6.11. Here it is assumed that power output of the electrical water pump is constant:
6.6.3 Increased Exhaust Gas Backpressure

The backpressure brought by the TEG can lead to an engine power loss. The pressure drop in the hot side HXR can be calculated as [164]:

$$\Delta p = 4f(L/D_f)(\rho_{exh}u_{exh}^2/2)$$  \hspace{1cm} (6.17)

where $D_f$ is the hydraulic diameter; $\rho_{exh}$ and $u_{exh}$ are respectively the density and velocity of the exhaust gas. $f$ is the Darcy resistance coefficient, given in the literature [118].

The power loss of the engine ($P_{back}$) can be be expressed as a function of $\Delta p$ and $\omega_{ic}$ [118].

$$P_{pump} = 15W$$  \hspace{1cm} (6.16)
\[ P_{\text{back}} = P_{\text{back}}(\Delta p, \omega_{ic}) \]  

(6.18)

The power losses per pressure drop at different \( \omega_{ic} \) for a 2L gasoline engine given by reference [118] is adapted here. Figure 6.12 shows the change in the \( P_{\text{back}} \) due to the change in the back pressure for different engine rotational speeds from reference [118]. It can be seen that the engine power loss increases linearly when the pressure drop increases.

### 6.6.4 Energy Loss in DC-DC Converter

The DC-DC converter is commonly used to convert the voltage supplied by the TEG to reach the voltage levels required by the electrical system in the car. Through a DC-DC converter, a stable voltage can be obtained from the TEG to the in-car electronics. However, the impedance matching between the internal resistance of the TEMs and the input resistance of DC-DC converter can lead to a power loss. Here it is assumed that the efficiency of the DC-DC converter is constant [106]:

\[ \eta_{DC-DC} = 90\% \]  

(6.19)

### 6.7 Fuel Saving Estimation Method

A method to estimate the fuel saving of TEG in light-duty vehicle is proposed in this subsection. The fuel saving is estimated based on the power output of TEG \( P_{\text{TEG, out}} \) and taking the listed four negative integration effects into account.

By taking the effects of added electrical water pump, exhaust back pressure and energy loss in DC-DC converter into account, a modified power output from TEG \( P_{\text{TEG, mod}} \) can be expressed as:

\[ P_{\text{TEG, mod}} = P_{\text{TEG, out}}\eta_{DC-DC} - P_{\text{back}} - P_{\text{pump}} \]  

(6.20)

Here it is assumed that the power produced by TEG is used to relieve the load on the
alternator so as to reduce the original engine torque. Taking the added mass of TEG into consideration ($Tq_{m\text{TEG}}$), a modified engine torque profile can be expressed as:

$$Tq_{\text{TEG,ic}} = Tq_{\text{ic}} + Tq_{m\text{TEG}} - \frac{P_{\text{TEG,mod}}}{\omega_{\text{ic}}\eta_{\text{alt}}},$$ \hspace{1cm} (6.21)

$\eta_{\text{alt}}$ is the overall efficiency of the alternator and belt. Here $\eta_{\text{alt}} = 50\%$ \cite{21}

By using different engine torque profiles ($Tq_{\text{ic}}$ and $Tq_{\text{TEG,ic}}$), the cumulated fuel consumptions $E_{\text{fuel}}(Tq_{\text{ic}})$ and $E_{\text{fuel}}(Tq_{\text{TEG,ic}})$ can be obtained from the quasi-static vehicle model. Then the fuel saving percentage $\Delta E_{\text{fuel}}(\%)$ can be expressed as:

$$\Delta E_{\text{fuel}}(\%) = \frac{E_{\text{fuel}}(Tq_{\text{ic}}) - E_{\text{fuel}}(Tq_{\text{TEG,ic}})}{E_{\text{fuel}}(Tq_{\text{ic}})} \times 100\%$$ \hspace{1cm} (6.22)

### 6.8 Summary

When predicting vehicular TEG performance and its fuel saving potential, the results depend strongly on the assumed depth of vehicle integration and resulting interactions with the vehicle. To give a comprehensive assessment of the fuel saving potential of a vehicular TEG while also considering integration effects, a skutterudite TEG integrated with a conventional light-duty vehicle is investigated in this chapter.

Based on the two scenarios of the TEG integrated in different positions of a conventional light-duty vehicle, a semi-empirical vehicular TEG model is developed, which includes a quasi-static vehicle model, a dynamic exhaust model, a dynamic coolant model, and a dynamic TEG model. Four TEG integration effects: the additional mass, the power consumption of an electric circulation pump, the effect of exhaust back-pressure and the energy loss in the DC-DC converter, are all modelled in the semi-empirical vehicular TEG model. Both experimental and published data are used to tune and validate the model. The semi-empirical vehicular TEG model will be used in Chapter 7 for fuel saving prediction, integration effects analysis and economic analysis.
Chapter 7

Applications of Semi-empirical Vehicular TEG Model

The application of the semi-empirical vehicular TEG model developed in Chapter 6 are presented in this chapter. The semi-empirical vehicular TEG model are used in the following applications:

- prediction of power output and fuel saving of TEG based on different driving cycles,
- identification of integration effects on the fuel saving potential,
- exploration of the possible method for TEG fuel saving improvement,
- economic analysis of vehicular TEG on light-duty vehicles.

Based on the integration scenario of skutterudite TEG into a light-duty vehicles, the power output and fuel saving potential of TEG are both predicted based on different driving cycles. The TEG integration effects on the fuel saving potential are identified. By comparing these integration effects on the TEG fuel saving potential, the possible improvement measures are explored. Based on the fuel saving results, an economic analysis of TEG are conducted at the end of this chapter.
Table 7.1: Different integration scenarios of TEG

<table>
<thead>
<tr>
<th></th>
<th>Scenario 1</th>
<th>Scenario 2</th>
</tr>
</thead>
<tbody>
<tr>
<td>TEG position</td>
<td>Upstream TWC</td>
<td>Downstream TWC</td>
</tr>
<tr>
<td>Added weight</td>
<td>20kg</td>
<td>20kg</td>
</tr>
<tr>
<td>Efficiency of DC-DC converter</td>
<td>90%</td>
<td>90%</td>
</tr>
<tr>
<td>Added electrical pump</td>
<td>15W</td>
<td>15W</td>
</tr>
<tr>
<td>Increased backpressure</td>
<td>800-1000Pa</td>
<td>800-1000Pa</td>
</tr>
</tbody>
</table>

7.1 Power Output Potential Prediction

The two integration scenarios of TEG into the light-duty vehicle are presented in Table 7.1. The results of power output of TEG $P_{TEG, out}$ at different dynamic driving cycles are presented in this subsection. Figure 7.1 shows the evolution for the $P_{TEG, out}$ of the two different scenarios at NEDC with average power output. $P_{TEG, out}$ of Scenarios 1 is always higher than Scenario 2 due to the higher exhaust temperature upstream the TWC than the downstream. In the urban driving cycle average $P_{TEG, out}$ are only 72W (Scenario 1) and 28W (Scenario 2). This can be explained by the relatively less thermal energy at the exhaust due to the frequent stops at urban driving cycle and relatively lower efficiency of skutterudite modules at low exhaust temperature (300°C). The average $P_{TEG, out}$ respectively increase to 296W (Scenario 1) and 168W (Scenario 2) in the extra-urban driving cycle when the vehicle runs continuously with high speed. Likewise, the power outputs of TEG at WLTP (Figure 7.2), FTP-75 (Figure 7.3) and FTP-highway (Figure 7.4) increase with the vehicle speed. The TEG works most effectively for fast driving patterns.

Compared with these speed changing driving patterns, evolution of the $P_{TEG, out}$ of reference vehicle running at constant speed are shown in FigureS 7.5 and 7.6. The power outputs of TEG at constant speed driving patterns increase quickly at first and then remain unchanged. Additionally, the power output of TEG increases as the constant vehicle speed increases.

The average $P_{TEG, out}$ at different driving cycles are presented in Figure 7.7. The driving profiles with constant high speed give higher average $P_{TEG, out}$, such as FTP-highway, constant speed 90 km/h and 120 km/h. The highest average $P_{TEG, out}$ comes from constant
Figure 7.1: Result of $P_{TEG.out}$ at NEDC.

Figure 7.2: Result of $P_{TEG.out}$ at WLTP.
Figure 7.3: Result of $P_{TEG.out}$ at FTP-75.

Figure 7.4: Prediction of $P_{TEG.out}$ at FTP-highway.
Figure 7.5: Prediction of $P_{TEG, out}$ at constant speed 90km/h.

Figure 7.6: Prediction of $P_{TEG, out}$ at constant speed 120km/h.
speed 120 km/h with average $P_{TEG.out} = 661W$.

These simulation results of $P_{TEG.out}$ show the skutterudite TEG performs effectively with high average $P_{TEG.out}$ when the reference vehicle is running continuously with high speed. However, at the driving cycles with frequent stops and low vehicle speeds the $P_{TEG.out}$ is limited.

### 7.2 Fuel Saving Potential Prediction

By using the fuel saving method in Chapter 6, the fuel saving percentages $\Delta E_{fuel}(\%)$ are estimated based on previous $P_{TEG.out}$. Figure 7.8 shows the $\Delta E_{fuel}(\%)$ of Scenario 1 and Scenario 2 at different driving cycles. The fuel economy improvements between 0.5% and 3.6% depending on integration positions in the exhaust line and driving cycles. $\Delta E_{fuel}(\%)$ of the NEDC and the FTP-75 for both scenarios are relatively lower compared with other driving cycles. The driving cycles of the WLTP, FTP-highway and constant-speed 90km/h show higher potentials with around 3% of fuel saving for Scenario 1 and 1.8% for Scenario 2. The constant-speed 120km/h shows the most promising results for both scenarios: 3.6% fuel saving for Scenario 1 and 2.4% fuel saving for Scenario 2. These comparisons further underline that the most promising fuel economy improvement of TEG can obtained when
TEG is integrated closer to the engine and running a highway driving cycle.

7.3 Integration Effects on Fuel Saving Potential

The integration effects on saving fuel are investigated based on the 120km/h driving profile for Scenario 2. Figure 7.9 shows the fuel saving potential of TEG with and without considering the four integration effects. Because of the four integration effects the saving potential is decreased by 25% from $\Delta E_{fuel} = 3.2\%$ to $\Delta E_{fuel} = 2.4\%$. This further underlines the importance and necessity of taking integration effects into consideration when evaluating the fuel saving potential. The contributions of the four integration effects to the decrease of fuel saving percentage are also presented in Figure 7.9. The biggest reduction in fuel saving comes from the DC-DC converter, which leads to the 10% decrease in fuel saving. The added weight of TEG is identified as the second biggest reduction of fuel saving (6.9%). In comparison to the previously integration effects, increased exhaust gas backpressure and power consumption in added electrical pump have relatively less significant effects on the fuel saving potential.
7.4 Possibilities of Improving Fuel Saving Potential

As shown in Figure 7.9, fuel saving potential of the TEG is reduced when considering the TEG installation position and integration effects. The identifications of these effects on fuel saving can be used as a guidance for the optimization of the vehicular TEG. The possibilities of optimizing the vehicular TEG and improving the fuel saving potential are investigated. The different scenarios for TEG integration and their fuel saving percentages are presented in Table 7.2 and Figure 7.10.

From the comparison of Scenario 1 and Scenario 2, the installation position of the vehicular TEG is identified as one of the main effects on fuel saving potential. Placing the TEG closer to the main exhaust manifold can significantly improve the fuel saving percentage. However, the inlet temperature of the catalytic converter can be influenced by the TEG installed upstream of the TWC. A falling gas temperature could cause the TWC to work ineffectively resulting in an increased pollutant release [73]. Furthermore, the temperature
Table 7.2: Different integration scenarios of TEG

<table>
<thead>
<tr>
<th>TEG position</th>
<th>Scenario 2</th>
<th>Scenario 1</th>
<th>Scenario 1(A)</th>
<th>Scenario 1(B)</th>
</tr>
</thead>
<tbody>
<tr>
<td>TEG position</td>
<td>Downstream TWC</td>
<td>Upstream TWC</td>
<td>Upstream TWC</td>
<td>Upstream TWC</td>
</tr>
<tr>
<td>Added weight</td>
<td>20kg</td>
<td>20kg</td>
<td>15kg</td>
<td>15kg</td>
</tr>
<tr>
<td>Efficiency of DC-DC converter</td>
<td>90%</td>
<td>90%</td>
<td>95%</td>
<td>95%</td>
</tr>
<tr>
<td>Added electrical pump</td>
<td>15W</td>
<td>15W</td>
<td>15W</td>
<td>12W</td>
</tr>
<tr>
<td>Increased backpressure</td>
<td>800-1000Pa</td>
<td>800-1000Pa</td>
<td>800-1000Pa</td>
<td>640-800Pa</td>
</tr>
</tbody>
</table>

Figure 7.10: Effects of different improvement on fuel saving potential in the 120km/h driving profile.
limits of the TEMs also need to be considered. To solve these issues, a module-based temperature control of bypass valve has been proposed by Loughborough University [75], can be used to ensure that the temperature limits of the TEG are not exceeded and that the TEG is guaranteed to remain operational. Taking the 120km/h driving profile as an example, placing the TEG downstream of the CCC can increase the fuel saving by 50% from $\Delta E_{fuel} = 2.4\%$ (downstream of the TWC) to $\Delta E_{fuel} = 3.6\%$.

The efficiency of DC-DC converter and added weight are the main contributors for the reduction of fuel saving potential among the four integration effects. A two-stage cascade boost converter topology was proposed by Ni [107] and the average efficiency of DC-DC converter could be around 95%. A weight reduction can be possibly achieved by optimizing the wall thickness of HXRs [165]. A reduced TEG weight of 15kg and $\eta_{DC-DC} = 95\%$ are assumed here. Figure 7.10 shows the improvements of these two integration effects together can increase $\Delta E_{fuel}$ from 3.6% (Scenario 1) to 3.9% (improved Scenario 1(A))

The power consumption of the added electrical pump and exhaust backpressure are respectively related to the performance of the cold side HXR and the hot side HXR. Increasing the pumping power consumption, which is proportional to the coolant flow rate, can increase the temperature difference of the modules and the power output of the TEG. Likewise, increasing the heat transfer coefficient of hot side HXR can also lead to an increase of exhaust backpressure. Furthermore, different engine’s speeds and torques require different optimal coolant flow rates [21]. Thus, to reduce the effects of added pump and exhaust backpressure on fuel saving, a system level comprehensive optimization of HXRs [85] and a coolant pump control strategy is suggested. It assumed through these methods the exhaust backpressure can decrease 20% and electric pump power is reduced to 12W while maintaining the heat transfer coefficients of hot and cold side HXRs unchanged. Figure 7.10 shows the improvements of these two integration effects can increase $\Delta E_{fuel}$ from 3.9% (improved Scenario 1(A)) to 4.0% (improved Scenario 1(B)).

In total, the fuel saving potential increases by 66.7% from $\Delta E_{fuel} = 2.4\%$ (Scenario 2) to $\Delta E_{fuel} = 4.0\%$ (Improved Scenario 1(B)). 50% of this improvement is contributed to installing TEG closer to the exhaust manifold. The second biggest increase in fuel saving potential comes from higher efficiency of DC-DC converter. Reducing the added weight of TEG and decreasing power consumption of electrical pump and backpressure a minor effect.
on fuel saving potential.

7.5 Economic Analysis

7.5.1 TEG Components

Based on the integration scenarios of TEG in the light-duty vehicle (Figures 6.1 and 6.2), this vehicular TEG consists of several general components:

- A hot side HXR to take heat from the exhaust gases and deliver it to the hot side of the TEMs and a cold side HXR to maintain the cold side of the TEMs by taking heat from the module and radiating it to a liquid coolant.
- Skutterudite TEMs
- Thermal insulation materials to reduce 'stray' heat transfer and thereby maintaining the temperature difference between the modules.
- An electric pump to control the flow of coolant to the TEG
- Pipes to connect radiator, electric pump, and TEG.
- A DC-DC converter to match the power output of the TEMs to the vehicle electrical system.
- Electric wirings for the TEMs and the electrical systems

Additional components are required when the TEG is installed before the TWC (Scenario 1). The components are the followings:

- A by-pass route and valve to bypass the TEG when the exhaust temperature is hot or to help manage the TWC temperature.
- Sensors for temperatures and flow rates to improve the temperature control of the TEG.
Table 7.3: Unit cost for a skutterudite TEM

<table>
<thead>
<tr>
<th>Item</th>
<th>Unit Cost</th>
<th>Weight/Size</th>
<th>Cost</th>
</tr>
</thead>
<tbody>
<tr>
<td>Thermoelectric materials</td>
<td>€20/kg</td>
<td>1.0×10^{-3}kg</td>
<td>0.02</td>
</tr>
<tr>
<td>Silver in the braze</td>
<td>€0.5/g</td>
<td>0.2×10^{-3}kg</td>
<td>0.1</td>
</tr>
<tr>
<td>Ceramic materials</td>
<td>€3/kg</td>
<td>1.9×10^{-3}kg</td>
<td>0.0057</td>
</tr>
<tr>
<td>Copper</td>
<td>€4/kg</td>
<td>0.3×10^{-3}kg</td>
<td>0.0012</td>
</tr>
<tr>
<td>Module manufacturing</td>
<td>€8</td>
<td>1</td>
<td>8</td>
</tr>
<tr>
<td>Overall cost for a TEM</td>
<td></td>
<td></td>
<td>8.13€</td>
</tr>
</tbody>
</table>

Table 7.4: Unit cost for the TEG system

<table>
<thead>
<tr>
<th>Item</th>
<th>Unit Cost</th>
<th>Weight/Size</th>
<th>Cost</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cost of HXRs $G_{hxr}$</td>
<td>€8</td>
<td>3 cold side HXR</td>
<td>40€</td>
</tr>
<tr>
<td></td>
<td></td>
<td>2 hot side HXR</td>
<td></td>
</tr>
<tr>
<td>Cost of TEMs $G_{TEMs}$</td>
<td>8.13€</td>
<td>400</td>
<td>3252€</td>
</tr>
<tr>
<td>Cost of Ins $G_{Ins}$</td>
<td>€4/m²</td>
<td>0.4m²</td>
<td>1.6€</td>
</tr>
<tr>
<td>Cost of separated cooling system $G_{col}$</td>
<td>1</td>
<td>2 pipes</td>
<td>32€</td>
</tr>
<tr>
<td></td>
<td></td>
<td>30€</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>an electric pump</td>
<td></td>
</tr>
<tr>
<td>Cost DC-DC converter $G_{DC−DC}$</td>
<td>40€</td>
<td>1</td>
<td>40€</td>
</tr>
<tr>
<td>Cost of electrical wiring $G_{wir}$</td>
<td>1€/m</td>
<td>20m</td>
<td>20€</td>
</tr>
<tr>
<td>Cost of assembling the systems $G_{ab}$</td>
<td>15€</td>
<td>-</td>
<td>15€</td>
</tr>
<tr>
<td>Cost of by-pass system $G_{bp}$</td>
<td>20€</td>
<td>a by-pass route and valve</td>
<td>43€</td>
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<tr>
<td></td>
<td>8€</td>
<td>a temperature sensor</td>
<td></td>
</tr>
<tr>
<td></td>
<td>15€</td>
<td>a flow rate sensor</td>
<td></td>
</tr>
<tr>
<td>Overall cost for Scenario 1 TEG system $G_{TEG}$</td>
<td>3443€</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Overall cost for Scenario 2 TEG system $G_{TEG}$</td>
<td>3400€</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

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7.5.2 TEG System Cost Estimation

Based on the components listed, the total cost of a TEG system $G_{TEG}$ can be expressed as follow:

$$G_{TEG} = G_{hxr} + G_{TEMs} + G_{Ins} + G_{col} + G_{wir} + G_{ab} + (G_{bp})$$  \ (7.1)

As can be seen that $G_{TEG}$ is a sum of the follow costs:

- Cost of hot and cold side HXRs $G_{hxr}$, which is usually decided by their heat transfer coefficients and its sizes.

- Cost of skutterudite TEMs $G_{TEMs}$, which is the overall cost for all the skutterudite TEMs.

- Cost of insulation materials $G_{Ins}$, which is the overall cost for the insulation materials using in the HXRs.

- Cost of separated cooling system $G_{col}$, which includes the cost for the electric pump and pipes.

- Cost DC-DC converter $G_{DC-DC}$, which is usually decided by the maximum power of TEG.

- Cost of electrical wiring $G_{wir}$, which is the overall cost for cable between the channels, TEG to DC-DC converter and DC-DC converter to the battery.

- Cost of assembling the systems $G_{ab}$.

- Cost of by-pass route $G_{bp}$, when the TEG is mounted before the TWC (Scenario 1), a by-pass route is needed, which includes pipes, valves, and sensors.

Based on the data of skutterudite TEMs [31], the cost calculation for this TEM is presented in Table 7.3. The manufacturing fee is very hard to estimate since this TEMs are not in mass production and the equipment capital cost is unknown. Therefore, 8 €is given here based on experience. As can be seen, the overall cost for a skutterudite TEM is about 8.13€. Based on the integration Scenario 1 and Scenario 2, the overall cost of TEGs are calculated and presented in Table 7.4. The overall cost for TEG in Scenario 1 and Scenario 2 are
Table 7.5: Annual fuel saving and CO₂ reduction of TEG

<table>
<thead>
<tr>
<th>Vehicle configuration</th>
<th>Fuel consumption (litres/100 km)</th>
<th>CO₂ performance (g/km)</th>
<th>Annual mileage (km)</th>
<th>Annual CO₂ reduction (g)</th>
<th>Annual fuel saving (litre)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Baseline</td>
<td>6.54</td>
<td>153</td>
<td>11,600</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Scenario 1</td>
<td>6.34</td>
<td>148</td>
<td>11,600</td>
<td>58,000</td>
<td>23.2</td>
</tr>
<tr>
<td>Scenario 2</td>
<td>6.44</td>
<td>151</td>
<td>11,600</td>
<td>23,200</td>
<td>11.6</td>
</tr>
</tbody>
</table>

respectively 3443€ and 3400€. It can be seen that the biggest cost of the TEG system for both scenarios come from the skutterudite TEMs, which occupies more than 90% the total cost of the TEG system. Therefore, minimizing the cost of TEG system strongly depends on reducing the of TEMs’ manufacturing costs.

7.5.3 TEG System Benefit Estimation

According to previous section, the fuels saving and CO₂ reduction can be more significant when the vehicles running on the urban highways. Here the calculation for fuel saving and CO₂ reduction is based on the estimation results of WLTP for Scenario 1 and Scenario 2, which is expected to give an average estimation. According to Roland Berger’s report [166], the annual driving distance for a passenger car is around 11,600 km. Then using the fuel consumption rate and CO₂ emission rate calculated from the semi-empirical vehicular TEG model, fuel savings per year and annual CO₂ reduction are computed and presented in Table 7.5.

For a D segment light-duty vehicle, the application of a TEG can annually reduce about 11-23 litres at a typical WLTP depending on the integration scenarios. For the original equipment manufacturer (OEM), the annual CO₂ reduction for Scenario 1 and Scenario 2 are respectively 58 kg and 23.2 kg, which can help to reduce the CO₂ emission target for the vehicle fleet. As can be seen from Table 7.5, both the annual fuel saving and CO₂ reduction of Scenario 1 is significantly higher than the Scenario 2. This is due to the higher power output of Scenario 1, where TEG is installed upstream of the TWC.

To further analysis the economic benefit of the TEG, the fuel savings in litre per year in Table
7.5 is subsequently used to estimate the fuel saving in Euro of the TEG over its lifetime. Here the net present value (NPV) of the TEGs life time fuel savings can be expressed as:

\[
N.P.V = \sum_{t=0}^{n} \frac{AF}{(1 + i)^t}
\]  

(7.2)

Where \(i\) is the social discount rate, \(AF\) is the annual fuel saving in Euro, \(t\) is the lifetime of the TEG. Here it is assumed that the gasoline cost is 1.5€/litre. Then the \(AF_1\) for Scenario 1 and \(AF_1\) for Scenario 2 can be calculated as

\[
AF_1 = 23.2 \times 1.5 = 34.8€
\]  

(7.3)

\[
AF_1 = 11.6 \times 1.5 = 17.4€
\]  

(7.4)

With an assumption on the social discount rate \(i=6\%\), the NPV of the TEG’s lifetime fuel savings for the two scenarios changing with TEG’s lifetime is presented in Figure 7.11. As
can be seen that the NPV of the TEG’s lifetime fuel savings increase as the lifetime of the TEG system. It implies that achieving good reliability is extremely important for successful commercialization of TEGs for vehicular applications. With a 15-year lifetime TEG, the NPV of fuel saving for Scenario 1 and Scenario 2 are respectively 358€ and 179€.

The fuel saving reduction benefit is mainly for the customers. Moreover, the CO\textsubscript{2} emission reduction can also give benefit to the OEMs. The CO\textsubscript{2} emission reduction from the TEG can help the OEMs to reduce their average vehicle fleet CO\textsubscript{2} emission so as to avoid the CO\textsubscript{2} penalty (Chapter 1). It is hard to predict the CO\textsubscript{2} reduction benefit for the OEMs with sufficient accuracy, for this CO\textsubscript{2} emission reduction is only based on one reference car instead of the whole fleet. Therefore, the following benefit cost ratio analysis is only based on the fuel saving benefit from the customers’ point of views.

### 7.5.4 TEG System Cost and Benefit Analysis

In this subsection, the benefit cost ratios for 15-year lifetime TEG are calculated by using the estimation results of TEG system cost and lifetime fuel saving. As can be seen from Table 7.6, for both scenarios, the fuel saving benefit is much lower than the cost of the TEGs. The comparison benefit cost ratio between the two scenarios shows that integrating TEG upstream the TWC (Scenario 1) can be more cost effective that integrating TEG downstream the TWC (Scenario 2). The reason is that the TEG recovers more energy when it is installed upstream the TWC and the bypass route is both economical and practical. The benefit of CO\textsubscript{2} emission reduction for the OEMs is not included in this benefit cost ratio calculation. Therefore, benefit cost ratio for the OEMs should be higher.

Further cost reduction for the TEG system is needed so as to achieve a better economically acceptable cost. With technical development and mass production, the cost of TEG system can definitely be reduced, especially for the cost of the skutterudite TEMs.

<table>
<thead>
<tr>
<th>Scenario</th>
<th>TEG cost</th>
<th>Fuel saving benefit</th>
<th>Benefit cost ratio</th>
</tr>
</thead>
<tbody>
<tr>
<td>Scenario1</td>
<td>3443€</td>
<td>358€</td>
<td>0.1</td>
</tr>
<tr>
<td>Scenario2</td>
<td>3400€</td>
<td>179€</td>
<td>0.05</td>
</tr>
</tbody>
</table>
7.6 Conclusions

Based on the semi-empirical vehicular TEG model developed in Chapter 6, the power output and fuel saving percentage of TEG were estimated by taking the integration effects of added weight, added electrical pump, exhaust backpressure and energy loss in DC-DC converter into account. These four integration effects on the fuel saving was study individually and possibilities to increase the fuel saving potential was also investigated. By using the fuels saving estimation results, the economic benefit and cost of the TEG system are analysed at the end of this chapter. Conclusions can be drawn as follows:

• The fuel economy improved by the skutterudite TEG is between 0.5% and 3.6% depending on integration positions in the exhaust line and driving cycles. It was found out the skutterudite TEG has better performance in highway driving than city driving cycle.

• From the comparison of two TEG integration scenarios, the TEG installation position was identified as the most important effect to the fuel saving potential.Positing skutterudite upstream of the TWC can increase the fuel saving potential by 50% compared with TEG installed downstream of the TWC.

• The listed four integration effects altogether lead to a 25% reduction of fuel saving potential. Among the four integration effects, the energy loss in the DC-DC converter and the added mass due to the TEG were most significant at 10% and 6.9% respectively. The losses due to electrical pump load and the effect of exhaust back pressure had a minor effect at 5% and 3.1% respectively.

• Based on the identifications of integration effect, possible methods of optimizing TEG integration, such as bypass valve control strategy, optimization of the HXRs, mass reduction, coolant pump control strategy, can be deployed. Relative to Scenario 2, the fuel saving potential was improved by 67% and 4% fuel consumption reduction was achieved at a steady vehicle speed of 120km/h.

• The overall cost for the TEG in this simulation is around 3400-3443€ depending on the integration position in the exhaust line. The cost of the TEMs accounts for more than 90% of the overall cost the TEG system, which can be the key to minimize the
TEG system cost.

- By comparing the TEG system cost and fuel saving of a 15-year lifetime TEG, the fuel saving benefits in both scenarios are much lower than the cost. Therefore, further cost reduction for the TEG system is needed.
Chapter 8

Upgrade a Single-mode TEM Model to a Dual-mode TEM Model

The thermoelectric modules (TEMs) have the bidirectional characteristic, which can work either in power generation mode based on Seebeck effect or in heating-cooling mode based on Peltier effect. This chapter upgrade the single-mode TEM model only for power generation, which is presented in Chapter 3, to a dual-mode TEM model for both power generation and heating-cooling. The simulation results for the two modes are both verified with experiments. The four-quadrant operation diagram of TEM, which clearly presents the cooling, heating and power generation curves of a TEM, is produced based on the validated dual-mode TEM model.
Table 8.1: Difference between a TEC module and a TEG module

<table>
<thead>
<tr>
<th>Items</th>
<th>TEC module</th>
<th>TEG module</th>
</tr>
</thead>
<tbody>
<tr>
<td>Thermoelectric element size</td>
<td>smaller</td>
<td>bigger</td>
</tr>
<tr>
<td>Solder melt temperature</td>
<td>lower</td>
<td>higher</td>
</tr>
<tr>
<td>Slitting ceramic</td>
<td>not required</td>
<td>done on either side or both sides</td>
</tr>
<tr>
<td>Conductor leads</td>
<td>thicker</td>
<td>relatively thicker</td>
</tr>
<tr>
<td>Wire leads</td>
<td>insulated with PVC (rated 90°C)</td>
<td>insulated with Teflon (rated 250°C)</td>
</tr>
</tbody>
</table>

8.1 Difference Between a TEC Module and a TEG Module

According to thermoelectric effects, TEMs have two different operating modes: power generation mode and heating-cooling mode. The power generation mode is based on Seebeck effect using for thermoelectric generators (TEGs) to directly convert thermal energy into electrical energy. The heating-cooling mode is based on Peltier effect using for thermoelectric coolers (TECs) to create a heat flux between the two side of the TEM by inputting electrical energy. These two effects are reversible. A TEM can switch between these two modes: If a voltage is applied to a TEM, it will pump heat, but if a temperature difference is applied across a TEM, a voltage will be produced. Therefore, a TEM can act as a cooler (heating-cooling mode), a heater (heating-cooling mode) or a generator (power generation mode).

However, because of this different applications, the TEM manufactures have optimized the TEMs based on their specific application. The main difference between the TEG module and TEC module is the operating temperature range. For the TEC modules, their most effective operating temperatures closer to room temperature, as they are usually found in cooler applications. In comparison, the TEG modules are usually optimised for higher temperatures. Some difference for the design parameters for the TEG module and TEC module are summarize in Table 8.1. For the TEG modules, the bigger thermoelectric element size is designed for larger power generation. The wiring lead installed with Teflon, slitting ceramic and higher solder melt temperature enable the TEG module to withstand higher
temperature. For the TEC module, thicker conductor leads are used for larger electric current. Because the TEG modules have to withstand higher temperatures, the specially designed TEG modules are available in the market for a cost 10 times higher compared to TEC modules [167]. Therefore, the cost of power generation using the TEG module is still an impediment in the commercialization of the vehicular TEG, which can be seen from the economic analysis in Chapter 7.

Among the related research, the concept of using TEC modules for power generation was developed by Min and Rowe [125]. They noted that commercially available TEC modules could not only be used for refrigeration but also for low-temperature waste heat recovery. Riffat et al. [168] explored TEC modules for thermoelectric power generation and found out that the conversion efficiency of TEC is relatively low, typically around 5%. Chen et al. [169] proposed that compared with originally designed TEG module, the TEC modules, which have lower cost, are more suitable to be used for temperature waste heat recover. Ding et al. [167] tested commercially available TEC modules in temperature regime from ambient temperature up to 250 °C so as to evaluate the performance of TEC modules used for power generation. The results shown that the TEC module was reliable under thermally cycled hot side temperature below 90 °C. Irreversible damage was found after the TEC module being tested at hot side temperature of around 210 °C continuously for 7 hours.

8.2 Assumption

The quasi-static TEM model developed in Chapter 3 can only be used to model TEM operating in the power generation mode. In this chapter, the TEM model will be upgrade up a dual-mode TEM model, which can both model the power generation mode and heating-cooling mode. Based on this purpose, the following assumptions are made for the dual-mode TEM model to simplify the complex problem of modelling.

- Seebeck coefficient, thermal conductivity and electrical resistance of the material changes with the average temperature of the two sides of the thermocouple.
- The Thomson effect in the TEM can be neglected.
- Heat conduction through the conductive tabs is ignored.
The TEM operates in power generation mode or heating-cooling mode with different thermal contact resistance and electrical contact resistance.

8.3 Dual-mode TEM Modelling

The TEM consists of a generating mode and heating-cooling mode. Figures 3.4 and 8.1 depict the temperature distribution in a TEM and its energy balance in generation mode and heating-cooling mode, respectively. This chapter only focus on the modelling of the heating-cooling mode.

In the heating-cooling mode, an electrical current $I$ is introduced to the thermoelectric module. On the cold side, the cooling load $Q_{cm}$ is pumped from the atmosphere to the TEM, and on the hot side, the heating load $Q_{hm}$ is emitted to the atmosphere. The energy balance equations for the hot side and cold side of the thermocouples for the heating-cooling mode can be respectively expressed as:

$$ Q_{hm} = IS_{tc}T_{tc, h} - Q_{tm} + \frac{1}{2}I^2R_{int} $$(8.1)
\[ Q_{cm} = IS_{tc}T_{tc.c} - Q_{tm} - \frac{1}{2} I^2 R_{int} \]  

(8.2)

\( R_{int} \) is the overall electrical resistance of the TEM, which includes the electrical resistance of the thermocouples \( R_{tc} \) and electrical contact resistance \( R_{ct} \).

\[ R_{int} = R_{tc} + R_{ct} \]  

(8.3)

\( Q_{hm} \) and \( Q_{cm} \) are respectively the heat conducted through the hot and cold side of the module. \( Q_{tm} \) includes the heat conducted through the thermocouples and the air gap between the thermocouples. They can be calculated respectively as follows:

\[ Q_{hm} = K_{hm}(T_{cp.h} - T_{tc.h}) \]  

(8.4)

\[ Q_{cm} = K_{cm}(T_{tc.c} - T_{cp.c}) \]  

(8.5)

\[ Q_{tm} = (K_{tc} + K_{gap})(T_{tc.h} - T_{tc.c}) \]  

(8.6)

where \( K_{hm} \) and \( K_{cm} \) are respectively the overall thermal conductance of hot and cold side of the module. They can be expressed as follows:

\[ \frac{1}{K_{hm}} = \frac{1}{K_{cp}} + \frac{1}{K_{ct.h}} \]  

(8.7)

\[ \frac{1}{K_{cm}} = \frac{1}{K_{cp}} + \frac{1}{K_{ct.c}} \]  

(8.8)

where \( K_{ct.h} \) and \( K_{ct.c} \) are respectively the hot and cold side thermal contact conductance, which include thermal contact conductance inside TEMs and between the TEMs and the aluminium plates.

Figure 8.2 presents the electrical network of a TEM. Based on the Seebeck effect, when there is temperature difference between a TEM, a Seebeck effect voltage \( U_{TEM,sb} \) can be generated, which can be expressed as follow:
In the heating-cooling mode, the voltage input $U_{TEM.in}$ is the sum of Seebeck effect voltage and voltage of internal electrical resistance of the TEM. The power input $P_{TEM.in}$ is the sum of the Seebeck effect power and the electrical loss in the thermoelectric module.

\[
U_{TEM.in} = U_{TEM.sb} + IR_{int}
\]  
\[
P_{TEM.in} = U_{TEM.sb}I + I^2R_{int}
\]

### 8.4 Experimental Setup

The performance of TEM in terms of power generation and heating-cooling are respectively evaluated by a power generation test rig and a heating-cooling test rig. The power generation test rig (Figure 3.6) have been presented in Chapter 3. Therefore, the section only gives a description of the heating-cooling test rig. The tested TEM is the Bi$_2$Te$_3$ TEM bought
from European Thermodynamics Ltd [42].

The scheme of the heating-cooling test rig and its structured diagram are shown in Figure 8.3. The system consists of five parts:

- Electric heater,
- Aluminium plates,
- TEM module,
- Radiator,
- Data acquisition system.

To minimize the thermal contact resistance at the TEM interfaces, g-clamps are used to apply clamping force and a thermal grease is applied to the interfaces. The heat loss from the system via convection is reduced by insulating the cold aluminium plate with balsa wood. Four K-type thermocouples sensors, whose location are indicated by black dots on Figure 8.3, are installed. $T_{\text{heat}}$, $T_{\text{cd}}$, $T_{\text{hd}}$ and $T_{\text{env}}$ are respectively temperatures at the radiator, cold side aluminium plate, hot side aluminium plate, and ambient. These temperature data, electrical power consumed by the heater ($P_{\text{heat}}$), and voltage ($U_{\text{TEM,in}}$) and current (I) supplied to the TEM are all monitored and collected through the data acquisition system. The uncertainty for voltage and current measurements are respectively $\pm 0.05$ A and $\pm 0.05$ V. The maximum uncertainty for measuring the temperature is 0.1K.

8.5 Model Validation

The real tested properties of a TEM in the applications of power generation and heating-cooling can be different from a direct calculation from the materials and geometrical parameters [128, 129], for different thermal contact resistance and electrical contact resistance in these applications. Like the single-model TEM model developed in Chapter 3, a constant electrical contact resistance $R_{\text{ct}}$ and linear functions of temperature for thermal contact conductance $K_{\text{ct,h}}$ and $K_{\text{ct,c}}$ are assumed in the dual-mode TEM model.
Figure 8.3: TEM heating-cooling test rig and its structure diagram.
\begin{equation}
R_{ct} = b_{ct.0} \tag{8.12}
\end{equation}

\begin{equation}
K_{ct.h} = b_{ct.1} + b_{ct.2}T_{hd} \tag{8.13}
\end{equation}

\begin{equation}
K_{ct.c} = b_{ct.1} + b_{ct.2}T_{cd} \tag{8.14}
\end{equation}

\(b_{ct.0}, b_{ct.1}\) and \(b_{ct.2}\) are tuning parameters.

The tuning process and results for the Bi\(_2\)Te\(_3\) TEM used in power generation mode has been presented in Chapter 3. Therefore, this section only gives the model validation process of the Bi\(_2\)Te\(_3\) TEM used in heating-cooling mode. The experiment is started by setting temperature of cold side aluminium plate to constant. Two different cold side temperatures \(T_{cd}(T_{cd} = 26^\circ C\) and \(T_{cd} = 44^\circ C\)) are conducted here for the validation. The electric current \(I\) is increased from 0 A to 3.5 A and data acquisition system simultaneously records all the data. Each experiment is repeated at least three times to obtain reproducible results.

The tuning parameters \(b_{ct.0}, b_{ct.1}, b_{ct.2}\) are determined by solving a least-squares optimization problem that minimizes \(J_2\), defined as:

\begin{equation}
J_2(b_{ct.0}, b_{ct.1}, b_{ct.2}) = (Q_{cm} - Q_{cm, meas})^2 \tag{8.15}
\end{equation}

where \(Q_{cm}\) is the model output and \(Q_{cm, meas}\) is measured data. To decrease the measurement error from natural convective heat loss, the measured cooling load \(Q_{cm, meas}\) at the cold side aluminium plate to the TEM can be calculated as:

\begin{equation}
Q_{cm, meas} = P_{heat} - (T_{heat} - T_{env})h_{nc}A_{heat} - (T_{cd} - T_{env})h_{nc}A_{Al} \tag{8.16}
\end{equation}

where \(h_{nc} = 10W/(m^2.K)\) is the natural convective heat transfer coefficient. \(A_{Al}\) and \(A_{heat}\) are respectively surface area of aluminium plate and electric heater.

For the heating-cooling mode, \(R_{ct}, K_{ct.h}\) and \(K_{ct.c}\) can be expressed respectively as follows:
Figure 8.4: Experimental data and simulation results of TEM in heating-cooling mode with error bars.

\[ R_{ct} = 0.25\Omega \]  
\[ K_{ct.h} = (0.038T_{hd} - 9.84)W/K \]  
\[ K_{ct.c} = (0.038T_{cd} - 9.84)W/K \]

The comparison of the simulation results with the experimental data of power generation mode and heating-cooling mode are respectively presented in Figures 3.8 and 8.4. It can be seen that both simulation results correspond well with the test results. This validation shows that both the electrical contact resistance and thermal contact conductances give good fits for the tested TEM in both power generation mode and heating and cooling mode.
8.6 Analysis of TEMs’ Bifunctional Characteristic

Based on the validated bifunctional TEM model, four-quadrant operation diagrams of the TEM are plotted in Figure 8.5, which show both the electric power generation curves in generation mode and heat absorption and rejection curves in heating-cooling mode. The first quadrant of the four-quadrant operation diagram represents the power generation mode, where the generated electric current and power are both positive. The heating-cooling mode is presented in the third quadrant of the four-quadrant operation diagram, where the input electric current and the absorbed heat at cold side (cooling load) and rejected heat at hot side (heating load) are all negative. The cold side temperature of TEM is set constant $T_{cd}=80^\circ C$ for power generation mode. For the heating-cooling mode, $T_{cd}$ is respectively set as $20^\circ C$ for heating and $80^\circ C$ for cooling.

It can be seen from Figure 8.5 that bigger temperature difference between the hot and cold side of the TEM gives higher power output in the power generation. However, both heat rejection at hot side and heat absorption at cold side decrease as the temperature difference ($\Delta T$) increases. It means that the TEM works more efficiently in power generation mode when higher temperature difference exists at hot and cold sides. While in heating-cooling mode, the TEM works most efficiently when the hot and cold side of the module are at the same temperature. Comparing the heating mode with the cooling mode, it is found out that an optimal input current exists in the cooling mode which gives the best cooling effect. However, for the heating mode the heating effect always increases with the input current. This difference can be explained by examining the energy balance equations for the hot and cold sides in heating-cooling mode (Equations 8.1 and 8.2): the TEM pumps the half of the Joule heat ($I^2R_{int}$) to the hot side and another half to the cold side.

This four-quadrant operation diagram of the TEM can be used to analyse the bifunctional characteristics of the TEM. By using the four-quadrant operation diagram, the appropriate operating conditions (I and $\Delta T$ ) in the both power generation mode and heating-cooling mode can be selected. Guidance can be given to design a TEG system that operates in both power generation mode and heating-cooling mode.
(a) Cooling and generation curves of the TEM.

(b) Heating and generation curves of the TEM.

Figure 8.5: Four-quadrant operation diagrams of the TEM.
To investigate the bidirectional characteristic of the TEMs, a dual-mode TEM model, which can simulate both power generation mode and heating-cooling mode, is developed and presented in this paper. Experiments are carried out in both a power generation test rig and a heating-cooling test rig. The good agreements between the simulated results and experimental data in both modes have confirmed the reasonability of the dual-mode TEM model.

A four-quadrant diagram for the TEM is produced based on the validated TEM model, which clearly presents the cooling, heating and power generation curves of a TEM in heating-cooling mode and power generation mode. Based on the analysis of the four-quadrant diagram, conclusions can be drawn as follows:

- TEM works more efficiently in power generation mode when higher temperature difference exists at hot and cold sides. While in heating-cooling mode, the TEM works most efficiently when the hot and cold side of the module are at the same temperature.
- Optimal input current exists in the cooling mode which gives the best cooling effect. However, for the heating mode the heating effect always increases with the input current.
- This four-quadrant diagram can be used to analyse the bidirectional characteristic of the TEM and select appropriate operating conditions for both power generation mode and heating-cooling mode.
Chapter 9

Feasibility Study of a Bifunctional Vehicular TEG

In this chapter, a bifunctional vehicular TEG, which can be used for both waste heat recovery (WHR) and engine warm-up (EWP), has been proposed. Simulation models consisting of a bifunctional TEG model and engine oil and coolant circuit model have been developed to evaluate the performance of this vehicular TEG in terms of WHR and EWP. The feasibility and effectiveness for the proposed system will be demonstrated by comparing with the vehicular TEG operating only for WHR.
9.1 Novelty of a Bifunctional Vehicular TEG

Because of the bidirectional characteristic of the thermoelectric modules (TEMs), the same TEM can not only work in power generation mode (Seebeck effect), but also in heating-cooling mode (Peltier effect). Theoretically, a TEG can not only be used as a power generator but also can be used as a heating or cooling device. When compared with existing studies for thermoelectric cooling applications [170–173], there are relatively few studies focusing on thermoelectric heating. Cosnier et al. [170] investigated the feasibility of cooling or heating air through thermoelectric modules. The test results showed that the heating coefficient of performance (COP) were higher than the cooling COP, which could easily reach near 2.0. Liu et al. [171] developed a thermoelectric heating system with multiple channels. Experimental results showed that the average heating coefficient of the thermoelectric heating was greater than that of electric heating. He et al. [172, 173] tested a thermoelectric heating system with solar energy, which could release heat to increase the room temperature in winter by applying voltage on thermoelectric device. The test results showed that the average COP of this system in heating mode could be about 1.7. All these studies have suggested that TEMs can be utilized for heating, which can compete with or be even better than the traditional heating method.

Routing coolant from the original engine coolant circuit to the cold side of TEG is implemented by many vehicular TEG prototypes [89,90,111]. To further optimize the integration of TEG cooling units, a few studies proposed using the heat rejected to coolant from TEG to warm up the engine, gearbox and vehicle interior [76,90,174,175]. However, most of these studies have not given any simulation or experimental results for the warm-up effect of the TEG. Furthermore, the only test from Crane et al. [90] did not prove a faster warm-up effect for the TEG integration with engine coolant circuit. Based on their analysis, the main reason for the failure of warming up were only small quantities of heat entered into the coolant and most of the exhaust heat was wasted for warming up the TEG system.

Reviewing the published papers [77,89,90,111,115,116] in the vehicular TEG field, all the studies focused on applying the vehicular TEGs for the WHR based on Seebeck effect. There are no studies using a TEG as a heating device based on Peltier effect for engine warm-up (EWP), although the potential of thermoelectric heating effect has been proved in many
9.2 Description of the Bifunctional Vehicular TEG

New technology is usually firstly adopted in high-end cars and then gradually being used in standard cars. Consequently, for the purposes of this study, the bifunctional TEG is assumed to be integrated in a 2l-diesel and D-segment passenger car whose specification is shown in Table 9.1. The integration scenario for the TEG is presented in Figure 9.1. The TEG is installed between the diesel oxidation catalyst (DOC) and diesel particulate filter.
Table 9.1: Specification for reference car

<table>
<thead>
<tr>
<th>Specification</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total mass of the vehicle [kg]</td>
<td>2025</td>
</tr>
<tr>
<td>Frontal area [m²]</td>
<td>2.26</td>
</tr>
<tr>
<td>Tyre radius [m]</td>
<td>0.326</td>
</tr>
<tr>
<td>Drag coefficient [-]</td>
<td>0.29</td>
</tr>
<tr>
<td>Transmission ratio 1st to 5th gear [-]</td>
<td>3.727/2.043/1.322/0.947/0.723</td>
</tr>
<tr>
<td>Differential gear [-]</td>
<td>4.266</td>
</tr>
<tr>
<td>Engine type</td>
<td>diesel</td>
</tr>
<tr>
<td>Cylinders</td>
<td>4</td>
</tr>
<tr>
<td>Engine displacement [L]</td>
<td>1.944</td>
</tr>
<tr>
<td>Bore [mm]</td>
<td>84</td>
</tr>
<tr>
<td>Stroke [mm]</td>
<td>90</td>
</tr>
<tr>
<td>Engine maximum power [kW]</td>
<td>110</td>
</tr>
<tr>
<td>Engine maximum torque [Nm]</td>
<td>323</td>
</tr>
<tr>
<td>Engine oil capacity [L]</td>
<td>4.05</td>
</tr>
<tr>
<td>Cooling system capacity [L]</td>
<td>9.7</td>
</tr>
</tbody>
</table>

(DPF). A bypass line, which is used to protect the TEG from high exhaust temperature and avoid the engine oil being overheated, controls the flow through the TEG by adjusting valve 1. The TEG is also integrated with the engine oil circuit, which is incorporated in series with the original oil-coolant cooler. Valve 2 controls the engine oil through the oil cooler. This bifunctional TEG can operate in two modes: EWP mode and WHR mode. When it is used in EWP mode, the vehicle battery supplies electric current to it. Based on Peltier effect, the TEG transfers heat from exhaust to the engine oil, which is heated up by the TEG. When the oil is already hot, the vehicle battery stops supplying current. The TEG begins to operate in WHR model and the oil cooler permits the thermal regulation of the oil at the cold side. Based on Seebeck effect, the TEG converts part of the exhaust energy into electricity and then through the DC-DC converter, the regenerated electrical power is converted to fit the electric system of the car.

Figure 5.1 shows the structure and size of the TEG system for this case study, which is
the same as the application of dynamic TEG model in Chapter 5. The TEG system is symmetrical about the hot channel. The TEG can be divided into three major regions: hot end, cold end, and central region. Both the hot and cold end are made up of a HXR and an aluminium plate. The hot side HXR is connected to the exhaust line of the engine and the cold side HXR is connected to the engine oil circuit. The function of the aluminium plates is to even the temperature distribution along the flow direction and reduce the spreading resistance with their relatively higher thermal conductivity. Each central region consists of 10 European Thermodynamics TEMs (GM250-127-28-10) and insulation materials. It is assumed that all the TEMs are evenly distributed on the surface of HXR and electrically connected in series. The air gap between the TEMs are filled with insulation materials, which can effectively reduce the possible heat leakage through the air gaps.

9.3 Simulation Method

To estimate the performance of the proposed TEG in terms of EWP and WHR, a simulation model is established based on the validated bifunctional TEM model. The simulation model consists of a bifunctional TEG model and an engine oil and coolant circuit model, which are introduced below.

9.3.1 Bifunctional TEG Model

The dynamic TEG model developed in Chapter 4 is further extended from only modelling WHR to modelling both WHR and EWP. The main difference between modelling WHR mode and EWP mode are the energy equations for hot end and cold end.

For the WHR mode, the TEMs work in power generation mode and the energy equations for hot end and cold end in the ith control volume are expressed respectively as:

\[
(M_{hxr.CV}c_{hxr} + M_{ap.CV}c_{ap}) \frac{dT_{hd.i}}{dt} = Q_{hxr.i} - n_{TEM}Q_{hm} - Q_{Ins.i} \quad (9.1)
\]

\[
(M_{cxr.CV}c_{cxr} + M_{ap.CV}c_{ap}) \frac{dT_{cd.i}}{dt} = Q_{Ins.i} + n_{TEM}Q_{cm} - Q_{crr.i} \quad (9.2)
\]
Q_{hxr,i} and Q_{cxr,i} are respectively the heat absorbed by the hot side HXR and the heat dissipated to cold side HXR. Q_{Ins,i} is the heat conducted through the insulation materials. \( n_{TEG} \) is the number of TEMs in \( i \)th control volume.

For the EWP mode, the TEMs work in heating-cooling mode and energy equations for hot end and cold end in the \( i \)th control volume are expressed respectively as:

\[
(M_{hxr,CV}c_{hxr} + M_{ap,CV}c_{ap}) \frac{dT_{hd,i}}{dt} = Q_{hxr,i} - n_{TEM}Q_{cm} - Q_{Ins,i} \quad \text{(9.3)}
\]
\[
(M_{cxr,CV}c_{cxr} + M_{ap,CV}c_{ap}) \frac{dT_{cd,i}}{dt} = Q_{Ins,i} + n_{TEM}Q_{hm} - Q_{cxr,i} \quad \text{(9.4)}
\]

The rest of simulation settings for the TEG model in EWP mode are the same as previous work in Chapter 4 and are not explicitly given are in this chapter. It is assumed that the heat transfer coefficients of HXRs in this study are the same as our previous experimental validated values in Chapter 5 (Scenario 2).

### 9.3.2 Engine Oil and Coolant Circuit Model

An engine oil and coolant circuit model is developed by using GT-Power simulation software. The engine oil and coolant circuit model is able to simulate the warm-up characteristics of both engine oil and coolant based on driving cycles. The configuration of the original engine oil and coolant circuit before the TEG integration is shown in Figure 9.2. The model mainly includes: coolant pump, engine, thermostat, radiator, fan, oil pump, oil filter and oil cooler. The opening temperature of the thermostat is set to 82°C, open to a maximum temperature of 107°C. The valve 2 opens oil cooler branch when the the engine oil temperature is lower than coolant temperature or it exceeds 105°C. Opening temperature of the fan is 95°C.

The simulation result of the warm-up characteristic of coolant and engine oil at NEDC starting from ambient temperature 25°C is shown in Figure 9.3. As can be seen the coolant water warms up faster than the engine oil. The optimal temperature range for coolant and engine oil are respectively 95±5°C and 105±5°C \([176]\). The coolant reaches its optimal temperature in approximately 800s, but the engine oil is still below its optimal temperature at the end of the NEDC.
Figure 9.2: Configuration of the original engine oil and coolant circuit.

Figure 9.3: Warm up characteristics of the original coolant and engine oil at NEDC.
In order to investigate the EWP performance of TEG, the engine oil and coolant circuit model is coupled with the bifunctional TEG model based on the TEG integration scenario. The bifunctional TEG model requires the engine oil temperature and flow rate as input data. Then the calculation results of rejected heat rate to engine oil from the bifunctional TEG model is fed back to the engine oil and coolant circuit model.

9.4 Simulation Results and Discussion

The exhaust data downstream of the DOC from the reference engine running the NEDC based on the referenced vehicle is used as input for the bifunctional TEG model. 20A electrical current is assumed to be supplied when the TEG works in EWP mode. The ambient temperature is 25°C. The simulation results of engine oil temperature and TEG power output with different scenarios are presented in this subsection. The scenario baseline is the original engine oil circuit without TEG integration. The scenario TEG-WHR is the TEG being integrated as Figure 9.2 but only operating in WHR mode. The scenario TEG-EWP-WHR is the TEG operating in EWP mode for the first 900s and then operating in WHR mode.

9.4.1 TEG Performance in EWP

Figure 9.4 shows the engine oil temperature of NEDC for the three different scenarios. The maximum engine oil temperature for the baseline can only reach 88°C, which is about 10°C below the optimal temperature. In comparison, the warm-up time for engine oil reaching 88°C in scenario TEG-WHR (697s) and TEG-EWP-WHR (840s) are respectively reduced by 25% and 38% with respect to the baseline (1128s). The TEG-EWP-WHR scenario reaches the optimal engine oil temperature (100°C) at 868s, which is about 3 minutes faster than the TEG-WHR scenario (1050s).

Figure 9.5 presents the engine oil temperature at the first 200s of NEDC of the three different scenarios. When the TEG only operates in WHR mode, the faster warm-up effect is not obvious, especially in the first 100s of NEDC. The reason is that there is only a small amount of exhaust heat at first 200s of NEDC and the extracted exhaust energy is wasted.
Figure 9.4: Warm up characteristics of engine oil at NEDC with different strategies.

Figure 9.5: Warm up characteristics of engine oil at the first 200s of NEDC with different scenarios.
Figure 9.6: TEG power generation in NEDC with different scenarios.

for warming up the TEG (HXR, TEMs, aluminium plates). Therefore, there is no heat left which could be used for faster engine oil warming. In comparison, TEG in EWP mode speeds up the engine oil warm-up at the very beginning of the NEDC by both extracting the exhaust energy and heating the engine oil based on Peltier effect. As can be seen, the engine oil temperature in scenario TEG-EWP-WHR can be raised up about 7°C in the first 100s with respect to the baseline. Considering the higher viscosity of engine oil at lower temperature leading to higher friction loss, the fuel saving in scenario TEG-EWP-WHR can be more effective than scenario TEG-WHR.

In the view of engine oil warm-up, the TEG operating in EWP mode speeds up the warm-up more effectively than TEG operating in WHR mode. With small amount of electrical energy applied for the TEG to work in EWP mode, a faster warm-up effect can be obtained at the very beginning of the driving cycles and optimal engine oil temperature can be reached earlier, which can help the engine to reduce the friction loss and increase fuel efficiency.
9.4.2 TEG Performance in WHR

Figure 9.6 shows the evolution of electric power generation of the TEG in TEG-WHR scenario and TEG-EWP-WHR scenario. For the TEG-WHR scenario, the electric power output is less than 50W in the urban driving cycle (0s-780s). This can be explained by the relatively less thermal energy at the exhaust due to the frequent stops at urban driving cycle. The electric power output increases in the extra-urban driving cycle (780s-1180s) and the maximum power generation of 153W is achieved when the vehicle runs continuously with high speed. The total regenerated electric energy of TEG-WHR scenario in the NEDC is about 325 (W · min).

For the TEG-EWP-WHR scenario, no electric power is generated before 900s since the TEG is working in EWP mode. When the engine oil is warmed up, the TEG begins to work in EWP mode. The average electric power output of TEG-EWP-WHR scenario in the last 280s of the NEDC is about 45W, which is lower than the average power output of TEG-WHR scenario in the same time. This can be explained by the relatively higher engine oil temperature of the TEG-EWP-WHR scenario. The total regenerated electric energy of TEG-EWP-WHR scenario in the NEDC is about 204 (W · min). Even though the TEG only operates in WHR mode for 280s in this scenario, the total regenerated electric energy is more than 85% of the TEG-WHR scenario operating in WHR for 1180s.

In the view of WHR, TEG performs more effectively when a vehicle is running continuously at a high speed. However, during driving cycles with frequent stops and low vehicle speeds, the power generation is limited. Therefore, to achieve better fuel saving potential TEG can operate in EWP mode at the vehicle starting or low speed phrase and then turn to WHR mode when the engine oil warm-up finished.

9.5 Conclusions

By applying the dual-model TEM model to the previous developed TEG model and coupling with an engine oil and coolant circuit model, the feasibility of applying a bifunctional TEG to a 2l-diesel passenger car for both WHR and EWP is investigated in this chapter. Conclusions can be drawn as follows:
• It is shown that compared with the original engine oil circuit, a faster warm-up effect can be obtained for both TEG in WHR mode and TEG in EWP mode.

• The simulation results show that compared with the TEG only operating in WHR, a 3-minute faster warm-up effect of engine oil can be obtained when the bifunctional TEG works in EWP mode with electrical current applied.

• An obvious faster warm-up effect (engine oil temperature raises by 7°C in 100s) at the beginning of the driving cycle can only be obtained when the TEG works in EWP mode.

• It also finds out that the electric power generation from WHR at vehicle starting and low vehicle speed phrase is limited, while the faster warm-up effect can be obvious by operating the TEG in EWP mode. Therefore, it is suggested that operating TEG in EWP mode at the vehicle starting or low speed phrase and then turning to WHR mode when the engine oil warm-up is finished.
Chapter 10

Conclusions and Recommendation for Future Work

This chapter gives a review of the significant conclusions presented in each chapter of the thesis. Based on these conclusions, an introduction concerning the improvements, suggestions and recommendations for future work on vehicular TEG are presented.
10.1 Conclusions

The purpose of this thesis is to present the results of the investigation of the integration of TEG into a vehicle propulsion system. The design and modelling of a TEG have been fundamental aspects of this work. The three main challenges in the application of TEG include:

- Low conversion efficiency and low maximum operating temperature as dictated by the properties of the chosen thermoelectric materials,
- Integration effects arising from increased mass, increased exhaust backpressure, and installation complexity,
- High cost of many thermoelectric materials, which leads to a commercialization challenge to the TEG technology.

Addressing these three main challenges is a prerequisite for vehicular TEG to be widely accepted as a practical and economic technology. This project gives a deeper analysis of the challenges and certain solutions for successfully addressing these challenges.

To begin, a review of literature describing the current development of thermoelectric materials and modules and the implementation of vehicular TEG was conducted. This review revealed that many efforts have been made in previous research to improve the performance of TEG so as to solve the vehicular TEG commercialization challenges. Through the analysis of the literature, four research gaps for vehicular TEG have been identified. To fulfill the aim of the thesis, objectives for model development and model applications, which are intended to directly address the research gaps, have been identified.

The quasi-static TEM model has been developed and validated by testing two TEMs (Bi$_2$Te$_3$ and Skutterudite) on the TEM power generation test rig. Based on the validated TEM model, the dynamic TEG model has been developed and validated. Experiments are done on both a light-duty gasoline Skutterudite TEG engine test bench and a heavy-duty Bi$_2$Te$_3$ TEG diesel engine test bench. Major conclusions and technical issues identified in the application of the dynamic TEG model are as follows:

- Even in the relatively lower exhaust temperature of diesel engine, a bypass solution is
still needed to protect the Bi$_2$Te$_3$ TEG prototype under high speed and load engine conditions. The Skutterudite TEG can withstand higher temperatures and is more suitable to be used in gasoline engine WHR.

- The simulation results of power outputs show a TEG with 20 Bi$_2$Te$_3$ TEMs can produce average 170-224W electric power upstream of the DOC-DOF and average 132W electric power in the EGR path.

- It was found that TEG power generation is highly sensitive to heat transfer coefficient of hot side HXR and thermal contact resistance.

- The dynamic TEG model can be used as an useful tool for TEG model-based control system, performance prediction, and optimization design.

The semi-empirical vehicular TEG model for the Skutterudite TEG integrated in a conventional light-duty gasoline vehicle has been developed. The semi-empirical vehicular TEG model includes a quasi-static vehicle model, a dynamic exhaust model, a dynamic coolant model, and a dynamic TEG model. Both experimental and published data were used to validate the semi-empirical vehicular TEG model. Major conclusions and technical issues identified in the application of the semi-empirical vehicular TEG model are as follows:

- The fuel economy improved by the skutterudite TEG is between 0.5% and 3.6% depending on integration positions in the exhaust line and driving cycles. It was found out the skutterudite TEG has better performance in highway driving than city driving cycle.

- The TEG installation position was identified as the most important effect to the fuel saving potential. Positioning skutterudite TEG upstream of the TWC can increase the fuel saving potential by 50% compared with TEG installed downstream of the TWC.

- The listed four integration effects altogether lead to a 25% reduction of fuel saving potential. Among the four integration effects, the energy loss in the DC-DC converter and the added mass due to the TEG were most significant at 10% and 6.9% respectively. The losses due to electrical pump load and the effect of exhaust back pressure had a minor effect at 5% and 3.1%.

- The overall cost for the TEG in this simulation was around 3400-3443€ depending on
the integration position in the exhaust line. The cost of the TEMs accounted for more than 90% of the overall cost the TEG system, which can be the key to minimize the TEG system cost.

- The fuel saving benefit for a 15-year lifetime TEG was lower than the cost. Benefit cost ratio could reach 1 with 20% of TEG cost reduction when TEG was integrated upstream the TWC.

The single-mode TEM model has been upgrade to the dual-model TEM model. The simulation results for the Bi$_2$Te$_3$ TEM operating in the two modes were verified with experiments on TEM power generation test rig and TEM heating-cooling rig. A feasibility study of applying a bifunctional TEG to a 2l-diesel engine passenger car was then carried out based on a further extended bifunctional TEG model and an engine oil and coolant circuit model. Major conclusions and technical issues identified in the feasibility studies are as follows:

- The simulation results showed that compared with the TEG only operating in WHR, a 3-minute faster warm-up effect of engine oil could be obtained when the bifunctional TEG worked in EWP mode with electrical current applied.

- An obvious faster warm-up effect (engine oil temperature raised by 7°C in 100s) at the beginning of the driving cycle can only be obtained when the TEG worked in EWP mode, due to the exhaust energy was wasted for warming-up the TEG.

- It also found out that the electric power generation from WHR at vehicle starting and low vehicle speed phrase is limited, while the faster warm-up effect could be obvious by operating the TEG in EWP mode. Therefore, operating TEG in EWP mode at the vehicle starting or low speed phrase and then turning to WHR mode when the engine oil warm-up finished was suggested.

10.2 Recommendation for Future Work

From the three main models and model applications, the commercial solution for vehicular has been proposed and analysis, but further improvements of TEG performance and promote commercialisation are required.
• Heat transfer coefficient of hot side HXR and thermal contact resistance was identified as the most two sensitive parameters to the TEG power output in Chapter 5. Therefore, the next step would be to optimize the integration of TEMs on the HXRs and configuration of the hot side HXR. Currently, the geometry of the TEMs strongly limit the geometrical optimization of hot side HXR and the assembly process for the TEMs on the HXRs leading to a large thermal contact resistance. The method of materials jetting of thermoelectric materials can be adopted as a design optimization method, which fully utilise the design freedoms to match the complex geometries and temperature distribution.

• Based on the application of the materials jetting technology on the TEG design, a three-dimensional TEG model will be developed to analyse and optimize the the mass-flow distribution, temperature distribution and TEMs distribution.

• The developed dynamic TEG model can be further combined with the future developed three-dimensional TEG model. Based on their combination, a comprehensive system-level optimization maximizing the power output while also considering the system costs will be conducted.

• The two model-based TEG-temperature control systems were proposed in Chapter 5. Based on the proposed control structure, the control systems can be designed, fabricated and tested in the future.

• The loss in DC-DC convector was identified as the most significant integration effect in Chapter 7. Therefore, the selection of a DC-DC converter and wiring method for the TEG to the vehicle electrical bus need to be carried out in the future investigation.

• The bifunctional TEG proposed in Chapter 9 will be fabricated and tested. The simulation results for the WHR performance and EWP performance will be validated by the experiments data.
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Books

Conference Papers


Appendix A

A.1 Driving Cycle Data

The speed profile of New European Driving Cycle (NEDC) is presented in Figure A.1. It consists of four repeated ECE-15 urban driving cycles (UDC) and one Extra-Urban driving cycle.
The speed profile of Worldwide harmonized Light vehicles Test Procedure (WLTP) is presented in Figure A.2. The WLTC driving cycle for a Class 3 vehicle is divided in four parts for Low, Medium, High, and Extra High speed; if $V_{\text{max}} < 135\text{km/h}$, the Extra High speed part is replaced with Low speed part.

The Federal Test Procedure, commonly known as FTP-75 for the city driving cycle, are a series of tests defined by the US Environmental Protection Agency (EPA) to measure the emissions and fuel economy of passenger cars. The speed profile of FTP-75 is presented in Figure A.3.

FTP-highway is developed by the US EPA and is used to determine the highway fuel economy rating. The speed profile of FTP-highway is presented in Figure A.4.

The speed and load profile of Nonroad Transient Cycle (NRTC) is presented in Figure A.5. The NRTC is designed to take account of a wide range of engine outputs, and the legislation limits emissions of CO, HC, NOx and particulates.
Figure A.3: Speed profile of FTP-75.

Figure A.4: Speed profile of FTP-highway.
Figure A.5: Speed and load profile of NRTC.