Industrial Engineering Journal
ISSN: 0970-2555
Volume : 53, Issue 4, No. 5, April : 2024

COMPUTATIONAL FLUID DYNAMICS INVESTIGATION OF AN AUTOMOBILE THERMOELECTRIC GENERATOR'S EXHAUST HEAT EXCHANGER

Dr. Pankaj Kumar, Assistant Professor, Department of Mechanical Engineering, GMR Institute of Technology Rajam, India-532127.

Abstract

Automobiles are a significant source of wasted energy in the form of exhaust heat. To harness this heat and improve vehicle efficiency, thermoelectric generators (TEGs) are being integrated into exhaust systems. However, the performance of TEGs critically depends on their heat exchangers' design and efficiency. This study presents a comprehensive CFD analysis of an exhaust heat exchanger integrated with a TEG in the context of an automobile's exhaust system. The investigation focuses on modelling the heat transfer and fluid dynamics within the heat exchanger to optimize its performance. The CFD simulations consider parameters such as flow rate, temperature distribution, and pressure drop to evaluate the heat exchanger's efficiency and thermal characteristics. Results indicate that proper heat exchanger design and optimization can significantly enhance the TEG's power output and overall energy recovery from the exhaust stream. Furthermore, this study explores the impact of various design factors and materials on the heat exchanger's performance, providing valuable insights for engineers and researchers working on TEG integration in automobiles. Ultimately, the findings from this CFD investigation contribute to the advancement of sustainable energy recovery technologies, leading to improved vehicle fuel efficiency and reduced environmental impact.

Keywords: Computational Fluid Dynamics (CFD); Thermoelectric Generator (TEG); Waste Heat Recovery; Internal Structure Analysis.

1. Introduction

This study investigates the potential of thermoelectric generators (TEGs) in automobiles to recover waste heat, improve fuel efficiency, and reduce emissions. It focuses on optimizing the design of the TEG's exhaust heat exchanger through Computational Fluid Dynamics (CFD) simulations, comparing various internal structures for heat transfer efficiency. The research aims to contribute to more environmentally friendly automotive systems by harnessing waste heat efficiently, with innovative heat exchanger configurations offering promise for improved energy recovery. The automotive industry faces challenges related to fuel efficiency and emissions reduction. To address these issues, there is a need to optimize the design of exhaust heat exchangers for thermoelectric generators (TEGs). This study seeks to assess the heat transfer efficiency and fluid dynamics within TEG exhaust heat exchangers, comparing different internal structures. The goal is to identify the most effective design configurations that can maximize waste heat recovery from vehicle exhaust systems and contribute to more sustainable and energy-efficient automotive power generation. The study's objectives are to assess heat transfer efficiency and fluid dynamics in the exhaust heat exchanger of a thermoelectric generator (TEG) for automobiles. It aims to compare different internal structure configurations to identify the most efficient design and provide insights for optimization. Additionally, the research explores innovative heat exchanger solutions, contributing to improved sustainability and energy efficiency in automotive systems. In today’s scenario, there are lots of problems regarding energy crisis and thermal management. Engine exhaust management has been a major topic of discussion in automobile industries in recent years Internal combustion engines, lots of heat is wasted in the form of exhaust gases, and out of the total heat energy supplied to the engine combustion chamber in the form of fuel approximately 30-40% is been converted into useful work and the remaining one is expelled in the form of exhaust gases and this exhaust gas contains a lot of heat that can be recovered by using a waste heat recovery system. The temperature of the exhaust gases after the catalytic converter is between 300 to 600^{o}centigrade. Thermo-electric technology plays a vital role in generating electrical power from heat, temperature differences, and temperature gradients. Thermoelectric power generators are small with no moving parts and they are relatively efficient at these temperatures so they are ideal in such applications. In automobiles, big and heavy alternators are connected to the engines to meet the increasing electrical demands of different accessories. An alternator that operates at an efficiency of 50 to 62% consumes about 1 to 5% of the rated engine work output. About 40% of the thermal energy of the fuel injected into an IC engine is rejected in the form of exhaust gases as waste heat. If approximately 6% of waste heat can be utilized from the engine's exhaust, it can full fill the electrical requirements of our automobiles and it would be possible to reduce the fuel consumption by about 10%. As compared to heat rejected through coolant and lubricating oil a lot of heat is expelled through exhaust gases at very high temperatures. Thus, a thermo-electric generator (TEG) can be used for converting energy from exhaust heat. TEG is similar to a heat engine which is used to convert the heat energy into electrical energy and it works on the principle. Several criteria influence the quantity of energy that can be generated from exhaust gases, including the temperature difference between the exhaust gas and the surrounding air, the efficiency of the TEG, and the size of the exhaust gas generator. The use of TEGs to generate electricity from exhaust gases has several potential benefits. First, it can help to improve the fuel efficiency of vehicles. Second, the use of TEGs can help to reduce emissions. When a TEG is used to generate electricity, it does not produce any emissions. This can help to improve air quality and reduce the impact of vehicles on the environment. The thermoelectric potential of exhaust gases is a promising technology that has the potential to improve fuel efficiency, reduce emissions, and make vehicles more sustainable. However, there are still some challenges that need to be addressed before TEGs can be widely used in vehicles. These challenges include the high cost of TEGs, the low efficiency of TEGs, and the need for TEGs to be kept clean to operate effectively. As the technology continues to develop, TEGs are likely to become more affordable, efficient, and reliable. This will make them a more attractive option for vehicle manufacturers and consumers, and it will help to make vehicles more fuel-efficient, environmentally friendly, and sustainable

Thermoelectric generators (TEGs) are devices that use the See beck effect to directly convert thermal energy to electrical energy from a temperature differential. They are being investigated as a method of collecting waste energy from the exhaust gases of land vehicles, airplanes, industries, and so on. The exhaust gas from a combustion engine can reach temperatures of up to 1,000 degrees Fahrenheit, which is substantially hotter than the surrounding air. This temperature differential can be used to generate power using a TEG. Using TEGs to generate electricity from exhaust gases has a number of potential benefits, including improved fuel efficiency and reduced emissions. However, there are still some challenges that need to be addressed before TEGs can be widely used in vehicles, such as the high cost of TEGs and the low efficiency of TEGs. One of the main challenges in using TEGs for exhaust heat recovery is the low heat transfer coefficient of exhaust gases. As a result, heat exchangers are needed to boost heat transfer to the TEG modules. There are various studies in the literature that have addressed this issue, and as the technology continues to develop, TEGs are likely to become more affordable, efficient, and reliable. Overall, the thermoelectric potential of exhaust gases is a promising technology for improving fuel efficiency, reducing emissions, and making vehicles more sustainable.

1.1 Background and motivation

The backpressure produced by the heat exchanger must also be reduced in order to reduce the influence on engine performance. Built an experiment design to test the effects of interior geometrical features on a flat-shaped TEG heat exchanger. It was determined that pressure drop losses and transmitted heat had a trade-off coefficient. For a 1.2 L gasoline engine, Bai etal developed six exhaust heat exchangers and compared heat transfer and pressure drop numbers using

CFD models. A cylindrical heat exchanger was introduced and to analyse the enhance heat transfer rate, heat transfer area, and turbulence intensity. It increased TEG efficiency over other constructions while retaining a low backpressure. Evaluated the thermoelectric generators' inner channel designs' net power production. With panels that restrict alternate flow. With a global energy balance that takes into account all energy flows, present a thorough analysis of the impact of a thermoelectric generator in an internal combustion engine. In order to analyse the dynamic performance of a thermoelectric generator system for recovering waste heat from vehicular exhaust, a numerical model is used. The model provides precise predictions of system performance under transient situations by taking dynamic features, fluid-thermal-electric multiphasic coupling effects, and material temperature dependence into account. Insightful information about physical field distributions provided by the research makes it possible to better understand system behaviour and to optimize systems for increased energy recovery efficiency. The results of this study have important ramifications for developing waste heat recovery technologies in the automotive sector, resulting in enhanced energy efficiency and vehicle performance. Thermoelectric generators, or TEGs, transform heat into electricity. They have the ability to recover waste heat from a variety of sources, including industrial processes, exhaust gases, and even the human body. When used in conjunction with heat exchangers, TEGs can be very effective at recovering waste heat and turning it into energy. The following are a few reasons why TEGs are crucial for waste heat recovery using heat exchangers: When converting heat into electricity, TEGs can be incredibly effective. In some cases, they can achieve efficiencies of up to 20%. This is far more effective than common waste heat recovery methods like steam turbines. TEGs are pocket-sized and compact. As a result, they are suitable for use in compact applications like cars or tiny appliances. TEGs are incredibly dependable and low-maintenance because they don't have any moving parts. In situations where the TEG must run constantly for long periods of time, this is crucial. To meet the requirements of diverse applications, TEGs can be scaled up. As a result, they provide a variety of waste heat recovery options.

1.2 Problem statement

To evaluate the thermal and fluid dynamic performance of a thermoelectric generator's exhaust heat exchanger, conduct a thorough computational fluid dynamics (CFD) analysis. With the following precise aims, the objective is to evaluate the effectiveness of heat transfer and the fluid flow patterns within the heat exchanger.

- Assess the exhaust heat exchanger's temperature distribution and heat transfer rate under various operational settings and exhaust flow rates.
- Examine how the shape, components, and surface coatings of a heat exchanger affect the efficiency of heat transfer.
- To maximize performance while lowering resistance to exhaust flow, examine the pressure drop and flow distribution in the heat exchanger.
- Evaluate the possibilities for heat recovery from exhaust gases and how it might affect the efficiency of the thermoelectric generator system as a whole.
- To validate the CFD simulations and ensure the quality and dependability of the computational models, compare them to available literature or experimental data.

In order to increase energy efficiency and lessen environmental effect, the results of this CFD analysis will offer useful insights into the design and optimization of the exhaust heat exchanger for the automotive thermoelectric generator.

1.3 Objectives of the study

To research the Computational Fluid Dynamics literature that already exists Examination of the Exhaust Heat Exchanger of an Automobile Thermoelectric Generator to determine the heat exchanger geometry that will maximize heat transfer while reducing pressure drop. to look into how various operating factors, including exhaust gas temperature and flow rate, affect heat exchanger performance. To investigate how the performance of heat exchangers is impacted by fouling and fouling prevention measures. To create and validate a heat exchanger CFD model that may be used to forecast how the device will function under various operating circumstances. Evaluating the outcomes and finding areas for this kind of approach improvement.

- To study the existing literature of Computational Fluid Dynamics Investigation of an Automobile Thermoelectric Generator's Exhaust Heat Exchanger
- To identify the most effective heat exchanger geometry for maximizing heat transfer and minimizing pressure drop.
- To investigate the impact of different operating conditions, such as exhaust gas temperature and flow rate, on heat exchanger performance.
- To study the effects of fouling and fouling mitigation strategies on heat exchanger performance.
- To develop and validate a CFD model of the heat exchanger that can be used to predict its performance under different operating conditions.
- Analysing the results and identify opportunities to further improvement of this type techniques.

2. Literature Review

The utilization of thermoelectric generators (TEGs) to recover waste heat from automotive exhaust systems has emerged as a promising technique to enhance fuel efficiency and reduce pollutant emissions in the automotive industry. This study focuses on the critical aspect of designing efficient exhaust heat exchangers for TEGs. The exhaust heat exchanger's design significantly impacts the overall performance of the TEG system, making it a key area of investigation. This research lies in the pressing need to address environmental concerns and enhance the energy efficiency of vehicles. With the automotive sector being a major contributor to greenhouse gas emissions and fuel consumption, developing innovative technologies like TEGs can play a vital role in mitigating these issues. Waste heat recovery from the exhaust, a by-product of internal combustion engines, presents a valuable opportunity to increase energy efficiency and reduce the environmental footprint of automobiles. There are various studies and experiments were performed on this alike, Hsiao et al. (2010), conducted study on a thermoelectric module is designed to recover waste heat from automobile engines, achieving a maximum power output of 51.13 m/Wcm^2 with a 290°C temperature difference. The research suggests that the module is more effective when applied to the exhaust pipe compared to the radiator, offering potential improvements in fuel efficiency [1]. Lesage et al. (2013), explores enhanced thermoelectric power generation by improving heat transfer in liquid-to-liquid thermoelectric generators using flow tabulating inserts. Protruding panel inserts are found to be the most effective, promising improved efficiency in various applications, from microelectronics to industrial waste-heat recovery [2]. Wei et al. (2015) presents an advanced mathematical model for thermoelectric generators, accounting for temperature gradient effects in exhaust gas flow. It recommends a counterblow arrangement with an optimal module area of 0.3 m2 for maximizing power output, considering fluctuating exhaust gas parameters during engine operation [3]. Chinchow et al. (2013) investigates an energy-harvesting system that converts automotive exhaust heat into electricity using thermoelectric power generators (TEGs). Simulations reveal that increasing the number of TEG couples doesn't necessarily boost total power output, and it's more effective to leave some of the heat exchanger uncovered downstream, maintaining a hotter downstream wall for improved heat transfer and enhanced power generation efficiency [4]. Cheng-ting et al. (2011) presents the construction and evaluation of a waste heat recovery system featuring 24 thermoelectric generators (TEGs) to convert automobile exhaust heat into electricity. Simulations and experiments, along with the incorporation of a sloping block design, improve TEG module performance, establishing a foundation for an efficient low temperature waste heat thermoelectric generator system for vehicles [5]. Li et al. (2017) presents a novel heat supply approach using heat pipe technology to enhance thermoelectric power generation, addressing emissions reduction in the transport sector. Results indicate promising power output potential while considering space constraints beneath a passenger car's chassis, emphasizing the significance of heat transfer for efficient thermoelectric systems [6]. Twaha et al. (2016) provides a comprehensive review of thermoelectric (TE) technology, covering materials, applications, modelling, and performance enhancements. While significant progress has been made in improving TE devices, the challenge remains in balancing conflicting parameters like ZT and power factor in material design [7]. Liu et al. (2016) focuses on optimizing thermoelectric generator (TEG) performance by mathematically optimizing fin distribution in the heat exchanger. Through computational fluid dynamics simulations and parameter analysis, it identifies the significant impact of fin height and fin interval distance on temperature and pressure performance, ultimately achieving improved average temperature and reduced pressure drop, which can enhance TEG system efficiency [8]. Ding et al. (2018) introduces a converging thermoelectric generator (TEG) design for waste heat recovery from engines, featuring an inward incline in the hot-side wall. Through a mathematical model and numerical simulations, it shows that the tilt angle enhancement improves TEG performance, particularly with a mass flow rate exceeding 37.25 g/s, and offers guidance for TEG design and optimization in waste heat recovery applications [9]. Kim et al. (2011) introduces an innovative exhaust gas waste heat recovery system for hybrid vehicles, utilizing thermoelectric modules (TEMs) and heat pipes to generate electric power. By increasing the hot surface area through the integration of heat pipes, the system achieves a maximum power output of 350 W, offering promising prospects for energy efficient hybrid vehicle applications [10]. Wang et al. (2020) presents a novel high temperature waste heat recovery system integrating heat pipes and thermoelectric generators (TEGs) to address energy supply-demand disparities. The system employs potassium heat pipes and skutterudite TEGs, achieving passive thermal management and electricity generation, with proposed effective parameters for accurate performance assessment, promising advancements in energy efficiency and sustainability [11]. Fernández-Yáñez (2021) highlights the increasing interest in waste heat recovery driven by economic and environmental considerations, focusing on the use of thermoelectric generators (TEGs). It addresses the challenges associated with TEG integration, offering insights into tailored TEG design, evaluation methods for energy sources, and opportunities, advantages, and drawbacks across various sectors [12]. Ali et al. (2017) concerns about global warming and fossil fuel depletion, there's a rising interest in clean energy solutions, with thermoelectric generators (TEGs) gaining attention. This review delves into TEG principles, materials, performance, applications, and heat sink geometries, with a focus on addressing the challenges of assessing cost efficiency and economic viability related to TEGs, particularly concerning waste heat inputs [13]. Rafael et al. (2019) evaluates a thermoelectric generator with 20 modules and a waffle heat exchanger for recovering wasted energy from internal combustion engine exhaust. Experimental results show power recovery ranging from 57.87W to 71.13W, with biodiesel blends (B5 and B10) outperforming diesel in both power recovery and reduced gaseous emissions, albeit with increased NOx emissions in some cases [14]. Zu-Guo et al. (2019) provides a comprehensive review of automotive exhaust thermoelectric generators (AETEGs) as a solution to recover exhaust heat and address energy shortage and pollution in modern vehicles. Despite demonstrated feasibility, commercial implementation faces challenges, and the review outlines a research roadmap and promising directions to advance AETEG applications [15]. Lu et al. (2013) investigates the integration of exhaust heat exchangers and mufflers in different configurations for thermoelectric generator (TEG) power generation, revealing trade-offs between heat transfer, pressure drop, and TEG efficiency [16]. Ramesh et al. (2016) aims to enhance the performance of Thermoelectric Generators (TEGs) using Computational Fluid

Dynamics (CFD) techniques. It explores various parameters, including heat exchanger material, deflector inclination, exit gap, and baffles, identifying copper as the optimal heat exchanger material and specifying the ideal deflector inclination and exit gap for improved TEG performance [17]. Olabi et al. (2022) emphasizes the quest to improve energy harvesting efficiency, focusing on thermoelectric generators (TEGs) as eco-friendly power sources capable of converting waste heat into electricity via the See beck effect. It explores the integration of TEGs with various technologies for green power production, summarizes TEG materials, and outlines their application in harvesting waste heat from diverse sources while discussing key TEG characteristics and challenges in waste heat recovery applications [18]. Ding et al. (2021) present a pioneering transient numerical model that comprehensively assesses the dynamic performance of automotive thermoelectric generator systems under vehicle driving cycles, revealing delayed response to exhaust temperature changes and fluctuations in output power and efficiency [19].

3. METHOGOLGY

3.1 Computational tools and software used for CFD simulations

Computational fluid dynamics (CFD) is a branch of engineering that exploits numerical methods and algorithms to simulate and analyse fluid flow and heat transfer phenomena. It plays a central role in understanding, predicting and optimizing fluid behaviour in various applications across industries. Simulation software is used to create and run computer simulations of real-world systems. Popular simulation software packages include ANSYS Fluent, COMSOL Multiphysics and Simulink. Computational fluid dynamics (CFD) is a field that uses computational tools. Fluid and gas flow simulation is done using CFD software. It is utilized by engineers and scientists to build and enhance a wide variety of goods and procedures, including those for automobiles, aircraft extra. The geometry that will be simulated is meshed using meshing software. The mesh discretizes the geometry by breaking it up into a variety of tiny components. The simulation will be more precise with a finer mesh. The regulating equations of fluid flow are solved using solver software. The solver computes the fluid's velocity, pressure, and temperature at each element using the mesh. To view and examine the simulation's results, post-processing software is employed. Software for post-processing can be used to calculate many important numbers, such as drag and lift forces, as well as to make images and videos of the flow field. A variety of problems can be effectively solved using computational methods. They are applied in a number of fields to create and enhance goods and procedures as well as comprehend natural events.

The aim of this work is to assess the mass flow rates in the inner tube at constant wall heat transfer coefficient and the heat transfer characteristics of a heat exchanger to the surrounding environment. The ideal conditions for heat transfer were established based on the temperature and velocity contours at the outlets after numerous flow heat exchanger configurations were analysed with ANSYS FLUENT software. The current study looks at existing exhaust heat exchangers and makes many internal layout recommendations, including a pipe structure, an empty cavity, a serial plate arrangement, a wavy-fin plate design, and an obstruction-type configuration. Under the identical operating conditions, CFD models with solid domains, liquid domains, and fluid solid interfaces were developed to compare heat transmission and pressure drop for the three topologies. The numerical findings indicate that the serial plate construction provides the best heat transfer, but its pressure drop is extremely significant at maximum power output.

3.2 Geometric details of the TEG's exhaust heat exchanger model

For comparison, five internal structures: an empty cavity, serial plate arrangement, pipe structure, wavy-fin plate design, and an obstruction-type configuration. The same size was built, each with a shell measuring 280 mm by 110 mm by 30 mm and for five of the structures, an inlet and outlet of 40 mm in diameter. The pipe structure's diameter was reduced to 26 mm due to the shell body's 30 mm thickness. At each end of the box, there were small, 90 mm-long expansions and contractions intended to cushion and distribute exhaust flow. The internal design of each exhaust exchanger was distinct, varying from an empty hollow to a serial plate structure to a cutting-edge pipe and also wavy-fin plate design, and an obstruction-type configuration.

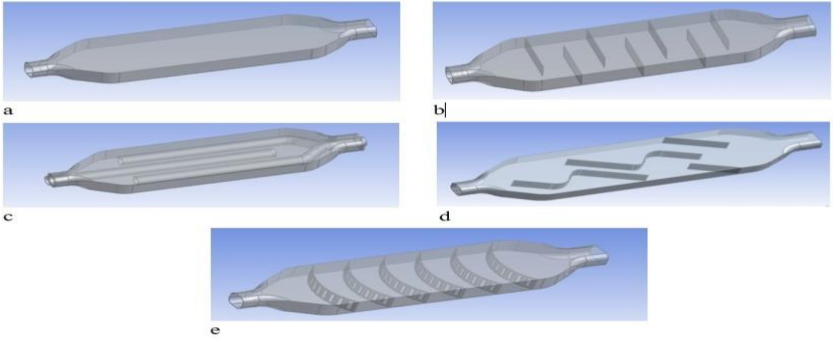


Figure 1: Five internal structures Geometry Models:- (a) Empty cavity, (b) Serial plate, (c) pipe structure, (d) Wavy-fin plate, (e) Obstruction

Table 1: Specifications of the geometry

Exhaust pipe Dia	(mm)	40
Heat exchanger Len	(mm)	280
Heat exchanger wide	(mm)	110
Heat exchanger H	(mm)	30
Material for heat exchanger		Stainless steel

Exhaust mass flow rate:

The mass flow rate of the exhaust gas, which is impacted by engine design and operating circumstances, is the most important component in determining the capacity of an automotive exhaust thermoelectric generator. The passenger car that was being tested had a 1.2 L gasoline engine. The standard k-epsilon model is employed in the CFD simulation to ensure that the exhaust flow in the heat exchanger is completely turbulent and that molecular viscosity can be discounted. The ambient temperature and the natural convection heat transfer coefficient are set using the conventional wall function and near-wall area processing.

$$Q_m = P_e b_e (L_0 \alpha j+1)$$

Exhaust state:

While the gas inlet temperature is adjusted to 450 C to take advantage of the performance of the TEMs used in the TEG, the car exhaust was approximately 300– 500 kPa in pressure and 500–700 C in temperature when it was newly ejected from the engine cylinder. The inlet flow velocity may be greater than 25 m/s depending on the engine's operating circumstances. LMU, P-TEC

Table 2: Engine configuration

Type of Engine	P-TEC, LMU
Transmission	MT-5
Displacement (cm3) Cylinders/Valves	1206
highest power (kW/rpm) The greatest	4/16
torque (N m/rpm) injection apparatus	63/6000
	108/4000
	Electric-controlled injection

Hot side temperature of a thermoelectric generator

Heat from the shell is absorbed by the hot side of the thermoelectric generator and transferred to the cold side. The thermoelectric material's upper temperature limit is determined by the highest sustained temperature that it can withstand; for example, Bi2Te3 can withstand temperatures between 150 and 250 °C. Urban and suburban driving cycles and maximum power output were identified as three typical operating circumstances based on the range of the aforementioned characteristics.

Table 3: Driving cycles

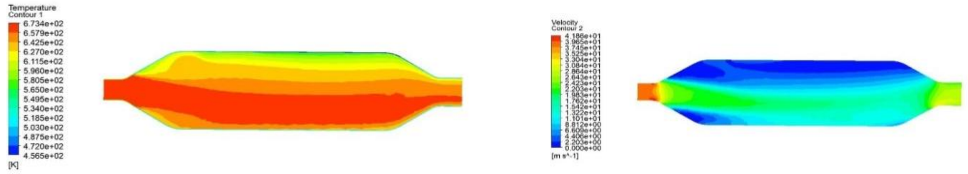
Driving cycle	Fuel consumption (L/100 km)	Time-averaged exhaust mass flow rate (g/s)
Urban	6.7	5.7
Suburban	5.1	14.4
Overall	5.7	8.43

a fluid inlet14.4 kg/s of mass flow at 673.15 K for the heat transfer coefficient, At the mixing flow's exit on the test bench, the pressure boundary condition is employed, and the gauge pressure is adjusted to 0 Pa. In addition, the ambient temperature is set to 25 C, and the heat transfer coefficient between the air and the heat exchanger's outer surface is set to 18 W/(m^2 K).The heat exchanger, which has roughly axial symmetry in its shape, and the flow, pressure, and temperature fields all display axisymmetric characteristics in the absence of ambient winds.

RESULTS AND DISSCUSIONS

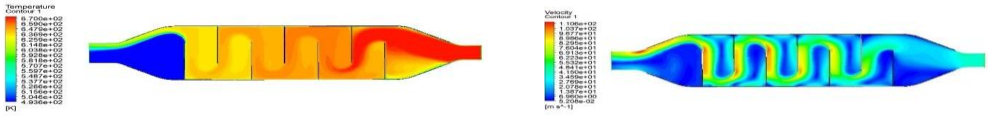
4.1 Presentation of CFD simulation results for each of the five internal structures

Five structures are compared regarding heat transfer and pressure drop under urban driving, suburban driving and maximum power output. Their temperature fields and the flow fields were analysed under the suburban driving cycle.



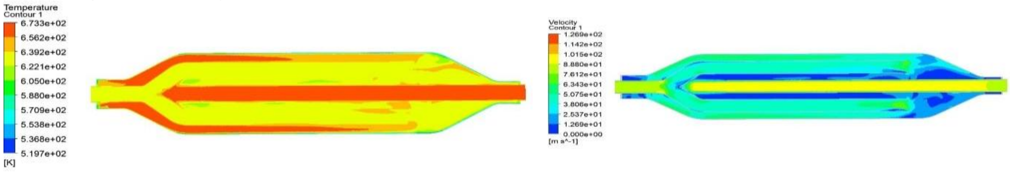
(a) Temperature field (b) velocity field

Figure 2: Physical distribution in an empty cavity.



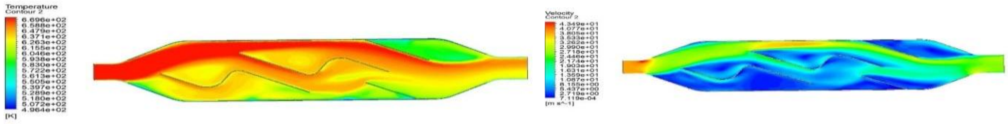
(a) Temperature field (b) velocity field

Figure 3: Physical distribution of a shell with a series of plates.



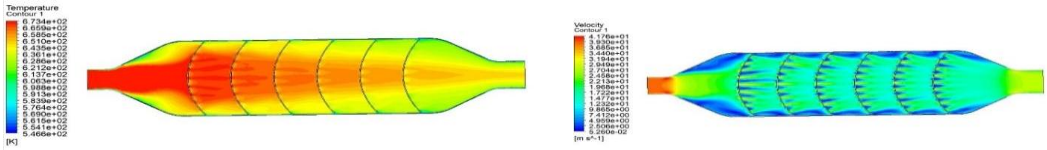
(a) Temperature field (b) velocity field

Figure 4: Physical distribution of a pipe structure.



(a) Temperature field (b) velocity field

Figure 5: Physical distribution of a Wavy fin plate.



(a) Temperature field (b) velocity field

Figure 6: Physical distribution of an Obstruction type

4.2 Analysis of heat transfer efficiency, flow patterns, and other relevant parameters

The amount of heat extracted from the exhaust was equal to the enthalpy difference of the exhaust at the intake and the outlet multiplied by the mass flow rate. The five constructions were ordered by increasing heat transmission as follows: serial plate structure, obstruction type, wavy fin type structure, pipe structure, and empty cavity. The five configurations varied in the rate of heat transfer and pressure drop (Figure.7). The serial plate structure, obstruction type had the maximum heat transfer rate of 602.67w, 988 W & 631.27,936.092, which were 3.73 and 2.96 times the empty cavity structure for across the exhaust temperatures operating conditions of suburban driving cycle and the maximum power output, respectively

The static pressure differential between the exhaust at the intake and outlet was the cause of the pressure drop caused by the heat exchanger at the exhaust side in response to the rate of heat transfer. Additionally, the 5 structures' pressure dips varied from one another. Under the typical operating conditions, the structures' decreasing order of the pressure drop was the same as for the heat transfer: serial plate structure, Obstruction type, pipe structure, wave-fin type and empty cavity Figure 7.

The serial plate structure had maximum pressure drops of 15.67 kPa and 176.3kPa, which are considered the several times of empty cavity structure under suburban driving cycle and maximum power output, respectively. This result corresponds to the Maximum heat transfer rate among the five structures. An empty cavity structure consists of two parallel plates with a space between them. Heat is transferred between the fluids as they move through the space through conduction. Only a small amount of heat is transferred across the wall, amounting to 438.93 watts, and the pressure drop in this structure is also very small, amounting to about 35. 087kpa.The existence of a Serial plate structure, as shown in figure. 3, kind of heat exchanger structure contain numerous plates that are stacked one on top of the other as opposed to the empty cavity.

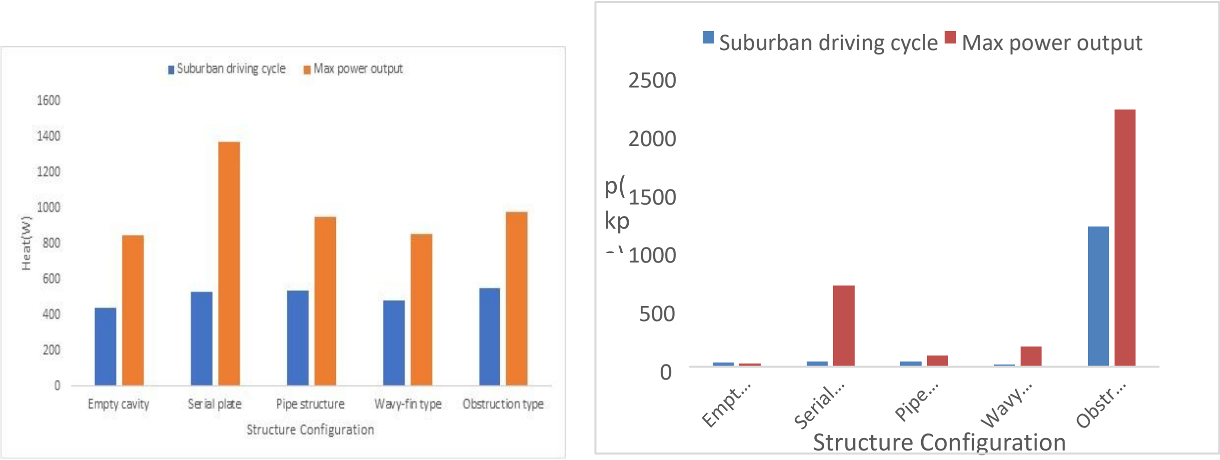
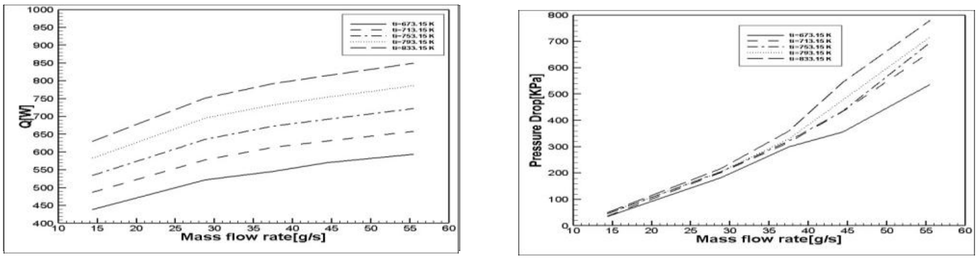


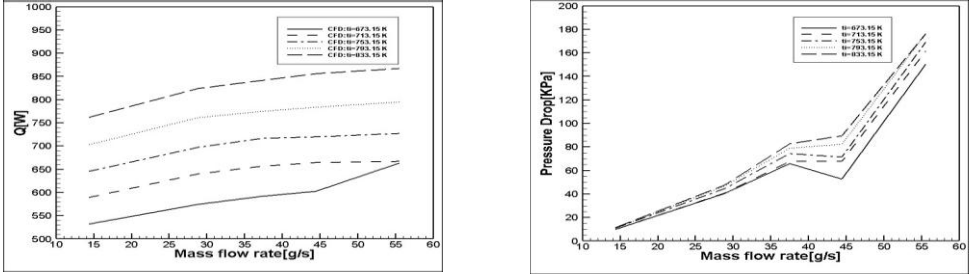
Figure 7: Performance under different cycles

The fluids pass through the plates in a serial fashion, lengthening the time they spend in contact with the heat exchanger surface. As a result, the maximum heat transfer rate for the serial plate construction increased to 988 W, which was accomplished by using 7 baffles to force exhaust to flow back and forth. The serial plate structure also had a maximum pressure drop of 176 kPa among the three, 115% more than empty cavity respectively.



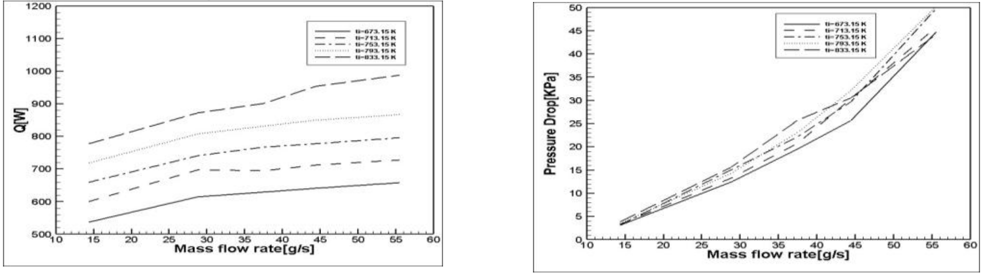
(a) Heat (b) pressure drop

Figure 8: CFD results for the Empty cavity structure.



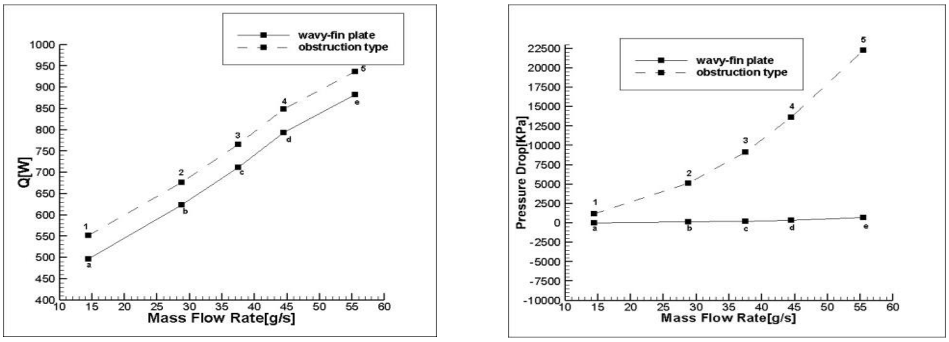
(a) Heat (b) pressure drop

Figure 9: CFD results for the Serial plate structure.



(a) Heat (b) pressure drop

Figure 10: CFD results for the Pipe structure



(a) Heat (b) pressure drop

Figure 11: CFD results for the Wavy fin & Obstruction structures.

Regarding the pipe structure, the exhaust exited the main inlet at the body's outlet side and dispersed till the main outlet's end region, which was opposite the inlet's outlet. There, as depicted in Figure 4, it reflected and flowed into the two exit pipes. Overall, the temperature field was rather uniform, although it only released 953.28 W of heat, Or 46.3% of the heat released by the serial plate, while releasing 6.5 kPa of pressure, or 66.8% of the heat released by the serial plate. There was a greater pressure drop than in other constructions as a result of the rapid expansions and contractions of the inlet or outlets .We are checking with the existing mass flow rate with different temperatures and different operating conditions against the Wavy fin plate and Obstruction type configures Shown fig 11. Regarding the wavy fin structure, the exhaust exited from the primary inlet on the body's outlet side and diffused along a nearly straight path towards the primary outlet, which was situated opposite the inlet's exit, as depicted in Figure 5. Upon reaching this point, it experienced minimal obstruction and continued its flow. In general, the temperature distribution remained relatively uniform, with a moderate heat release of 496W, simultaneously, it exerted a pressure of 6.5 kPa, which was relatively lower due to the simpler structure with fewer obstructions and a more direct flow path compared to other configurations.

Table 4: Structural Characteristics

Structure	**Driving cycle**	**Mass flowrate(g/s)**	**Heat transfer(w)**
Empty cavity	Sub-Urban	14.4	438.93
Serial plate	Sub-Urban	14.4	532.28
Pipe structure	Sub-Urban	14.4	527.22
Wavy-fin plate	Sub-Urban	14.4	496.702
Obstruction	Sub-Urban	14.4	551.42

In the obstruction -type design the exhaust followed a convoluted path through an array of attenuation plates meticulously positioned within the structure. These plates played a pivotal role in significantly reducing pressure along the flow path while simultaneously intensifying the rate of heat transfer from the structure. This enhancement stemmed from the increased interaction of the gas with the interior structure, resulting in a considerably expanded surface area available for heat exchange. Consequently, the temperature distribution within the structure displayed notable fluctuations, accompanied by a substantial heat generation rate. In this configuration, there was a moderate heat extraction of 551W, equivalent to 46.3% of the heat generated by the serial plate. Figure 6, Simultaneously, it exerted a pressure of 122kPa, reflecting the significant pressure reduction due to the intricate arrangement of attenuation plates, resulting in a heightened heat transfer rate and increased heat extraction.

4.3 How each structure performs under varying operating conditions?

The boundary conditions in CFD were the same as in the experiment: inlet temperature and inlet mass flow rate, but the coefficient of convective heat transfer was set to 18 W/(m^2 ^{0}C) in consideration of a radiant heat transfer. In Figure 7 and 10 the numerical and simulating results are shown at 25 operating points with different temperatures and pressures, the averaged relative error between the numerical and simulating results heat transferred. While for the obviously, the relative error was small for the low inlet temperature and small mass flow rate; it rose with the increasing inlet temperature and mass flow rate. In our study, from figure 1, a; empty cavity structure, featuring two parallel plates with a space between them, displayed straightforward heat transfer characteristics. Heat primarily transferred between the fluids through conduction within this uncomplicated geometry. We observed a limited amount of heat crossing the wall, equivalent to 438.93 watts, and a minimal pressure drop of approximately 35.087 kPa under sub-urban driving cycles. This aligns with our initial expectation of relatively low heat transfer and pressure drop in a straightforward heat exchanger design.

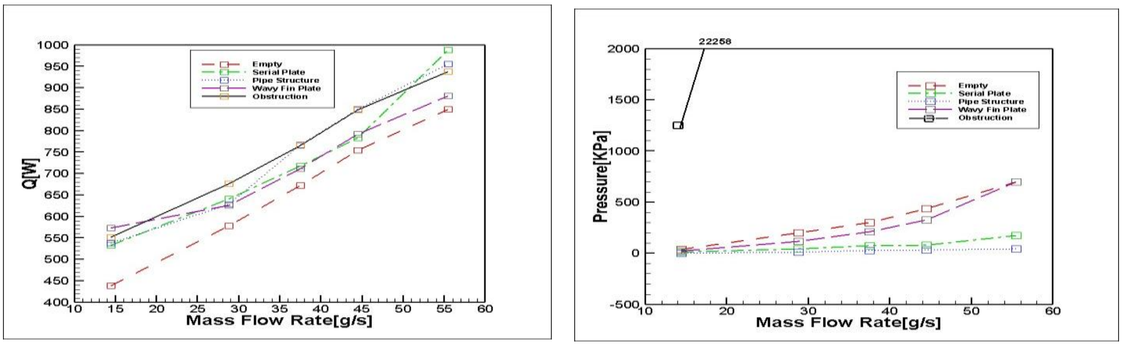


Figure 12: Comparison of five internal structures

Upon investigation, based on figure 1-b, the serial plate structure with its stacked plates and baffles revealed notable improvements in heat transfer compared to the empty cavity design. By inducing back-and-forth fluid flow, we achieved a maximum heat transfer rate of 988 W. This aligns with our anticipation that the serial plate design, with extended fluid-surface contact, would lead to enhanced heat transfer. However, the trade-off was a significantly increased pressure drop, reaching 176 kPa, which exceeded our expectations by 115%. Our examination from figure 1-c of the pipe structure, where exhaust flow featured unique expansions and contractions, resulted in a moderate heat release of 953.28 amounted to 46.3% of the heat generated by the serial plate structure. Our predictions regarding the lower heat transfer compared to the serial plate structure due to the specific flow pattern and geometry were confirmed. Additionally, the configuration led to a pressure drop of 6.5 kPa, or 66.8% of that observed in the serial plate structure.

CONCLUSION

Thermoelectric generators (TEGS] for waste heat recovery from automotive exhaust systems, shedding light on key findings and their implications. One aspect of this investigation was the design of adverse heat exchanger configurations ranging from traditional setups to innovative structures introduced in the study. The examination commenced with the Empty Cavity Structure a basic and straightforward configuration, which demonstrated minimal heat transfer and pressure DMP, serving as a benchmark for further comparisons. The Serial Plate Structure, characterized by stacked plates emerged as a noteworthy contender, significantly enhancing heat transfer while at the cost of increased pressure drop. Conversely, the Pipe Structure featuring a unique pattern with expansions and contractions, revealed moderate heat transfer efficiency and a moderate pressure drop. The research then into two novel heat exchanger designs, the Wavy Fin Structure and the Obstruction-Type Design, both of which exhibited distinctive advantages. The Wavy Fin Structure offered a streamlined partly very moderate yet consistent heat transfer with a remarkably low-pressure drop in contrast, the Obstruction-Type Design demonstrated exceptional heat extraction capabilities achieving high heat transfer while maintaining a manageable pressure drop importantly, it also presented the potential for the integration of a pressure seduction system, adding versatility impressive attribute. Collectively these findings underscore the potential of TEG technology in addressing energy efficiency and environmental concerns in the automotive industry. The innovative structures introduced in this study, the Wavy Fin Structure and the Obstruction-Type Design offer practical solutions to the challenges of heat transfer and pressure more management, bridging the gap between real-world applicability. These advancements have far-reaching implications, extending beyond automotive systems to industrial applications, providing promising avenues for reducing greenhouse gas emissions, enhancing fuel efficiency, and promoting sustainability in diverse sectors. As exploration and refinement of TEG technology continue these findings pave the way for more efficient and eco-friendly solutions in the pursuit of a greener, more energy-efficient future.

REFERENCES

1. Hsiao, Y. Y., Chang, W. C., & Chen, S. L. (2010). A mathematic model of thermoelectric module with applications on waste heat recovery from automobile engine. Energy, 35(3), 1447-1454.
2. Lesage, F. J., Sempels, É. V., & Lalande-Bertrand, N. (2013). A study on heat transfer enhancement using flow channel inserts for thermoelectric power generation. Energy Conversion and Management, 75, 532-541.
3. He, W., Wang, S., Zhang, X., Li, Y., & Lu, C. (2015). Optimization design method of thermoelectric generator based on exhaust gas parameters for recovery of engine waste heat. Energy, 91, 1-9.
4. Weng, C. C., & Huang, M. J. (2013). A simulation study of automotive waste heat recovery using a thermoelectric power generator. International journal of thermal sciences, 71, 302-309.
5. Hsu, C. T., Huang, G. Y., Chu, H. S., Yu, B., & Yao, D. J. (2011). Experiments and simulations on low-temperature waste heat harvesting system by thermoelectric power generators. Applied Energy, 88(4), 1291-1297.
6. Li, B., Huang, K., Yan, Y., Li, Y., Twaha, S., & Zhu, J. (2017). Heat transfer enhancement of a modularised thermoelectric power generator for passenger vehicles. Applied Energy, 205, 868-879.
7. Twaha, S., Zhu, J., Yan, Y., & Li, B. (2016). A comprehensive review of thermoelectric technology: Materials, applications, modelling and performance improvement. Renewable and sustainable energy reviews, 65, 698-726.
8. Liu, C., Deng, Y. D., Wang, X. Y., Liu, X., Wang, Y. P., & Su, C. Q. (2016). Multiobjective optimization of heat exchanger in an automotive exhaust thermoelectric generator. Applied Thermal Engineering, 108, 916-926.
9. Luo, D., Wang, R., Yu, W., Sun, Z., & Meng, X. (2019). Modelling and simulation study of a converging thermoelectric generator for engine waste heat recovery. Applied Thermal Engineering, 153, 837-847.
10. Kim, S. K., Won, B. C., Rhi, S. H., Kim, S. H., Yoo, J. H., & Jang, J. C. (2011). Thermoelectric power generation system for future hybrid vehicles using hot exhaust gas. Journal of electronic materials, 40, 778-783.
11. Wang, C., Tang, S., Liu, X., Su, G. H., Tian, W., & Qiu, S. (2020). Experimental study on heat pipe thermoelectric generator for industrial high temperature waste heat recovery. Applied Thermal Engineering, 175, 115299.
12. Fernández-Yáñez, P., Romero, V., Armas, O., & Cerretti, G. (2021). Thermal management of thermoelectric generators for waste energy recovery. Applied Thermal Engineering, 196, 117291.
13. Elghool, A., Basrawi, F., Ibrahim, T. K., Habib, K., Ibrahim, H., & Idris, D. M. N. D. (2017). A review on heat sink for thermo-electric power generation: Classifications and parameters affecting performance. Energy conversion and management, 134, 260-277.
14. Ramírez, R., Gutiérrez, A. S., Eras, J. J. C., Valencia, K., Hernández, B., & Forero, J. D. (2019). Evaluation of the energy recovery potential of thermoelectric generators in diesel engines. Journal of Cleaner Production, 241, 118412.
15. Shen, Z. G., Tian, L. L., & Liu, X. (2019). Automotive exhaust thermoelectric generators: Current status, challenges and future prospects. Energy Conversion and Management, 195, 1138-1173.
16. Lu, H., Wu, T., Bai, S., Xu, K., Huang, Y., Gao, W & Chen, L. (2013). Experiment on thermal uniformity and pressure drop of exhaust heat exchanger for automotive thermoelectric generator. Energy, 54, 372-377.

17. Bejjam, R. B., Dabot, M., Wondatir, T., & Negash, S. (2021). Performance evaluation of thermoelectric generator using CFD. Materials Today: Proceedings, 47, 2498-2504.
18. Olabi, A. G., Al-Murisi, M., Maghrabie, H. M., Yousef, B. A., Sayed, E. T., Alami, A. H., & Abdelkareem, M. A. (2022). Potential applications of thermoelectric generators (TEGs) in various waste heat recovery systems. International Journal of Thermofluids, 16, 100249.
19. Luo, D., Wang, R., Yan, Y., Yu, W., & Zhou, W. (2021). Transient numerical modelling of a thermoelectric generator system used for automotive exhaust waste heat recovery. Applied Energy, 297, 117151.