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# HARNESSING HEAT FROM VEHICLE EXHAUST FOR AUTOMOTIVE APPLICATION

BY

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**Abstract.** Hybrid vehicles, with their dual power sources of internal combustion engines and electric motors, represent a pivotal step towards greener transportation solutions. This study explores the complex domain of electric energy generation through heat recovery, specifically designed for hybrid vehicle exhaust systems. This study explores the complex domain of electric energy generation through heat recovery, specifically designed for hybrid vehicle exhaust systems.

Through an analysis of various heat recovery technologies, including thermoelectric generators (TEGs), this paper highlight mechanism, advantages, and challenges in the context of hybrid vehicles.

A thermal analysis will be performed for different operating parameters of the vehicle, which will generate different temperature values. These will be analyzed from an energetic point of view, when the thermal energy is transformed into electrical energy.

In conclusion, heat recovery systems for hybrid vehicle exhausts represent a novel system towards sustainable transportation.

**Keywords:** heat recovery, electric energy generation, automotive exhaust, thermoelectric generators, electric vehicles.

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## 1. Introduction

The automotive industry is at a pivotal industry, with increasing emphasis on sustainability, energy efficiency, and emissions reduction. In response to these challenges, hybrid vehicles have emerged as a promising solution, offering a path of conventional internal combustion engine technology with electric propulsion systems (Asaduzzaman *et al*., 2023). This fusion not only enhances fuel efficiency but also reduces greenhouse gas emissions and reliance on fossil fuels. However, the quest for greater efficiency and sustainability persists, driving researchers and engineers to explore innovative technologies to further optimize hybrid vehicle performance (Chien and Mei, 2013).

One such technology gaining significant attention is heat recovery systems created for hybrid vehicle exhausts. Traditionally, exhaust systems in internal combustion engine vehicles are viewed solely as conduits for expelling waste gases as Din L. et al. have studied in their research. However, they also represent a significant source of thermal energy, which, if effectively harnessed, could contribute to improving overall vehicle efficiency (Dhruv and Rashmi, 2021), as presented in thermal picture of Fig. 1.

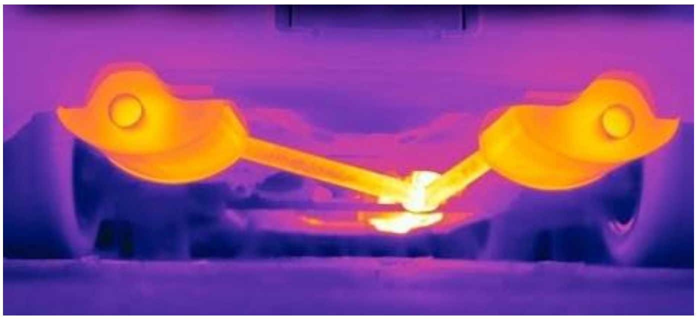

Fig. 1 – Thermal loss for exhaust system.

The integration of heat recovery systems into hybrid vehicle exhausts is a mechanism based on the principles of thermodynamics and energy conversion. By capturing and converting wasted heat energy into usable electric power, these systems offer the potential to extend the driving range of hybrid vehicles, reduce fuel consumption, and further mitigate environmental impact (Din *et al*., 2021; Ding *et al*., 2018).

The motivation for this research stands from the recognition of the big potential residing within hybrid vehicle exhausts, Ganesh et al. mention this aspect their article. While hybrid vehicles already boast impressive efficiency gains compared to their conventional counterparts, there remains a wealth of thermal energy dissipating into the atmosphere through the exhaust system. Harnessing this energy presents a compelling opportunity to enhance the sustainability and performance of hybrid vehicles, thereby accelerating the transition towards a greener automotive landscape (Gallon, 2022).

In this introduction chapter, it was outlined the objectives, aim of this paper. It was researched the objective behind investigating heat recovery systems for hybrid vehicle exhausts, highlighting their potential benefits and the challenges they occur. Furthermore, it provides an overview of the subsequent chapters, which will explore the principles, technologies, challenges, and future prospects of heat recovery in hybrid vehicle exhaust systems in greater detail.

### 1.1. Thermoelectrical generators

Thermoelectric generators (TEGs) have emerged as a promising technology for harnessing waste heat in automotive exhaust systems. This subchapter explores the application of TEGs specifically created for exhaust heat recovery in hybrid vehicles, the model is presented in Fig. 2 (Ganesh *et al.*, 2020). By capturing thermal energy from the exhaust gases and converting it into electricity, TEGs offer the potential to enhance vehicle efficiency, reduce fuel consumption, and reduce the environmental impact.

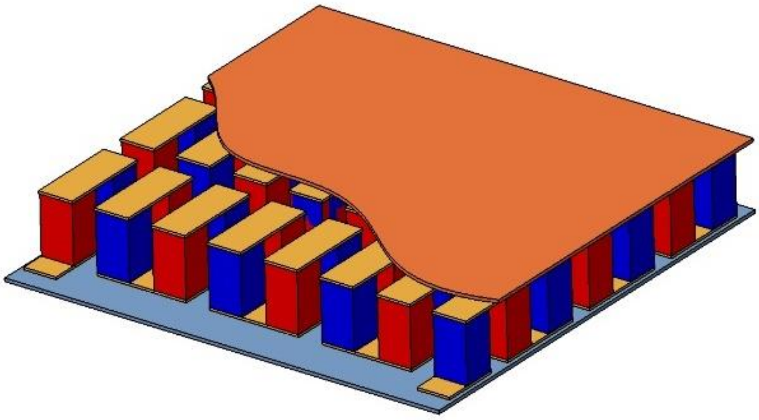

Fig. 2 – CAD model for TEG component.

The operating principle of TEGs is based on the Seebeck effect, which describes the generation of a voltage when a temperature gradient is applied across a thermoelectric material (Liu *et al.*, 2014; Burnete *et al.*, 2022). When one side of the TEG is exposed to a heat source, such as exhaust gases, and the other side is cooled, a potential difference is generated, leading to the flow of electrical current, schematic diagram being shown in Fig. 3. This direct conversion of heat into electricity makes TEGs particularly suitable for capturing waste heat in exhaust systems.

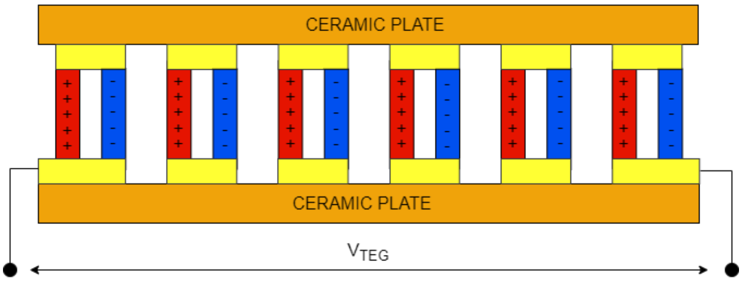

Fig. 3 – Functional principle for TEG components.

In the context of automotive exhaust systems, TEGs offer a promising solution for recovering waste heat and improving the overall efficiency of hybrid vehicles. By integrating TEG modules into the exhaust system, heat energy that would otherwise be lost to the environment can be converted into electrical power and used to supplement onboard systems or recharge the vehicle's battery (Shen *et al*., 2019). The next section of this subchapter explores the specific application of TEGs in automotive exhaust heat recovery, including design considerations, performance optimization, and real-world implementation examples.

## 2. Recovery system modelling for exhaust system

This chapter focuses on the modelling of recovery systems for exhaust systems in hybrid vehicles. The modelling process involves creating mathematical representations of the components and processes involved in capturing and utilizing waste heat from the exhaust and the models also (Yulong *et al*., 2024). By developing comprehensive models, the research aims to gain insights into the thermal dynamics, energy conversion efficiency, and overall performance of the recovery system.

### 2.1. Theoretical background and thermal equations

The thermal equations for the electric generator primarily are based around the principles of thermoelectric conversion and heat transfer. These equations describe the relationship between temperature differentials, electric voltage, current flow, and power output in the generator.

Seebeck effect equation: the Seebeck effect equation is Eq. (1) and it relates the voltage generated by the electric generator ($V$) to the temperature difference ($\Delta T$) across the thermoelectric material:

$$V = S \cdot \Delta T \tag{1}$$

where $S$ is the Seebeck coefficient, representing the material's ability to generate a voltage in response to a temperature gradient.

Electrical power equation, Eq. (2), the electrical power output ($P_{electrical}$) of the generator can be calculated using Ohm's law:

$$P_{electrical} = V \cdot I \qquad (2)$$

where $I$ is the electric current flowing through the circuit.

The rate of heat transfer (Q) from the exhaust gases to the thermoelectric material can be described by Fourier's law heat conduction (Eq. (3)):

$$Q = \frac{k \cdot A \cdot \Delta T}{L} \qquad (3)$$

where $k$ is the thermal conductivity of the material and $A$ is the cross-sectional area through which heat flows and L is the thickness of the material layer.

Through numerical simulations and mathematical analysis, it is possible to use these thermal equations to predict the performance characteristics of the electric generator in the heat recovery system.

### 2.2. System components and structure

The structure of the heat-to-electric energy conversion system involves the physical arrangement and integration of the components within the vehicle exhaust system.

Integration with Exhaust System: the TEG modules and heat exchangers are integrated into the exhaust system to capture waste heat directly from the exhaust gases. Their placement and design considerations are necessary to minimize pressure drop and maximize heat transfer efficiency.

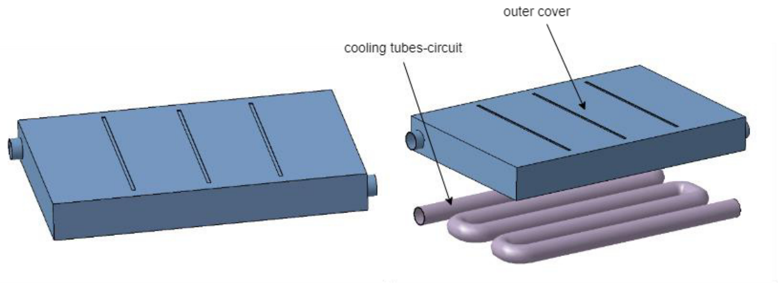

Fig. 4 – Cooling system for TEG components.

With exhaust temperatures reaching up to 600 degrees Celsius, effective thermal management is essential to ensure the longevity and efficiency of system components. The cooling system, consisting of an outer cover and cooling tubes filled with coolant, plays a major role in dissipating heat and maintaining optimal operating temperatures for TEG modules, which is presented in Fig. 4, integrated into the heat recovery system.

Outer Cover: the outer cover encapsulates the heat recovery system, providing thermal insulation and protection against external elements.

Its primary function is to contain and direct the flow of coolant through the cooling tubes while preventing heat loss to the surroundings.

Cooling Tubes: the cooling tubes are embedded within the outer cover and circulate a coolant, approximately 60-80ºC, to dissipate heat from the system components. Constructed from materials with excellent thermal conductivity, such as copper or aluminium, the cooling tubes efficiently transfer heat away from critical components.

As the hot exhaust gases flow through the heat recovery system, heat is absorbed by the TEG components, and the coolant within absorbs this heat to keep a low temperature for the cold plate of TEG component.

The cooling component plays an important role in thermal management, ensuring that system components operate within safe temperature limits and optimizing energy conversion efficiency. Its key functions include: temperature regulation, the cooling component helps maintain optimal operating temperatures for thermoelectric generators (TEGs) and other system components, maximizing energy conversion efficiency and prolonging component lifespan.

Three distinct patterns were created to optimize exhaust gas circulation and enhance heat transfer efficiency, as presented in Fig. 5.

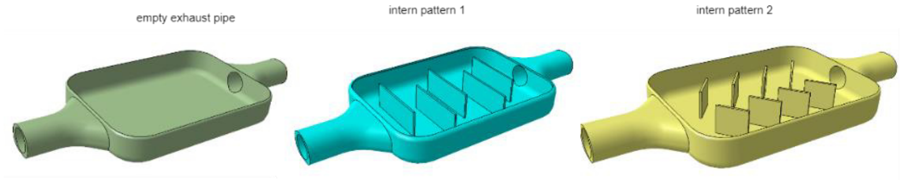

Fig. 5 – Patterns for exhaust system.

The exhaust component is an important element of the heat recovery system, responsible for channelling exhaust gases and facilitating heat exchange with thermoelectric generators (TEGs). The design of the exhaust component significantly influences heat transfer efficiency and energy recovery potential. Three variants were developed for this research, each with different internal patterns to optimize exhaust gas circulation and thermal performance.

The TEG components serve as the primary energy conversion elements within the heat recovery system, transforming waste heat from the exhaust gases into usable electrical energy. Technical data are presented below:

Dimensions - the TEG component measures 40x40 mm, which is a balance between compactness and efficiency. This size allows for effective integration within the heat recovery system without compromising on performance, the TEG system is presented in Fig. 6.

Operating at a voltage of 12 volts and a current of 2 amperes, the TEG component delivers an optimal power output for the intended application and a temperature range up to 650ºC from the manufactured specification.

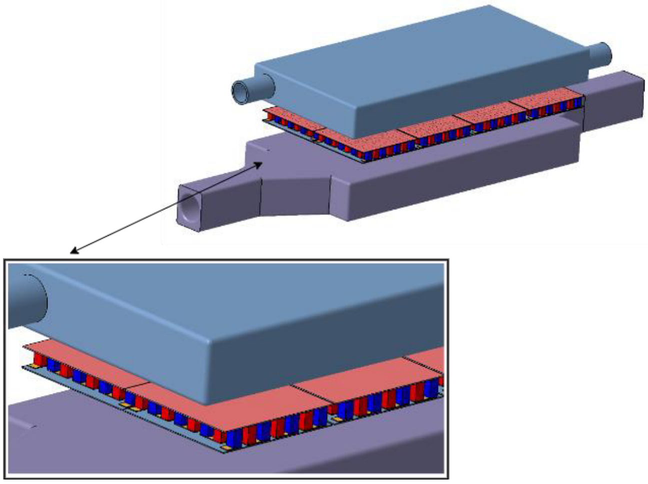

Fig. 6 – TEG components on recovery system.

Electrical circuit modelling- electrical circuit models are developed to simulate the behaviour of the TEG modules, predict power generation, and optimize electrical connectivity and load matching, as in Fig. 7.

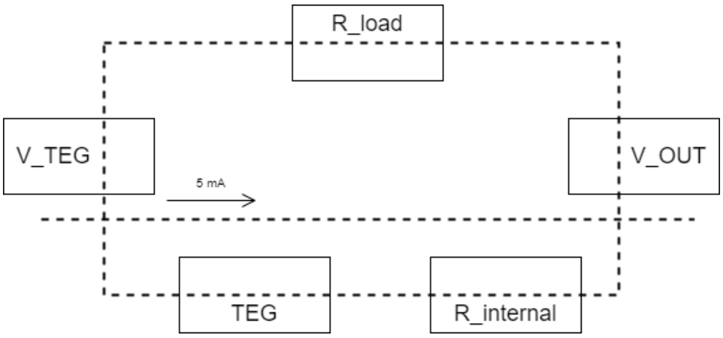

Fig. 7 – Electrical circuit diagram for TEG behaviour.

V_TEG: represents the voltage generated by the TEG due to the Seebeck effect. It is typically modelled as a voltage source.

R_internal: represents the internal resistance of the TEG, which accounts for losses within the TEG itself.

R_load: represents the external load connected to the TEG, such as an electrical load or a battery. This resistance determines the current flow through the circuit and affects the power output of the TEG.

V_out: represents the output voltage across the load resistor, which can be measured to analyse the performance of the TEG.

The TEG components are configured in a series arrangement to capitalize on the cumulative voltage output while maintaining a manageable current load. This configuration enhances system efficiency by maximizing the voltage potential across the entire TEG array.

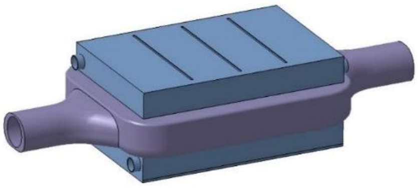

Fig. 8 – Recovery system.

Sixteen TEG components are mounted onto the heat recovery system, ensuring uniform heat capture and distribution, the regeneration system as in Fig. 8. The mounting arrangement is optimized to maximize surface area exposure to exhaust gases, enhancing heat transfer efficiency.

Efficient thermal coupling between the TEG components and the exhaust gases is facilitated through the integration of heat exchangers and cooling systems. These components ensure effective heat transfer, minimizing thermal losses and maximizing energy recovery.

## 3. Numerical analysis

Mathematical modelling and simulation techniques are used to predict the performance and behaviour of the heat-to-electric energy conversion system.

Finite Element Analysis (FEA) simulations are conducted to assess structural integrity, thermal stresses, and deformation of the system components under various operating conditions for analysing time of 40 seconds.

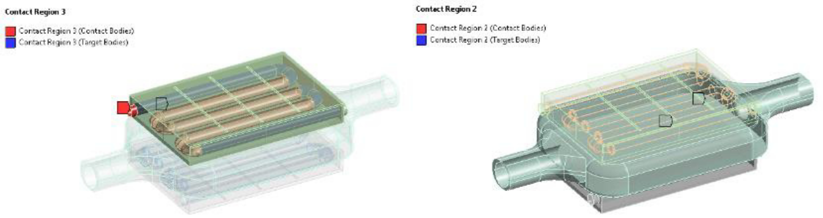

Fig. 9 – Contact zone for exhaust system and cooling system.

A critical aspect of the numerical analysis involves defining the contact zone between the cooling system and the exhaust components, which are represented in Fig. 9 and Fig. 10. This contact zone plays a main role in facilitating efficient heat exchange between the hot exhaust gases and the coolant circulating through the cooling system.

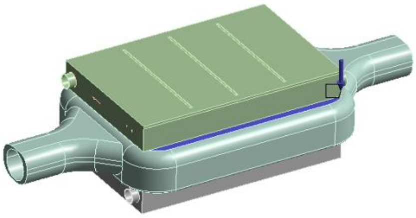

Fig. 10 – Heat flow zone.

Computational Fluid Dynamics simulations are used to analyse fluid flow patterns, temperature distributions, and heat transfer characteristics within the exhaust system and heat exchangers.

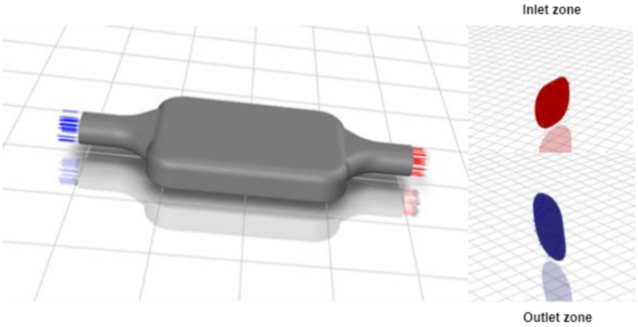

Fig. 11 – Input parameters for exhaust in CFD module.

By defining inlet and outlet boundaries for the exhaust component, it is possible to simulate and analyse gas circuit flow patterns, turbulence effects, and heat transfer characteristics, the inlet and the outlet are presented in Fig. 11 above.

## 4. Results and discussions

This chapter presents the thermal and Computational Fluid Dynamics (CFD) results obtained from simulations conducted on the heat-to-electric energy conversion system designed for automotive exhaust heat recovery. The analyses focus on understanding the temperature distributions, heat transfer characteristics, fluid flow patterns, and overall performance of the system under various operating conditions. The findings from these simulations are discussed to provide insights into system behaviour, efficiency, and optimization opportunities.

### 4.1. Thermal results

The interpretation of thermal analysis results obtained through Finite Element Analysis (FEA) is crucial for validating design choices and ensuring the reliability of engineering systems under thermal loads.

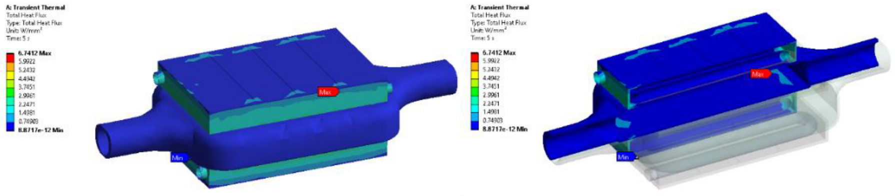

Fig. 12 – Heat flux for empty exhaust.

The first parameter analysed is the heat flux for the entire system. In Fig. 12, Fig. 13 and Fig. 14 are presented the numerical results for heat flux in which it is visible that the highest value was for the first variant, the empty exhaust, due to its construction, and the best value was for the second variant.

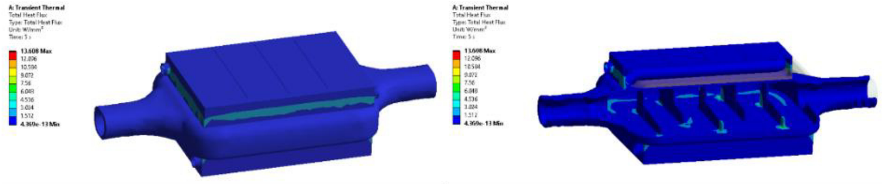

Fig. 13 – Heat flux for second exhaust variant.

Due to its geometrical intern patterns, the second exhaust variant obtained the best values for heat flux parameter, which is observed in Fig. 13.

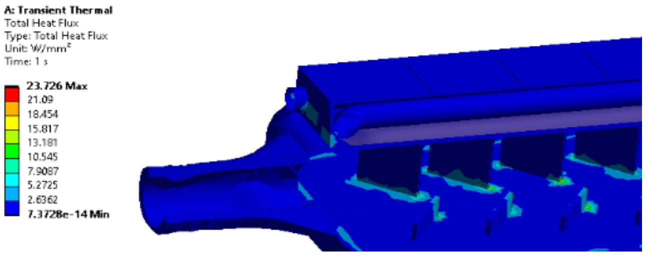

Fig. 14 – Heat flux for third exhaust variant.

The analysis aims to evaluate the temperature distribution across each variant and compare the thermal performance under operating conditions.

Through detailed examination and comparison of temperature values, it is possible to obtain details into the effectiveness of design modifications and their impact on heat transfer efficiency.

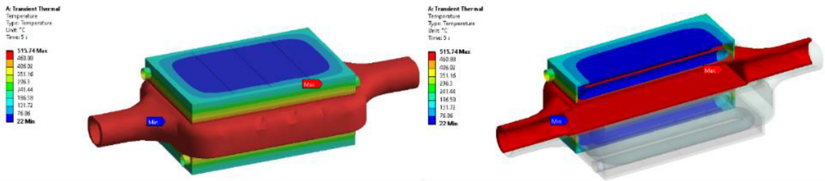

Fig. 15 – Temperature values for empty exhaust.

The temperature value obtained for the empty exhaust variant during the thermal analysis is 515.74ºC, as in Fig. 15. This temperature represents the thermal condition within the exhaust system when no interior patterns or heat exchange surfaces are present. By addressing thermal inefficiencies through the implementation of interior patterns or heat exchange surfaces, the exhaust system can achieve improved heat dissipation and enhanced energy recovery efficiency.

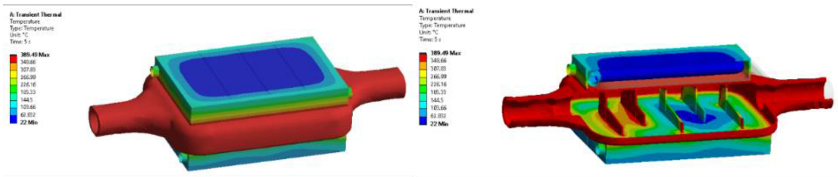

Fig. 16 – Temperature values for second variant.

The temperature value obtained for the second exhaust variant during the thermal analysis is 389.49ºC, which is presented in Fig. 16. This temperature value represents the thermal condition within the exhaust system with internal pattern, characterized by a series of baffles or fins. By incorporating internal pattern, the exhaust system achieves improved thermal performance, leading to lower exhaust gas temperatures.

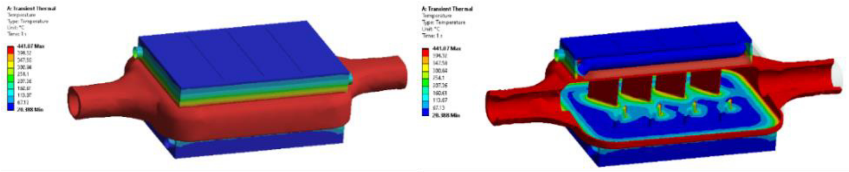

Fig. 17 – Heat flux for third exhaust variant.

The temperature value obtained for the third exhaust variant is 441.07ºC, Fig. 17 above. The temperature value indicates improved heat dissipation and enhanced thermal performance compared to the empty exhaust variant. While slightly higher than second variant, pattern three still demonstrates effectiveness in reducing exhaust gas temperatures.

**Table 1**

*Temperature values obtained*

| Variant | Temperature (ºC) |
|---|---|
| Empty Exhaust | 515.74 |
| Variant 1 | 389.49 |
| Variant 2 | 441.07 |

Table 1 provides a clear comparison of the temperature values obtained for each exhaust variant from the thermal analysis. It illustrates the differences in thermal performance among the variants, highlighting the impact of design modifications, such as interior patterns.

### 4.2. CFD results

In this subchapter, it is presented the results of the Computational Fluid Dynamics analysis conducted to evaluate the flow characteristics within the exhaust component of the heat recovery system. Specifically, the focus is on two parameters: velocity and pressure. The analysis is performed on the variant corresponding to the empty exhaust configuration, chosen due to its highest temperature values, to assess the flow dynamics.

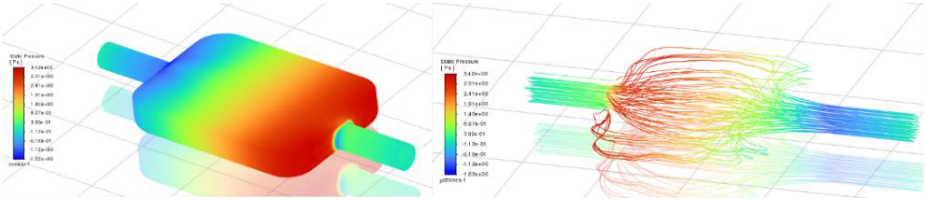

Fig. 18 – CFD component pressure.

The pressure distribution within the empty exhaust variant is also examined through CFD simulation, shedding light on the pressure gradients and flow resistance experienced by the exhaust gases, presented in Fig. 18. The maximum pressure value recorded within the exhaust component is determined to be 3.42 Pa. This pressure value reflects the resistance encountered by the exhaust gases as they navigate through the system, indicating areas of high pressure and potential flow constriction.

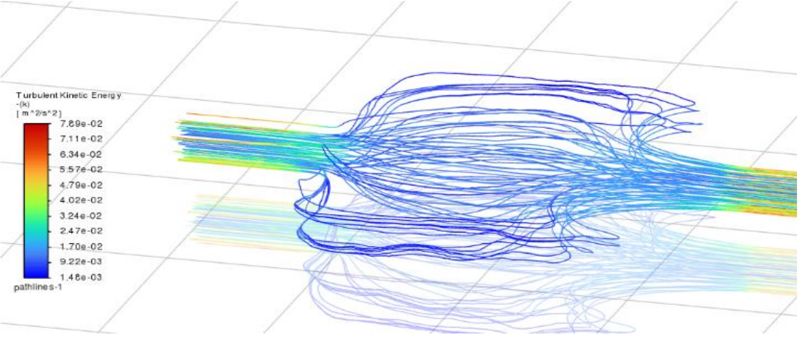

Fig. 19 – Velocity and turbulences.

The CFD simulation reveals the velocity distribution within the empty exhaust variant, providing insights into the flow behaviour of the exhaust gases, as in the Fig. 19 and Fig. 20. The maximum velocity value observed within the exhaust component is determined to be 2.25 m/s. This velocity represents the peak flow rate achieved by the exhaust gases as they traverse through the system.

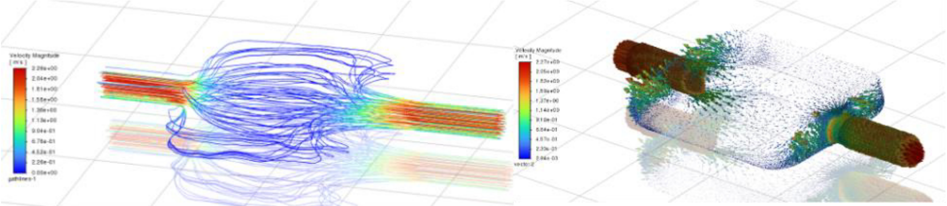

Fig. 20 – Vectors for velocity parameter.

The velocity analysis highlights areas of high flow velocity and identifies potential regions of turbulence or restriction within the exhaust component, as in the Fig. 21, which is the velocity map.

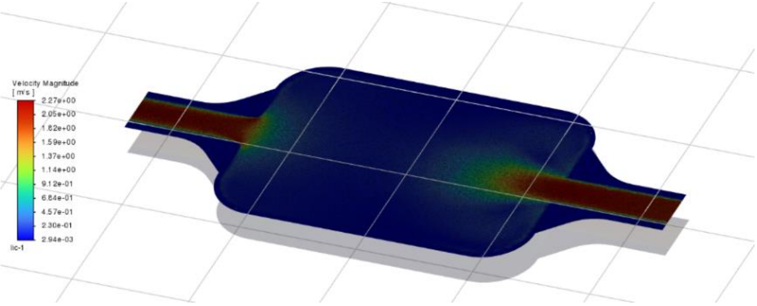

Fig. 21 – Velocity map for exhaust component.

The velocity and pressure analyses offer valuable insights into the flow dynamics and thermal performance of the empty exhaust variant. The observed velocity distribution indicates efficient gas flow through the system, with localized regions of increased velocity corresponding to areas of enhanced heat transfer.

### 4.3. Discussions

The discussion section provides insights and interpretations of the thermal and CFD results, addressing key findings, implications, and potential areas for improvement.

Thermal performance is an interpretation of temperature profiles, thermal gradients, and heat fluxes in relation to thermoelectric conversion efficiency and system effectiveness.

Comparison of simulation results with experimental data or real-world performance benchmarks to validate the accuracy and reliability of the models was made.

### 4.4. Electric energy results

In this subchapter, it is presented the electrical energy output results obtained from the Thermoelectric Generator (TEG) within the heat recovery system. The energy recovery process involves harnessing waste heat from the exhaust gases to generate electrical power through the Seebeck effect. By comparing the energy outputs for each exhaust variant, it is assessing the impact of thermal performance on energy recovery efficiency.

The electrical energy output is calculated using the Eq. (4):

$$P = V \cdot I \tag{4}$$

where $P$ - the power output (W); $V$ - the output voltage (V); $I$ - the current (A).

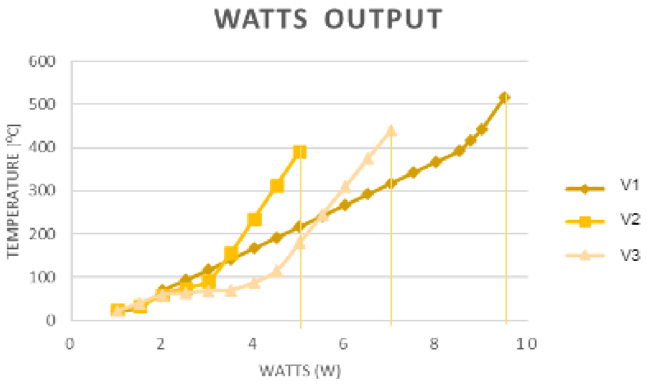

Fig. 22 – Watts output for each variant compared to temperature value.

The energy output is directly influenced by the exhaust gas temperature, with higher temperatures resulting in increased power generation, as presented in Fig 22. Variants with internal patterns demonstrate lower exhaust gas temperatures and correspondingly lower energy outputs compared to the empty exhaust variant, which due to its high temperature values, the recovered electrical energy is highest, the temperature values and electrical outputs are presented in Table 2.

In conclusion, the thermal analysis and electrical energy recovery results highlight the importance of optimizing thermal performance within the exhaust system for enhanced energy recovery efficiency.

**Table 2**

*Energy values outputs*

| Variant | Temperature ($^{O}$C) | Power Output (W) |
|---|---|---|
| Empty Exhaust | 515.74 | 9.4 |
| Variant 1 | 389.49 | 4.8 |
| Variant 2 | 441.07 | 7.0 |

This subchapter provides a detailed analysis of the electrical energy output results obtained for each exhaust variant within the heat recovery system.

## 5. Conclusions

Throughout this research paper, it has been explored the principles, design, modelling, and performance evaluation of heat recovery systems for automotive exhausts, with a specific focus on thermoelectric generators (TEGs). In this study, the focus was on a comprehensive exploration of the thermal values obtained, Computational Fluid Dynamics insights, and electrical energy recovered from the exhaust system variants. The objective was to assess the thermal behaviour, flow dynamics, and energy recovery efficiency within the heat recovery system, aiming to optimize performance and sustainability in automotive engineering:

- The thermal analysis marked significant variations in exhaust gas temperatures across the different exhaust variants. The presence of internal patterns, played a crucial role in enhancing convective heat transfer and reducing thermal losses;
- The CFD analysis provided valuable insights into the flow dynamics and pressure distributions within the exhaust system;
- While the empty exhaust variant generated the highest power output, variants with internal patterns also exhibited substantial energy recovery efficiency.

In conclusion, this research paper provides valuable insights into the principles, design, modelling, and performance evaluation of heat recovery systems for automotive exhausts and the aim for reducing the impact of the vehicles on the environment, which is an important chapter for automotive industry so far, due to highest restrictions for fuel consumption and thermal engines.

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# RECUPERAREA CĂLDURII DE LA EŞAPAMENTUL AUTOVEHICULELOR PENTRU APLICAȚII AUTOMOTIVE

## (Rezumat)

Vehiculele hibride, cu sursele lor duale de energie de motoare cu ardere internă şi motoare electrice, reprezintă un pas esențial către soluții de transport mai ecologice. Acest studiu explorează domeniul complex al generării de energie electrică prin recuperarea căldurii, conceput special pentru sistemele de evacuare a vehiculelor hibride. Acest studiu explorează domeniul complex al generării de energie electrică prin recuperarea căldurii, conceput special pentru sistemele de evacuare a vehiculelor hibride.

Printr-o analiză a diferitelor tehnologii de recuperare a căldurii, inclusiv generatoare termoelectrice (TEG), această lucrare evidențiază mecanismul, avantajele și provocările în contextul vehiculelor hibride.

Se va efectua o analiză termică pentru diferiți parametri de funcționare ai vehiculului, care vor genera valori diferite de temperatură. Acestea vor fi analizate din punct de vedere energetic, atunci când energia termică este transformată în energie electrică.

În concluzie, sistemele de recuperare a căldurii pentru evacuarea vehiculelor hibride reprezintă un sistem nou pentru transportul durabil.