RESEARCH ON THERMOELECTRIC GENERATION IN THE RECOVERY OF AUTOMOBILE EXHAUST WASTE HEAT

Lappeenranta–Lahti University of Technology LUT
Bachelor’s Programme in Energy Technology, Bachelor's thesis
2024
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Examiner(s): Lecturer Liyao Xie
Professor Teemu Turunen Saaresti
ABSTRACT
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Research on thermoelectric generation in the recovery of automobile exhaust waste heat

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This thesis addresses the exploration of thermoelectric generation (TEG) in vehicle exhaust waste heat recovery with the aim of improving vehicle energy efficiency and reducing environmental impact. Based on the Seebeck effect, the study analyses how the thermal energy of the engine exhaust can be converted into electrical energy by exploiting the temperature difference between the engine exhaust and the cooler ambient air. Through simulations carried out in COMSOL Multiphysics software, the paper examines in detail the key factors affecting the performance of the TEG, including the air inlet temperature, mass flow rate and the number of fins in the heat exchanger. It is shown that optimising the number of fins in the heat exchanger not only significantly improves the heat transfer efficiency, but also maximises the net power output of the TEG system whilst reducing pressure losses.

The results of this thesis provide a comprehensive understanding of the design and efficiency of thermoelectric power generation systems and confirm the potential for integrating TEG into the automotive sector, pointing to the ability of these systems to efficiently convert waste heat into useful energy, contributing to the sustainable development of the automotive industry.
# SYMBOLS AND ABBREVIATIONS

**Roman characters**

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>$P$</td>
<td>pressure</td>
<td>Pa</td>
</tr>
<tr>
<td>$qm$</td>
<td>mass flow rate</td>
<td>kg/s</td>
</tr>
<tr>
<td>$T$</td>
<td>temperature</td>
<td>K</td>
</tr>
<tr>
<td>$U$</td>
<td>voltage</td>
<td>V</td>
</tr>
<tr>
<td>$V$</td>
<td>electric potential</td>
<td>V</td>
</tr>
<tr>
<td>$v$</td>
<td>specific volume</td>
<td></td>
</tr>
<tr>
<td>$\dot{Q}$</td>
<td>thermal power</td>
<td>W</td>
</tr>
<tr>
<td>$I$</td>
<td>current</td>
<td>A</td>
</tr>
<tr>
<td>$S$</td>
<td>Seebeck coefficient</td>
<td>V/K</td>
</tr>
<tr>
<td>$Cp$</td>
<td>specific heat capacity</td>
<td>J/kgK</td>
</tr>
<tr>
<td>$k$</td>
<td>conductivity</td>
<td>W/m K</td>
</tr>
<tr>
<td>$R$</td>
<td>resistance</td>
<td>Ω</td>
</tr>
</tbody>
</table>

**Greek characters**

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\beta$</td>
<td>Thomson coefficient</td>
<td>V/K</td>
</tr>
<tr>
<td>$\lambda$</td>
<td>thermal conductivity</td>
<td>W/mK</td>
</tr>
<tr>
<td>$\Pi$</td>
<td>Peltier coefficients</td>
<td>J/C</td>
</tr>
<tr>
<td>$\rho$</td>
<td>density</td>
<td>kg/m³</td>
</tr>
<tr>
<td>$\sigma$</td>
<td>resistivity</td>
<td>Ω m</td>
</tr>
<tr>
<td>$\mu$</td>
<td>viscosity</td>
<td>kg/m/s</td>
</tr>
</tbody>
</table>

**Subscripts**
h hot
c cold
P P-type
N N-type
A conductors A
B conductors B
P constant pressure process
L load
In internal

Abbreviations
TEM Thermoelectric module
TEMs Thermoelectric modules
TEG Thermoelectric generator
TEGs Thermoelectric generators
FCE Fuel conversion efficiency
EGR Hot exhaust gas recirculation
ORC Organic Rankine Cycle
GHGs greenhouse gases
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1 Introduction

1.1 Background and Significance

Today, vehicles have become an indispensable part of people's daily lives, and their popularity is inextricably linked to the rapid development of the global economy. With the acceleration of urbanisation and the growing demand for personal transport, the number of cars, as a convenient means of transport, continues to show rapid growth. As of 2022, the global production of motor vehicles has already reached a staggering 85,016,728 units, compared to 58,374,162 units in 2000, an increase of about 30 million units. This huge number not only reflects the rapid advancement of technology, but also highlights the extent to which modern mankind relies on mobility.

However, this reliance also brings with it the obvious problem of a huge impact on the environment. In this rapidly evolving automotive era, we need to think seriously about how to meet the demand for travel while minimising irreversible damage to the planet. Against this background, it is particularly urgent to think deeply about and improve the way cars use energy. In the current market, the majority of cars still use internal combustion engines, while vehicles fuelled by bioenergy and electricity have a relatively small market share. The exhaust of vehicles with internal combustion engines contains a large amount of greenhouse gases (GHGs), of which carbon dioxide is the main source of the greenhouse effect, accounting for 13% of the total exhaust emissions (IARC Working Group on the Evaluation of Carcinogenic Risks to Humans, 2014).

Interestingly, only 25% of the energy released from the combustion of vehicle fuel is used to propel the vehicle forward as shown in Figure 1. The other 30% is discharged through the coolant and 40% is emitted into the air as exhaust gases, indicating that most of the fuel is wasted. If we are able to use the exhaust gases from automotive fuel
combustion for recycling and conduct research on thermoelectric generation, it will greatly improve energy utilisation and thus reduce carbon emissions and carbon footprint. And the U.S. Department of Energy states that improving the efficiency of internal combustion engines is the most promising and cost-effective way to improve vehicle fuel economy over the next 30 years. (Rajoo et al., 2014) This initiative will help to promote environmentally friendly technologies and mitigate the negative impacts on the environment.

![Figure 1. Distribution of vehicle exhaust (Avaritsioti, 2016).](image)

1.2 Key findings of previous studies

Currently there are two main directions of exhaust gas waste heat recovery technology, cooling and heating and thermoelectric generation. This thesis focuses on thermoelectric generation. For example, in 1997, Dong Guitian from China proposed a study on semiconductor thermoelectric generation, proposing to use semiconductor lead telluride with iron electrodes for experiments. Although the choice of material was not optimal, it is still a great reference value for the current research. (Liu and Zhong, 2013) conducted a study on the internal combustion engines of vehicles in 2013, which produces about 30% of wasted heat in the exhaust gas and proposed a thermoelectric generation (TEG) prototype for exhaust gas heat recovery. The prototype was experimentally demonstrated to be effective in recovering exhaust gas heat at a high
temperature of 473 K with a maximum power output of 202 W and a system thermal efficiency of 4.04%. (Chmielewski et al., 2013) investigated how to improve the energy efficiency of internal combustion engines, with a particular focus on the exhaust system. Liu et al. (2015) research explored an energy harvesting system that can extract heat energy from vehicle exhausts and convert it into electricity using thermoelectric generators (TEGs). The performance of the TEG system was analysed by setting up a test bed to assess its feasibility in automotive applications. Characteristics of the system such as hot-side temperature, cold-side temperature, open-circuit voltage, and power output were investigated, and results were obtained for a maximum power of 944 watts, which fully satisfies the requirements of automotive applications. This study shows that low temperature exhaust heat recovery using this thermoelectric generator has a good potential in the automotive sector. The potential of using the Organic Rankine Cycle (ORC) to recover heat from the exhaust gases of a high-efficiency, low-emission dual-fuel, low-temperature combustion engine was also explored by Srinivasan et al. in 2010. By applying a combination of hot exhaust gas recirculation (EGR) and Organic Rankine Cycle (ORC) boosting technology, it is possible to significantly improve the fuel conversion efficiency (by an average of 7 percentage points) and reduce NOx and CO2 emissions (by an average of 18 %) (Srinivasan et al., 2010). In 2016 Meng and the group studied to develop a multi-physics field thermoelectric generator model suitable for automotive exhaust heat recovery, considering the realities of exhaust heat sources and water-cooled radiators. The study focused on analysing the effect of the temperature inhomogeneity of the thermoelectric unit along the flow direction on the system performance (Meng et al., 2016). Liu (2016) focused on thermoelectric conversion technology and studied the automotive waste heat recovery system through theoretical modelling and experimental verification. The mathematical models of the thermoelectric unit and the automotive exhaust gas thermoelectric power generation system were successfully established, and the effects of different factors on the system performance, such as contact pressure and thermal resistance of heat conduction, were verified in the experiments. Eventually, a mature on-board thermoelectric power generation system was mounted and the feasibility and performance advantages of the
system in improving fuel economy were demonstrated through bench and real vehicle tests. Ghorbani et al. (2018) focused on the automotive refrigeration system, and proposed a novel internal combustion engine-based cogeneration system, which generates electricity by recovering the heat of the engine exhaust gases and uses the electricity to drive the automotive cooling system. The system was demonstrated to meet the cooling needs of cars and buses by providing additional cooling capacity. It was found that the cooling capacity of the system can reach up to 130 kW when using diesel engine exhaust heat recovery.

(Rodriguez et al., 2019) study was focused on potential exhaust heat recovery locations, thermoelectric technologies applicable to vehicles, system components, thermoelectric generator modelling as well as experimental studies and future trends among others. The results showed that thermoelectric generators have potential advantages in waste heat recovery and can effectively improve the overall fuel efficiency of vehicles. Hewawasam et al. (2020) investigated the feasibility of integrating thermoelectric generators (TEGs) into the exhaust system of an internal combustion engine to recover waste heat. It was found that by conveniently integrating thermoelectric modules (TEMs) into the silencer, the waste heat from the hot gases could be effectively utilised to generate electrical energy without compromising the function of the silencer.

1.3 Content of the research in this paper

In vehicle exhaust waste heat recovery, thermoelectric generation technology has been widely studied and applied. This technology makes use of the high thermal energy in the engine exhaust and the low temperature in the environment to generate electricity by capturing the temperature difference between both. This is considered by us to be an innovative technology that promises to improve the efficiency of automotive energy use.
The high-temperature waste heat contained in engine exhaust has been an underutilised resource. By integrating a TEG in the exhaust system of a vehicle, we are able to convert this waste heat into electricity, thereby reducing the dependence on conventional energy sources and lowering the carbon footprint of the vehicle.

In this paper, the COMSOL software will be used to model the thermoelectric power generation of a vehicle exhaust waste heat recovery system. Firstly, the potential impact of TEG on engine performance and exhaust system efficiency is explored through a theoretical analysis of the integration of TEG in the exhaust system of an internal combustion engine. Secondly, the effect of different thermoelectric materials and design parameters on the performance of the TEG system will be investigated by comparing the literature. Further, I will develop numerical models with the help of COMSOL software to optimise the thermoelectric unit layout and thermal resistance distribution to improve the overall system efficiency. Finally, I will perform simulations using COMSOL to verify the theoretical analysis of the study and the feasibility of the simulation results. By integrating COMSOL software, this study aims to provide in-depth theoretical analyses and practical validation of the thermoelectric power generation technology in automotive exhaust waste heat recovery and to promote the development of this field.
2 Principles of Thermoelectric Power Generation

2.1 Principles of semiconductor thermal power generation

Semiconductor thermoelectric generation technology, also known as thermoelectric conversion technology, uses semiconductor materials to convert thermal energy to electrical energy in the presence of a temperature difference. The core of this technology is based on the thermoelectric effect, which describes the ability of a temperature difference to generate a potential difference under specific conditions, thereby generating an electric current in the semiconductor material. The thermoelectric effect is mainly manifested in the Seebeck effect, the Peltier effect and the Thomson effect, which together form the theoretical basis of thermoelectric generation.

2.2 Seebeck Effect

The Seebeck effect describes a potential difference in a closed loop consisting of two different semiconductor materials (usually P-type and N-type) that produces an electric current when there is a temperature difference between the two materials at the point of junction. This effect was discovered by the German scientist Seebeck in 1821 and is also known as the thermoelectric first effect.

The principle of this phenomenon is that the temperature difference causes carriers (electrons or holes) inside the material to move from the high to the low temperature end due to the difference in thermal energy, forming an electric current. This process can be expressed by the equation.

\[ V = (S_p - S_N)(T_h - T_c) \]  (1)
where \( V \) is the potential difference generated, \( T_h \) and \( T_c \) are the temperatures at the hot and cold ends, and \( S_P \) is the Seebeck coefficient from the P-type, \( S_N \) is the Seebeck coefficient from the N-type material.

2.3 Peltier effect

The Peltier effect is the inverse of the Seebeck Effect (Bhattacharya et al., 2011), in which one junction cools and the other heats up when current is held in a circuit of materials consisting of two different conductors; when current flows through the junction between the two conductors A and B, heat may be generated or carried away at the junction. This effect is stronger in circuits containing different semiconductors. It can be expressed by the following equation.

\[
\dot{Q} = (\Pi_A - \Pi_B) I \tag{2}
\]

Where \( \Pi_A \) and \( \Pi_B \) are the Peltier coefficients of conductors A and B, and \( I \) is the electric current (from A to B).

2.4 Thomson effect

In different substances the Seebeck coefficient is not constant but varies with temperature. Thus, when there is an electric current flowing through a region of varying temperature, a continuous inverse process of the Peltier effect occurs, which is known as the Thomson effect. It involves the phenomenon that a conductor through which a current is flowing is heated or cooled in the presence of a temperature gradient. The Thomson effect describes the rate of heat produced per unit volume when the current density \( I \) passes uniformly through the conductor.
\[ Q_T = \beta I \frac{dT}{dx} \]  \hspace{1cm} (3)

Where \( \beta \) represents the Thomson coefficient, \( I \) is the current through the conductor, and \( \frac{dT}{dx} \) refers to the temperature gradient. The Thomson effect is characterised by the movement of electrons across a temperature gradient: when they move against the temperature gradient they absorb energy and increase their potential energy; when they move with the temperature gradient they release energy and decrease their potential energy. The Thomson coefficient is related to the Seebeck coefficient by the relation.

\[ \beta = T \frac{dS}{dT} \]  \hspace{1cm} (4)
3 Modelling and Boundary Conditions

3.1 Model dimensions and materials

In this study, the model used includes a heat exchanger, 16 thermoelectric modules (TEMs), and two cooling water heat exchangers. The exhaust gas heat exchanger has a length of 312 mm, a width of 111 mm, and a height of 70 mm. Both its inlet and outlet end consisted of rectangular extension runners of 50 mm in length, and the wall thickness of the rectangular runners and their extensions at both ends was the same, 4 mm. The cooling water exchanger was located on the upper side, with dimensions of 200 mm × 40 mm × 12 mm. The diameter of the water flow pipes was 5.5 mm (Luo et al., 2022.).

Figure 2. Model
The interior of the thermoelectric module contains 256 evenly spaced copper sheets mounted on a ceramic sheet with dimensions of 44 mm x 40 mm x 0.8 mm. Moreover, 128 pairs of PN-type thermoelectric legs are equally spaced on copper sheets with dimensions of 3.8 mm × 1.4 mm × 0.35 mm, which also connect both P-type and N-type thermoelectric legs. The topmost layer is a ceramic sheet aligned with the edge of the bottom ceramic plate with dimensions of 40 mm × 40 mm × 0.8 mm. The geometrical dimensions of the P-type and N-type semiconductors are the same, both being 1.4 mm × 1.4 mm × 1.0 mm rectangles.
Figure 4. TEM

The materials used in this study are shown in the table below.

**Table 1. Properties of materials for thermoelectric generation systems**

<table>
<thead>
<tr>
<th>Component</th>
<th>Material</th>
<th>Parameters</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ceramic</td>
<td>Al₂O₃</td>
<td>$C_p$ 850 J/kgK, $k$ 165.64 W/m K, $\rho$ 3600 kg/m³</td>
</tr>
<tr>
<td>Heat exchanger</td>
<td>Al</td>
<td>$C_p$ 871 J/kgK, $k$ 217.7 W/m K, $\rho$ 2719 kg/m³</td>
</tr>
<tr>
<td>Copper Electrode</td>
<td>Cu</td>
<td>$\sigma$ 1.75*10^-8 Ωm, $C_p$ 381 J/kgK, $\rho$ 8978 kg/m³</td>
</tr>
<tr>
<td>P</td>
<td>Bi₂Te₃</td>
<td>$S$ (161-1.818<em>T+1.113e-2</em>T²-2.035e-5<em>T³+1.134e-8</em>T⁴)/10⁶ V/K, $\sigma$ 1/((-5.01+3.519e-2<em>T-7.74e-5</em>T²+8.94e-8<em>T³-4.32e-11</em>T⁴)/10⁵) Ω·m, $k$ (-469.7+4.57<em>T-1.575e-2</em>T²+2.331e-5<em>T³-1.242e-8</em>T⁴)/10 W/(m·K)</td>
</tr>
<tr>
<td>N</td>
<td>Bi₂Te₃</td>
<td>$S$ (-442.8+3.469<em>T-1.42e-2</em>T²+2.325e-5<em>T³-1.3e-8</em>T⁴)/10⁶ V/K, $\sigma$ 1/((-0.8072+4.507e-3<em>T-7.827e-6</em>T²+2.305e-8<em>T³-1.317e-11</em>T⁴)/10⁵) Ω·m, $k$ (101.2-0.7414<em>T+2.246e-3</em>T²-3.019e-6<em>T³+1.537e-9</em>T⁴)/10 W/(m·K)</td>
</tr>
<tr>
<td>Water</td>
<td>water</td>
<td>$\rho$ 996.5 kg/m³, $C_p$ 4177 J/(kg K), $k$ 0.612 W/(m·K), $\mu$ 8.623 Pa s</td>
</tr>
<tr>
<td>Air</td>
<td>air</td>
<td>$\rho$ 3.1589-1.052e-2<em>T+1.6237e-5</em>T²-2.1708e-8<em>T³+3.178e-12</em>T⁴ kg/m³, $C_p$ 1073.1-5.7059e-1<em>T+1.4411e-3</em>T²-2.0838e-6<em>T³+2.8163e-10</em>T⁴ J/(kg K), $k$ -1.8174e-3+1.085e-4<em>T-5.2381e-8</em>T²+1.4149e-11<em>T³ W/(m·K), $\mu$ 2.68e-6+6.0982e-8</em>T-2.8219e-11<em>T²+7.0048e-15</em>T³ Pa s</td>
</tr>
</tbody>
</table>
When designing a thermoelectric power generation system for a small vehicle, the limitations of its installation space are a key consideration. To improve thermal efficiency, it is typically incorporated barriers inside the pipework, which not only simplifies the installation process, but also enhances heat transfer between the fluid and the heat exchanger. However, excessive pressure losses may reduce the total output of the system. For this reason, I avoided the use of closely spaced straight ribs and instead allowed space between them to reduce pressure losses at the wall. My modification consists of installing straight ribs of a specific size at the thermoelectric module in the exhaust gas channel, optimising the temperature difference and thus increasing the efficiency of the thermoelectric module. This design was intended to balance installation space constraints with system performance to ensure efficient operation of the thermoelectric generation. So, I added the fins with specifications of 200 mm in length, 20 mm in height and 2 mm in width, which are evenly spaced in the heat exchanger.

Table 2. Fin number

<table>
<thead>
<tr>
<th>Fin number</th>
<th>Spacing between fin (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>10</td>
<td>8.4</td>
</tr>
<tr>
<td>12</td>
<td>6.5</td>
</tr>
<tr>
<td>14</td>
<td>5.2</td>
</tr>
<tr>
<td>16</td>
<td>4.2</td>
</tr>
<tr>
<td>18</td>
<td>3.5</td>
</tr>
</tbody>
</table>
3.3 Setting of boundary conditions

In this study, the models constructed involved two fluids: water and air. I used several different temperature settings for the air portion, 450K, 500K, 550K and 600K, to simulate the heat input of the air as it flows into the system from the inlet and subsequently leaves through the outlet. Also, the cold end temperature is considered in the model, which is controlled by cooling water at a constant 300K. In addition, the air flow rate is also considered as an influencing factor in the system to observe its effect on the output of the system. I have selected five different air mass flow velocities which are 6.57m/s, 7.46m/s, 8.35m/s, 9.23m/s and 10.07m/s. In the boundary condition setup of the system, the external walls are considered as adiabatic to exclude the environmental interference on the heat transfer process.
The simulations were carried out in COMSOL Multiphysics software using the four software packages "Solid-Fluid Heat Transfer", "Turbulence", "Current" and "Circuit". At the same time, the model also integrates three coupled interfaces, namely "thermoelectric effect", "electromagnetic heat" and "non-isothermal flow", in order to accurately capture the interactions between different physical phenomena.

Figure 6. Overall model grid

Figure 7. TEM grid
In the study of this thesis, for the general physics module I used an extremely coarse mesh such as Figures 6 and 7 and for the fluid dynamics domain such as figure 8 and boundaries I used a coarser mesh. For the cell size parameter, the maximum cell size is 156mm, the minimum cell size is 21.8mm, the maximum cell growth rate is 2, the curvature factor is 1, and the resolution of the narrow region is 0.1. The reason for using finer meshes in fluid dynamics modelling are multiple. The complexity of the fluid dynamics problem itself requires a higher spatial resolution to accurately capture the detailed behaviour of the fluid, such as turbulence and boundary layer effects when the fluid is in contact with a solid surface. Finer meshes can resolve rapid changes in velocity, pressure and temperature gradients, especially in those critical regions that have a significant impact on the overall fluid behaviour, such as flow separation points, jet inlets and vortex regions. In addition, the rapid changes in heat and mass transfer processes at the fluid-solid interface need to be accurately calculated using fine meshes. The requirement for accuracy and the stability of the numerical solver are also important considerations in fluid dynamics simulations for the selection of finer meshes, as this helps to ensure the quality of the solution and to avoid errors introduced by too coarse a mesh.
When performing numerical simulations, appropriate grid selection is a key factor in ensuring computational accuracy and efficiency. Due to the limitation of the computational capability of the equipment, the grid accuracy used in this study is mainly divided into two levels: extremely coarse and coarser. For the overall simulation area, the extremely coarse grid is used to maintain the feasibility of calculation and faster processing speed. For those critical parts that require higher accuracy of analysis, such as regions with significant hydrodynamic behaviours or critical parts of heat transfer, a coarser grid was used for detailed simulations. This strategy aims to minimise the consumption of computational resources while ensuring the accuracy of the results.

However, the accuracy of the simulation results could not be determined as grid-independence analysis was not performed in this study. Typically, grid-independence analysis assesses the extent to which the results are sensitive to grids by comparing the computational results of different accuracy grids. If the difference between the computational results of different grids is less than a set acceptable threshold, the simulation results can be insensitive to grid changes, i.e., grid-independence is achieved. In the future, if conditions permit, it is recommended that a grid-independent analysis or a finer grid be used to improve the accuracy of the simulation results.

3.3 Performance evaluation parameters of the Temperature difference power generator

Output power is a very important and major parameter in order to evaluate the performance of a thermoelectric generation plant. According to the equation 1 mentioned above,

\[ U_{total} = (S_p - S_N) (T_h - T_c) \]  \hspace{1cm} (5)
Where $U_{total}$ is the total voltage generated by the loop, $S_N$ and $S_P$ are the Seebeck coefficients of the temperature difference generator module; $T_h$ and $T_c$ are the temperatures of the hot and cold ends of the temperature difference generator module.

![Figure 9. Schematic diagram of the Seebeck effect (Bellucci et al, 2021)](image)

There is an internal resistance in the thermoelectric generation module itself, because after generating voltage, the internal resistance will also share part of the voltage, so this should be considered when calculating the output power. According to Ohm's law, it can be learnt that the maximum output power can be obtained when the external resistance and internal resistance are equal (Benziger et al., 2006).

\[
U_0 = (S_P - S_N)(T_h - T_c) \frac{R_L}{R_L + R_{in}} \tag{6}
\]

\[
I_0 = \frac{(S_P - S_N)(T_h - T_c)}{R_L + R_{in}} \tag{7}
\]

\[
P_{max} = \frac{(S_P - S_N)^2(T_h - T_c)^2}{4R} \tag{8}
\]

Where $R_{in}$ is the internal resistance value; $U_0$ is the actual voltage of the monocouple output; $I_0$ is the monocouple output current; $P_{max}$ is the maximum output power.
When analysing the optimum load as shown in figure 10, I chose a hot end temperature of 500K and a velocity of 8.35m/s and recorded the variation of the output power with the external resistance, which varied between 0.5 and 16 Ω.

Due to the insertion of the isotropic fin, in fluid machinery or fluid power systems, the isotropic fin produces some obstruction of the passing airflow. This hindering effect causes a change in velocity and pressure of the fluid as it passes through the fin, resulting in a pressure drop, which is the difference in pressure of the fluid between the inlet and the outlet. This pressure drop causes drag losses, whereby energy is converted into heat and lost due to the viscous nature of the fluid as well as friction and turbulence during the flow. Therefore, it cannot be ignored, especially when evaluating the energy efficiency and performance of a system.

In this context, the resistance power consumption due to pressure drop can be defined as the energy lost due to pressure drop per unit of time, while the net output power is the actual power output that the system is able to provide after deducting all the losses. The equation used is as follows:
\[ P_{\text{loss}} = \Delta p \left( \frac{qm}{\rho} \right) \]  
\[ (9) \]

\[ P_{\text{net}} = P - P_{\text{loss}} \]  
\[ (10) \]

Where \( P_{\text{loss}} \) refers to the resistance power consumption due to voltage drop, \( P_{\text{net}} \) refers to the net output power, and \( \Delta p \) refers to the pressure drop and \( qm \) refers to mass flow rate, \( \rho \) refers to density.
4. Performance of thermoelectric generators

4.1 Effect of fins

In the discussion that follows, I will delve into the specific effects of the fins on the performance of this device. To optimise the unit, one of the key objectives is to enhance the hot-side operating temperature of the thermoelectric material (TEM). An effective strategy to achieve this goal involves enhancing the heat transfer efficiency between the exhaust gases and the hot-side heat exchanger. This can be achieved in two main ways: firstly, by increasing the heat transfer area of the hot-side heat exchanger, and secondly, by extending the residence time of the exhaust gas in the flow path. For this purpose, I experimentally added several sets of fins in different quantities and observed their effect on the power output and net power of the unit.

From the analysis of the images provided, it is evident that as the number of fins increases, the output power and the net power of the unit show an increasing trend. This observation not only verifies that increasing the number of fins is effective in improving the performance of the heat exchanger, but also points to a positive correlation between the number of fins and the overall efficiency of the device. This finding provides an important design guideline for further optimisation of the unit and highlights the key role of fins in improving the efficiency of the heat transfer on the hot side.
Figure 11 shows the pressure drop at the inlet and outlet of the tail gas exchanger, according to the above-mentioned pressure drop is usually due to the resistance encountered by the fluid as it flows through the pipe or system. In this study this resistance stems from the variation in the cross section of the flow path. The basic reason for this is that these fins introduce an additional physical obstruction in the path of the fluid, resulting in more friction as the fluid flows, thus increasing the pressure drop in the system. As the number of fins increases, the greater the cross-sectional change in the flow path, the more friction is generated, and thus the pressure drop increases as the number of fins increases (Salman et al., 2022).
Figure 12. Pressure drop

Based on the data in figures 11 and 12, it can be clearly observed that the output power, the net power as well as the pressure drop of the device are at their lowest point when no fins have been added. In particular, the difference between the output power and the net power is almost non-existent when fins are not introduced, mainly since the pressure loss is negligible in this configuration. The absence of the fins means that the fluid flows through the heat exchanger with little additional resistance to flow, and therefore most of the energy input into the system is used to generate output power rather than being consumed in overcoming hydrodynamic resistance. This allows the device to convert the input energy into output power more efficiently in this configuration, so the system efficiency is higher in this case compared to the addition of fins, as there is almost no energy loss due to hydrodynamic resistance. However, this also means that the heat exchange efficiency is not improved because the main purpose of the fins is to increase the heat exchange area and hence the heat exchange efficiency. And it is easy to see that the net power reaches its maximum at the fin number of 16, and at the fin number of 18, although the output power is somewhat increased compared to the fin number of 16 but on the contrary, the net power decreases, so it can be judged that the fin number of 16 is the optimal solution for this device.

4.2 Effects of temperature

In my study, I chose three different air inlet temperatures: 400 K, 500 K, and 600 K. To ensure consistency in the simulation results, I fixed the velocity of the air at 8.35 m/s and observed the change in the output power of the device as the number of fins was increased from 0 to 18 at these different inlet temperatures, and the results are shown in the following figure.
Analysing the data from figure 13, a clear trend is that the output power of the device tends to increase as the number of fins increases. In addition, the output power increases as the inlet temperature increases, which indicates that temperature is an important factor affecting the output power. However, in the absence of fins, the effect of temperature on the output power is relatively small, indicating that simply increasing the inlet temperature does not significantly improve the performance of the device without increasing the heat transfer area. In contrast, when the unit was configured with fins, the combined effect of temperature and number of fins had a more significant effect on the increase in output power, which emphasises the importance of considering both temperature and heat transfer area increase strategies when designing and optimising similar units.

Figure 13. Effect of different temperatures on output power
Figure 14 shows the trend of the percentage increase in output power with increasing number of fins at different inlet temperatures. It can be seen from the figure 13 that at lower inlet temperatures, the percentage increase in output power is more significant with more fins than at higher temperatures. Specifically, the percentage increase in output power with increasing number of fins is higher at 450K than at 600K. This may indicate that the addition of fins contributes more to the heat exchange efficiency and TEG performance enhancement at low temperatures, as the system may be more dependent on the increase in fin surface area at low temperatures to enhance the energy conversion efficiency. This observation has important implications for the design of high-efficiency thermoelectric devices, suggesting that optimising the fin design may lead to greater performance enhancement at lower operating temperatures.

4.3 Effects of flow velocity

When observing the effect of flow velocity on this device I chose the velocity of air of 6.57 m/s, 7.46 m/s, 8.35 m/s, 9.23 m/s, 10.07 m/s and to ensure the accuracy of the
simulation I set the air input temperature of the device to 500 K. The results are shown in the following figure.

Figure 15 clearly illustrates a consistent pattern where the output power escalates with rising flow velocity. This trend is reflected in the curves for different number of fins, especially when the flow velocity increases from 6.574795 m/s to 10.06937 m/s, the corresponding output power also increases. This indicates that the flow velocity has a positive effect on the output power enhancement in this device. However, this enhancement is not linear as the interval between the curves does not widen significantly with the increase in flow rate, which implies that there may be a diminishing marginal benefit of flow rate enhancement on the output power.

At high fin counts, the output power curves produced by different flow rates tend to converge, implying that the gain in output power from increasing flow rate is limited in this region. This may indicate that after a certain number of fins, the increase in flow rate is no longer the main factor affecting the output power, and it may be that other
design parameters (for example fin configuration and surface properties) begin to play a more important role. Therefore, there may be an optimal range of flow rates for this device that will maximise output power without significantly increasing energy consumption.
5 Conclusions

This thesis makes comprehensive use of the simulation tools of COMSOL Multiphysics software to analyse the prospects of the application of thermoelectric generation (TEG) technology in the field of automotive exhaust waste heat recovery. In particular, the influence of key design parameters, such as the number of heat fins, inlet temperature and flow velocity, on the efficiency of the TEG system is thoroughly investigated. Simulation results reveal that increasing the number of heat sinks can significantly improve the heat exchange efficiency of the system, which directly enhances the system's thermoelectric conversion capability and increases the power output of the whole system. However, this design optimisation also brings negative impacts, mainly in the form of a significant increase in the pressure loss inside the system with the increase in the number of heat fins.

Further, the thesis's simulation study also provided preliminary evidence on the possible effects of inlet exhaust gas temperature and flow velocity on the performance of the TEG system. It was shown that higher inlet exhaust gas temperatures and appropriately increased flow velocity can help to improve the heat absorption efficiency of the TEG module under specific operating conditions.

Nevertheless, the results of the simulation study need to be further confirmed by actual experimental validation. Future studies could assess the practical impact of different design parameters by building experimental prototypes and conducting field tests to optimise the design of the TEG system more accurately. This will provide a more solid theoretical and technical foundation for the engineering realisation and commercial application of automotive exhaust waste heat recovery technology. Through these systematic research and developments, TEG technology is expected to contribute to the
sustainable development of the automotive industry on a global scale and provide an effective technical solution to the problems of energy inefficiency and environmental pollution.
Reference

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