CFD SIMULATION OF THERMO ELECTRIC GENERATION FOR WASTE HEAT RECOVERY OF EXHAUST GAS OF AN ENGINE

Abstract:

A novel way to boost the efficiency of engines, including those found in cars and power generators. Large amounts of heat are produced as engines run, yet this heat is frequently lost. We're seeking to alter that with the help of a thermoelectric generator, a device that can transform heat into power. We're using computer simulations (CFD analysis) to understand how heat moves through the engine and a special heat exchanger to figure out how to do so efficiently. With the aid of this exchanger, the engine's heat may be most efficiently transferred to the thermoelectric generator. Hopefully, this will lead to engines becoming more efficient, generating fewer dangerous gases, and requiring less fuel. and being more environmentally friendly. Here, we compared heat exchangers with different designs. By using CFD analysis we observed pressure drop and heat transfer rate. Heat exchanger types empty cavity, serial plate structure, Novel pipe structure, Wavy fin plate and Obstruction and created designs with changing the internal structure of heat exchanger, etc. By using CFD result we preferred the heat exchanger with low pressure drop and high heat transfer rate corresponding with exhaust mass flow rate. However, this will increase the pressure drop, this arrangement needs a pressure-relieving mechanism to work as desired. A compromise between heat transfer rate and pressure drop can be achieved by using a heat exchanger with a smaller heat transfer area and a higher flow rate. The results of this study show that CFD can be used to effectively design exhaust heat exchangers for TEGs. The CFD model can be used to optimize the design of the heat exchanger to achieve the desired balance between heat transfer rate and pressure drop.

Keywords: Thermoelectric Generator, Waste heat recovery, Heat exchanger, Heat transfer, pressure drop and internal structures.

1.Introduction

Waste energy from internal combustion engines' exhaust systems is one of the most alarming issues with fuel economy because it is known that about one-third of the fuel's energy input is lost. Thermoelectric generators (TEGs) are machines that directly transfer thermal energy from a temperature differential to electrical energy by using the SeeBeck phenomena. Thermoelectric generators are presently being investigated as a way to gather waste energy from the exhaust gases of land vehicles, airplanes, industries, and so on, despite initially being utilized almost exclusively in the space sector [1][2]. The system looked at whether it was possible to get energy from exhaust gases. In the same vehicle's bottom section, the impact of downstream airflow was also studied. Investigated in the bottom part of the same vehicle was the impact of downstream airflow. Utilizing the temperature differential between the hot exhaust gas and the cooler surrounding air to produce energy is known as the thermoelectric potential of exhaust gases. Using a thermoelectric generator (TEG), which turns heat into electricity directly, this can be done. An internal combustion engine's exhaust gas can get as hot as 1,000 degrees Fahrenheit. Compared to the ambient air, which is typically around 70 degrees Fahrenheit, this is far hotter. A TEG can be utilized to generate power from this temperature difference[3]. The sources mentioned above state that the exhaust gas potential for use as a waste heat source in internal combustion engines has been studied, albeit normally, when evaluating heat sources, the initial shape is taken into consideration. The heat transmission coefficient of exhaust gases is, nevertheless, quite low [4]. Building a heat exchanger to improve heat transport to the thermoelectric modules is the conventional approach. As a result, this issue has been the subject of numerous research in the literature. There are several issues with thermal management and the energy crises in the current environment. In recent years, the management of engine exhaust has received significant attention in the automotive sectors. In internal combustion engines, a large amount of heat is lost as exhaust gases. Of the total heat energy supplied to the engine combustion chamber in the form of fuel, about 30–40% is converted into useful work, and the remaining portion is released as exhaust gases. This exhaust gas contains a significant amount of heat that can be recovered by using a waste heat recovery system.Thermo-electric power generators are perfect for such applications since they are compact, free of moving parts, and relatively efficient at high temperatures[5]. To accommodate the rising electrical needs of various accessories, large, heavy alternators are linked to the engines of automobiles. 1 to 5% of the rated engine work output is used by an alternator with an efficiency of 50 to 62%. An IC engine rejects about 40% of the thermal energy of the fuel it injects as waste heat in the form of exhaust gases. It would be able to fulfill our cars' electrical needs and cut fuel consumption by around 6% if about 6% of the waste heat from the engine's exhaust could be used[6].A significant amount of heat is released by exhaust gases at extremely high temperatures as opposed to heat rejected through coolant and lubricating oil. Thus, energy from exhaust heat can be converted using a thermo-electric generator (TEG). The TEG operates on the same principal as a heat engine, which is used to transform heat energy into electrical energy. The amount of energy that can be produced from exhaust gases depends on a number of factors, including the temperature difference between the exhaust gas and the surrounding air, the TEG's efficiency, and the size of the exhaust gas generator [7].

Waste Heat Recovery Techniques

Waste heat recovery techniques involve capturing and utilizing thermal energy that would otherwise be wasted during industrial processes or in everyday applications. Methods such as heat exchangers, Organic Rankine Cycle (ORC), thermoelectric generators (TEGs), This approache aim to improve overall energy efficiency, reduce greenhouse gas emissions, and save on operational costs by converting waste heat into useful power, cooling, or heat for various applications. They play a vital role in optimizing resource utilization and promoting sustainable practices in industries.

Waste heat recovery technique from diesel engines:

Thermo-electric generator: Direct electrical conversion devices such as thermoelectric generator (TEG). Factors such as efficiency, power output, cost, weight, safety, flexibility in adjusting with the variation of temperature, etc. affect the selection of the WHR technique. Direct electrical conversion devices These devices directly convert waste heat to electricity without intermediate conversion to any other form of energy. These include the usage of solid-state devices such as TEG, TPV, etc. for electricity generation. The significant advantage here is the absence of moving parts, and the major drawback is the low efficiency of these devices. Thermo-electric generator is used in waste heat recovery from the exhaust of diesel engines using TEG is referred to as an automobile exhaust thermoelectric generator (AETEG). They are installed in series or parallel configurations on the exhaust line of automobiles. The hot side is exposed to exhaust gas, and the cold side is cooled using an engine coolant. The maximum conversion efficiency is 6%–7%.A large number of AETEG's are needed to be installed on the exhaust line to recover a considerable amount of waste heat. It leads to several issues, such as an increase in weight, backpressure in the exhaust line. The exhaust gas temperature fluctuates from 473 K to 873 K and TEG also has a constraint in its higher temperature limits (Maximum limit is around 593 K). The by-pass line is to be provided to protect the system, which increases the system's weight and volume. A phase change material (PCM) can be integrated with TEG to store energy at a constant temperature or over a limited range of temperature variation, thus providing low-temperature variation at the hot end of TEG examined the use of a TEG in the exhaust of hybrid vehicles on highway conditions.

Definition and properties of TEMs:

A thermoelectric module (TEM) is a heat-to-electricity converter (TEM) that does this. The temperature difference between the upper and lower surfaces of TEMs determines how quickly energy is converted. Serial connections between thermoelectric modules are used for electrical connections. Each TEM consists of several thermocouples that are positioned between two ceramic plates with a high heat conductivity and a low electrical conductivity. These thermocouples are made up of a serially coupled pair of p- and n-type semiconductors in each unit. In this setup, heat is removed from the exhausts by a hot surface (qh) and rejected toward the ambient temperature (qc) by a cool surface. High heat conductivity and low electrical conductivity ceramic plates contain semiconductors. There are known materials that can transform heat into electricity and electricity into heat.

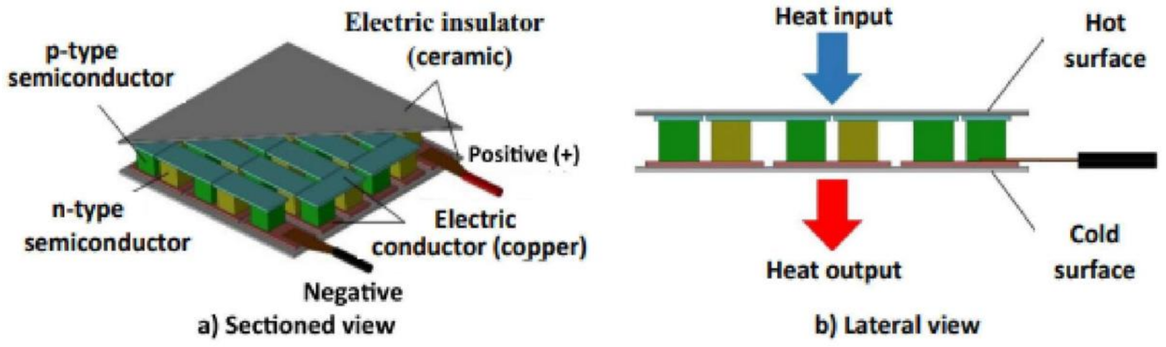


Figure 1 Thermo-electric module

Overview of waste heat recovery:

Waste heat is the energy that is connected to air waste streams, exhaust gases, and/or process byproducts that are released into the atmosphere after a process. The energy that is produced during numerous processes but is not put to any useful use instead escapes into the atmosphere. It is the energy that a process rejects when the temperature is high enough to allow for the economically viable recovery of a portion of the energy for usable purposes. It is assumed in the concept of waste heat that the waste streams conveying the heat will eventually mix with atmospheric air or groundwater and lose their ability to provide usable energy and the taking up of waste heat to the absorption of waste energy by the environment is often termed as thermal pollution [8].

Recovery of waste heat can be conducted through different waste heat recovery (WHR) technologies to provide valuable energy sources and reduce overall energy consumption. Several WHR technologies are available and can be used for capturing and recovering the waste heat. A considerable amount of energy used in industrial processes is wasted as heat in the form of exhaust gases, air streams, and liquids/solids leaving the process. It is not technically and economically feasible to recover all the waste heat. An increased use of WHR technologies also serves to mitigate greenhouse gas (GHG) emissions technologies consist of capturing and transferring the waste heat from a process with a gas, liquid, or solid back to the system as an extra energy source. The energy source can be used either to produce more heat or to provide mechanical and electrical power. At any temperature, waste heat can be rejected. The quality of waste heat is typically higher and the optimization of the WHR process is typically easier at higher temperatures for waste heat. Therefore, it is crucial to identify the largest possible quantity of heat that may be recovered from a process and to ensure that a WHR system operates at its highest possible efficiency. Sources of waste heat often include heat loss from products, equipment, and processes that are transported by conduction, convection, and radiation as well as heat released during combustion processes. High-temperature heat, medium-temperature heat, and low-temperature heat are the three categories into which heat loss can be divided. For each source of waste heat, there are WHR technologies available, allowing for the highest possible WHR efficiency [9].

Importance of waste heat recovery from engine exhaust gas

The significance of recovering waste heat from engine exhaust gas is that it can help to increase engine efficiency. The engine doesn't have to work as hard to produce the same amount of power when the heat from the exhaust gases is recycled. This may result in a large decrease in both fuel use and emissions. Additionally, waste heat recovery helps to reduce the impact of engines on the environment. We can reduce the amount of waste heat that is emitted into the atmosphere by capturing and recycling the heat from exhaust gases. This may help in reducing climate change and enhancing air quality [10]. Hot gas waste heat recovery is crucial for a variety of reasons, including Reduction in energy consumption: Waste heat recovery can aid in lowering energy waste. Reduced operational expenses and a lesser carbon footprint may result from this. Efficiency gain: Waste heat recovery can aid in a system's efficiency gain. Profitability and productivity may rise as a result. Enhanced sustainability: By lowering the quantity of energy wasted, waste heat recovery can help to increase the sustainability of a system. Natural resource conservation and environmental protection may both benefit from this.Reduced emissions: By reducing the amount of fuel burnt, waste heat recovery can help to reduce emissions. This could contribute to better air quality.

Selection criteria for TEM-based systems:

Depending on the particular application, different selection criteria for systems based on thermoelectric materials will be used. However, some of the most important considerations are the temperature range of operation for thermoelectric materials to function effectively. It is crucial to pick a material that is appropriate for the given and power output is also required. The Seebeck coefficient, electrical conductivity, and thermal conductivity of a material all affect a thermoelectric system's power output. It's crucial to pick a material that can produce the desired output of power.The material's price .It's crucial to select a material that is economical for the intended application because thermoelectric materials might be pricey. Availability of materials. Different thermoelectric materials are easier to find than others. Selecting a material that is readily available in the required quantity and quality.

1. LITERATURE REVIEW

"Modelling and simulation study of a converging thermoelectric generator for engine waste heat recovery" by Ding Luo et (5) examines the impact of the heat exchanger's tilt angle on the efficiency of thermoelectric generators (TEGs) that convert waste heat into electricity. Using a two-dimensional numerical model based on mass, momentum, and energy conservation, along with material properties of the TEG, the study reveals that a tilt angle of 2 degrees leads to an optimal performance, generating a maximum net power output of 2.2 watts. This underscores the critical role of the tilt angle in TEG performance. The article suggests future research directions should focus on enhancing both TEG and heat exchanger efficiency for more effective waste heat recovery[11].

"Performance evaluation of thermoelectric generator using CFD" by Ramesh Babu Bejjam studied that the study highlights the viability of utilizing thermoelectric generators (TEGs) to recover waste heat from engine exhaust systems. However, TEG performance is subject to various influencing factors, necessitating the optimization of TEG system design for optimal outcomes. To explore the impact of the exit gap between the heat deflector and exhaust pipe, the study varied the gap from 10 mm to 15 mm in 2.5 mm increments and altered the inclination angle of the heat deflector from 1° to 3.5° in 0.5° increments. The results indicated that a 2° deflector inclination angle with a 10 mm exit gap exhibited superior performance. Additionally, the study investigated the influence of heat exchanger material on TEG performance, considering pure copper, pure aluminum, aluminum alloy, and low-carbon steel. The findings revealed that pure copper demonstrated the best performance, showcasing a temperature difference of 184.98 K. This underscores the importance of material selection in optimizing TEG efficiency for waste heat recovery from exhaust systems[12].

“Evaluation of the energy recovery potential of thermoelectric generators in diesel engines” by etalevaluation of thermoelectric generators (TEGs) in diesel engines by Rafael Ramírez reveals several key points. The study, conducted on a single engine, might lack generalizability to all diesel engines. The focus on biodiesel blends and diesel fuel excludes potential variations with other fuels like ethanol or natural gas. Important aspects like TEG cost and installation impact on engine fuel efficiency were not considered, crucial for assessing economic viability. TEG energy conversion efficiency ranged from 2.5% to 3%, depending on fuel and conditions, with biodiesel blends showing higher power recovery than diesel fuel. TEG usage lowered emissions (CO, CO2, NO, NOX, HC), and reduced smoke opacity indicated reduced unburned fuel in exhaust gases. The study suggests TEGs hold promise for enhancing energy efficiency and reducing diesel engine environmental impacts, but optimization research is required for maximum benefits[13].

"A Mathematic Model of Thermoelectric Module with Applications on Waste Heat Recovery from Automobile Engine" by Hsiao et al. (2010) demonstrates that although the amount of heat loss decreases as the heating surface's temperature rises, the heat loss from the TEM does. become more crucial as the temperature rises.The model also demonstrates how the temperature difference between the heating and cooling surfaces enhances the power output of the TEM. However, as the temperature difference increases, the TEM's effectiveness drops. This is so because the Carnot efficiency, which depends on the temperature differential, is what keeps TEM efficiency in check[14].

"A Study on Heat Transfer Enhancement Using Flow Channel Inserts for Thermoelectric Power Generation" by Lesage et al. (2013) presents Different panel insert geometries were tested, and it was discovered that they could greatly increase the power output of the TEGs, particularly at greater temperature differentials.Because it can increase TEG efficiency and power production, heat transfer enhancement is a key field of research in thermoelectric power generation. Utilizing flow channel inserts is one method to improve heat transmission. Devices called flow channel inserts are inserted into a TEG's flow channel to enhance the surface area and/or alter the flow of the fluid. Increased heat transmission between the fluid and the thermoelectric modules may result from this[15].

The paper "Optimization Design Method of Thermoelectric Generator Based on Exhaust Gas Parameters for Recovery of Engine Waste Heat" by Wang et al. (2015) presents a method for optimizing the design of a thermoelectric generator (TEG) for recovering waste heat from automotive engines. The procedure accounts for the exhaust gas's characteristics, including flow rate, temperature, and composition.The performance of TEGs with various designs was simulated by the authors using a mathematical model of a TEG. They discovered that the precise exhaust gas conditions determine the best TEG design for waste heat recovery from vehicle engines[16].

"A Simulation Study of Automotive Waste Heat Recovery Using a Thermoelectric Power Generator" by Hsiao et al. (2010) presents a simulation study ofcreated a mathematical model of a TEG and utilized it to test the system's performance under various driving circumstances. The waste heat produced by the car engine might be used by the TEG system to provide a sizable amount of power. The efficiency of the TEG system was discovered to be rather low because the quantity of power produced by the TEG system is dependent on the driving circumstances, including the vehicle's speed and the temperature of the exhaust gas. TEGs, however, are solid-state devices without moving parts, making them dependable and long-lasting, therefore they concluded that they are a potential technology for waste heat recovery from automotive engines [17].

"Multi-objective optimization of heat exchanger in an automotive exhaust thermoelectric generator" by Liu et al. (2016) discovered that the TEG system's particular operating conditions affect the heat exchanger's ideal design. For instance, the authors discovered that employing a heat exchanger with a bigger surface area can result in a higher average temperature. A bigger surface area does, however, result in a greater pressure drop[18].

M. Hatamiet al. (2) described employing finned heat exchangers to numerically recover waste heat from engine exhaust. The quantity of heat transmitted to the cold fluid as recovered heat is determined by the study's successful simulation of heat transfer through the walls and fins. According to the findings, the RSM model does not produce correct results when compared to experimental data, but the SST k- and RNG k-viscous models are adequate. The numerical simulations in this work evaluate waste heat recovery at various engine speeds and loads using the FLUENT software. A graphic analysis of the effect of fin size, engine load, and speed on heat recovery is also included. Additionally, the significance of appropriate viscous models and adjusted fin characteristics for raising thermal efficiency in internal combustion engine heat recovery systems [19].

J. Ramos et al. (3) noted that the heat exchanger's experimental results revealed that when the mass flow rate increased, the temperature difference across the evaporator part reduced. Up to a pipe limit of 900 W/pipe, greater temperatures and mass flow rates lead to higher heat transfer rates. The thermal performance of a cross-flow heat pipe-based heat exchanger that uses six water-charged wickless heat pipes to transfer heat from air to water may be predicted with fair precision using CFD modeling and numerical computations. With the development of CFD models, it is now possible to simulate phase change processes, improve filling ratios, and analyze fluid behavior on the shell side of heat pipe heat exchangers [20].

D. Luo et al. (4) declare that The findings demonstrate delayed output reaction, a relationship between output voltage/power and exhaust mass flow rate, and a minimal influence of modest oscillations in exhaust gas pressure. To assess dynamic performance, a numerical model takes into account fluid-thermal-electric coupling effects, dynamic properties, and material temperature dependency. The steady-state simulation forecasts 12.6% more output power, while the model predicts stable voltage/power fluctuations but the reverse effects on conversion efficiency under rapid variation. To assess the dynamic performance of automobile TEG systems under erratic driving situations, a new transient fluid-thermal-electric Multiphysics coupling field numerical model is also proposed in this study [21].

Sangki Park et al. (1) explained that the numerical model of a heat storage device using phase-change material reduced the time to reach cooling water temperatures by 40.5% (95°C device) and 35.2% (70°C device) during the NEDC drive test. It also reduced the time to reach engine oil temperatures by 6.6% (95°C device) and 4.8% (70°C device). As a result, fuel consumption decreased by 2.71%

(95°C device) and 2.45% (70°C device), leading to improved fuel economy. Also, Modified heat exchangers with louver fins improved heat exchange rates with air, and Modelica-based software products, like AMESIM by LMS, can model heat transfer processes. Optimal parameters (fin pitch, temperature, flow rate) were identified through systematic adjustments[22].

J.A. Valencia et al.'s (2019) work "Evaluation of the energy recovery potential of thermoelectric generators in diesel engines" examines the ability of thermoelectric generators (TEGs) to recover waste heat from diesel engines.The authors created a TEG prototype out of 20 thermoelectric modules and a waffle heat exchanger. The TEG prototype was mounted on a diesel engine test bench and its performance was assessed under various engine operating circumstances. According to the trial results, the TEG prototype was capable of recovering up to 71.13 W of electricity from the diesel engine exhaust. The TEG prototype obtained the greatest energy conversion efficiency of 3% at maximum load and engine rpm.Researchers also created a theoretical model to forecast the potential energy recovery of TEGs in diesel engines. TEGs might collect up to 10% of the waste heat from diesel engine exhaust, leading to a considerable improvement in fuel economy, according to the modeling results. Overall, the article shows that employing TEGs to recover waste heat from diesel engines is feasible. The authors' findings indicate that TEGs have the potential to be a practical and effective technology for enhancing diesel engine fuel economy and lowering emissions[23].

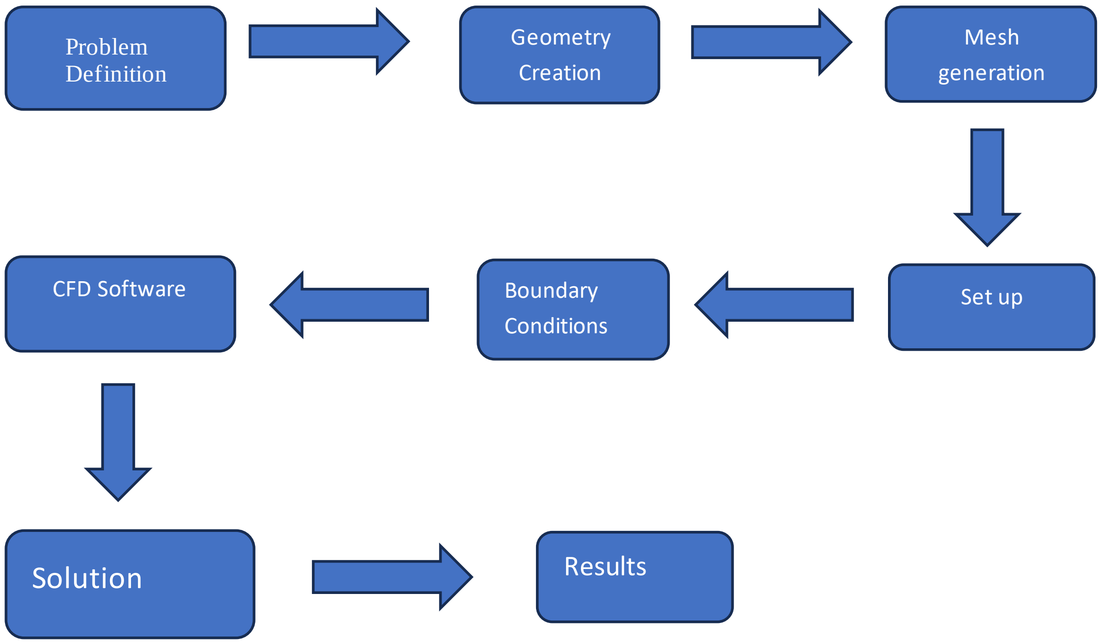
The paper "Automotive exhaust thermoelectric generators: Current status, challenges, and prospects" by Z.G. Shen et al.(2019) provides a comprehensive overview of the current state of the art of AETEGs, as well as the challenges and prospects of this technology.The authors address the fundamental concepts of thermoelectricity as well as the many types of thermoelectric materials utilized in AETEGs. They then go on to current developments in AETEG design, manufacturing, and testing. The authors also outline the major hurdles that must be overcome before AETEGs may be marketed, which include: Improving the efficiency of AETEGs, reducing the cost of AETEGs, developing long-lasting and dependable AETEGs that can handle demanding operating conditions in automotive applications.Finally, the authors evaluate AETEGs' future possibilities and propose several intriguing research avenues that might hasten the commercialization of this technology. Overall, the study is a useful resource for researchers and engineers working on AETEG development and implementation. Policymakers and other stakeholders interested in this new technology may find the report useful as wel[24]l.

METHODOLOGY

A heat exchanger is a mechanical device used in various industries and applications to transfer heat from one fluid or substance to another. Its primary purpose is to efficiently exchange thermal energy between two or more fluids while keeping them physically separated. Heat exchangers play a crucial role in heating, cooling, and energy recovery processes.Analyzing exhaust heat exchangers in automobile thermoelectric generators is essential for several reasons, primarily related to optimizing energy efficiency, reducing emissions, and ensuring the overall performance and durability of the system.

Performing a Computational Fluid Dynamics (CFD) analysis of an exhaust heat exchanger in an automobile thermoelectric generator involves several steps. This analysis helps in understanding the heat transfer, fluid flow, and temperature distribution within the heat exchanger. Here's a general methodology for conducting this CFD analysis[25].

Flow Chart



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 examinethe 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 usingcomputational 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 analyzed 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.

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. . 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 Displacement (cm3) Cylinders/Valves highest power (kW/rpm) The greatest torque (N m/rpm) injection apparatus	MT- 5 1206 4/16 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, Bi_2Te_3 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.

Meshing

The meshing approach, which is crucial for effectively representing the complexities of the physical system, is one of the key elements in numerical simulations of fluid solid interaction problems. By using a meshing strategy adapted to the design's complexity, we address this important feature in our research. The geometry under study has numerous nuances, thus the meshing procedure is tailored to account for these. To do this, we use a varied element size technique, meshing the structure with 3mm, 2mm, and 1mm-sized elements. We can balance computational accuracy and efficiency using this tiered strategy. Smaller element sizes are used in places that require finer resolution to capture fine features or boundary layers, while coarser meshing is used into regions that are less important. We use a thorough meshing process to make sure the mesh is fluid and water-tight. To be more precise, we concentrate on creating a water-tight geometry mesh, which is necessary for effectively simulating fluid-solid interactions. The accuracy of the mesh's conformance to the geometry's complex borders and interfaces is ensured by this painstaking process, which also makes sure that there are no leaks or discontinuities that could jeopardize the simulation's dependability. Additionally, we pay particular attention to the wall sections in our simulations of the fluid-solid interaction. On the fluid-solid interaction wall, we use a boundary layer meshing technique and include fiveboundary layers. We can measure the velocity using this methods and temperature gradients close to the wall with high accuracy, which is necessary for accurately simulating boundary layer behaviour and heat transport phenomena. The coupling of the solid and fluid zones within the mesh walls is a key element of our strategy. We can examine complicated phenomena like heat transport, stress distribution, and dynamic responses at the fluid-solid interface because of this connection, which ensures that interactions between the two domains are accurately captured. In conclusion, a crucial part of our research process that is built to adjust to the complexity of the issue at hand is our meshing strategy. With boundary layer meshing with solid-fluid coupling, variable element sizes, and water-tight geometry meshing, we want to build a solid basis for our simulations that will allow us to learn important things about the behaviour of fluid-solid interaction systems.

A fluid portion and a solid portion make up the entire computing domain. By resolving a series of mathematical equations in relation to the solid and computational fluid domains, the desired temperature field and flow field are obtained. To simulate fluid flow, heat transfer, and mass transfer within the fluid domains, the equations of mass, momentum, and energy conservation are solved.

Only the equation of heat transfer is solved for solid domains the continuity

equation is

$$\partial\rho/\partial t + \nabla.(\rho U) = 0 \qquad ----1$$

The Momentum equation is

$$\partial\rho U/\partial t + \nabla.(\rho UU) + \nabla p = \nabla P + \nabla\tau + S \qquad -----2$$

The energy equation is

$$\partial(\rho h)/\partial t - \partial P/\partial t(\rho U h_t) = (\lambda\nabla T) + \nabla(U\tau) + US_m + S \qquad -------- 3$$

The conservation of energy equation in solid domain is

$$\partial(\rho h)/\partial t + (\rho U_s h) = (\lambda\nabla T) + S_t \qquad -------- 4$$

Whether the flow is laminar or turbulent affects the viscous model. The input pipe's and box cavity's respective critical flow velocities are 0.92 m/s and 0.42 m/s, which are both considerably slower than the actual velocities. The k-epsilon turbulence model was used to simulate the exhaust because it is the industry standard model for many commercial CFD models. This model's stability and numerical dependability have been established. Since they are thermodynamically in close proximity to one another, the fluid material for the exhaust employs a calorically perfect ideal gas and the solid material for the shell is made of steel. For the fluid-solid interface, such as the exhaust with a shell and the exhaust, grids of the solid domain and the fluid domain that do not match each other were connected using a general connection technique. Due to their close thermodynamic proximity, the fluid material for the exhaust uses an ideal gas that is calorically perfect, and the solid material for the shell uses steel. Nonmatching grids of the solid domain and the fluid domain, such as the exhaust with a shell and the exhaust with a pipe, were connected using a general connection method for the fluid-solid interface. After applying the energy equation to the exhaust domain and making modifications to the fluid-solid interface, it was possible to calculate heat transfer from the exhaust to the shell.

Investigated of five Internal Structures

In the paper, the study investigates five different internal structures within the exhaust heat exchanger of a thermoelectric generator (TEG). Each of these structures represents a different design or configuration for the heat exchanger, and the research aims to analyse their performance in terms of heat transfer efficiency and flow characteristics. Here's an explanation of the five internal structures being investigated.

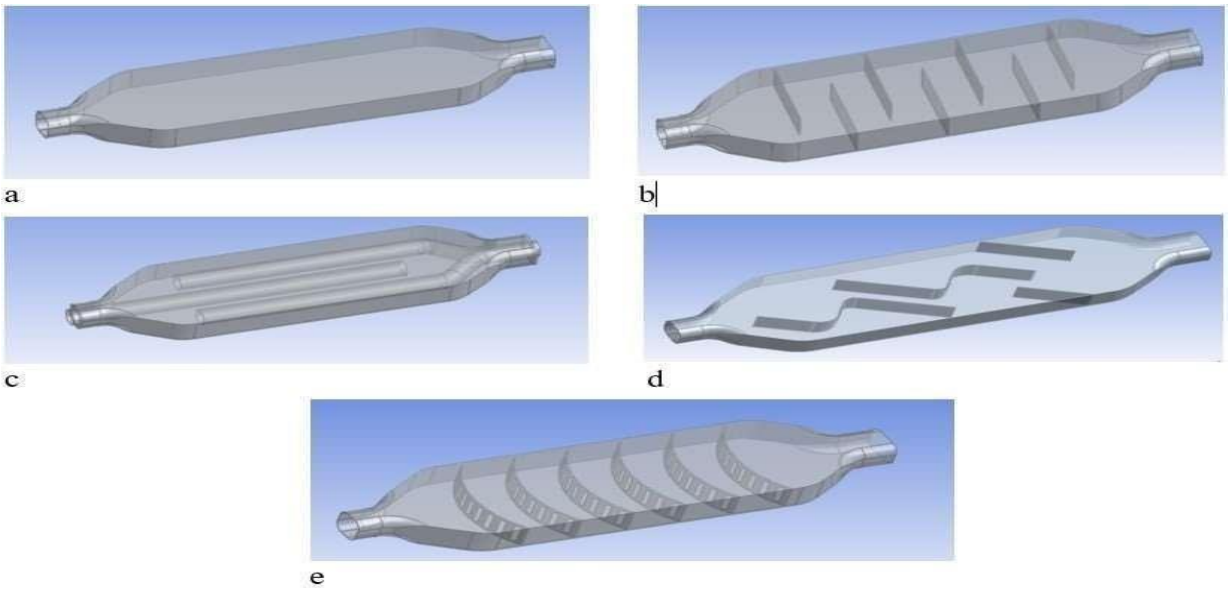
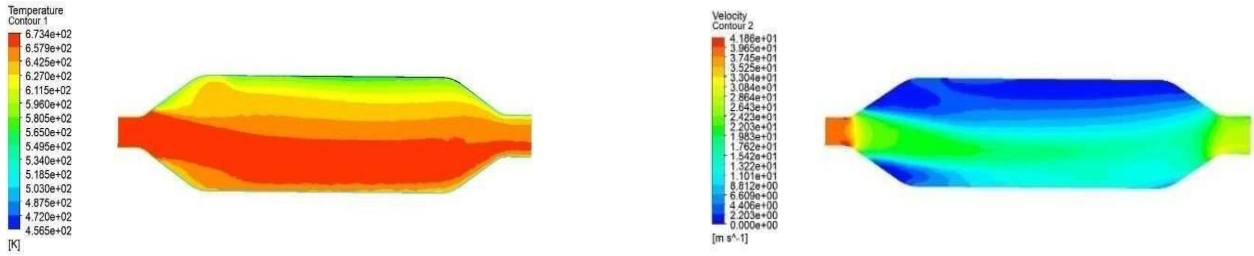


Figure 1. Five internal structures a) Empty cavity b) Serial plate c) pipe structure d) Wavy-fin plate e) Obstruction

RESULTS AND DISCUSSIONS

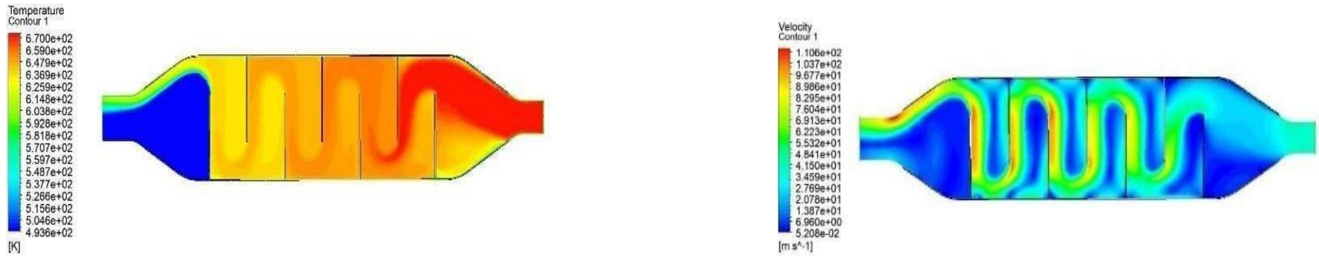
Presentation of CFD Simulation Results for each of the five internal structures

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.



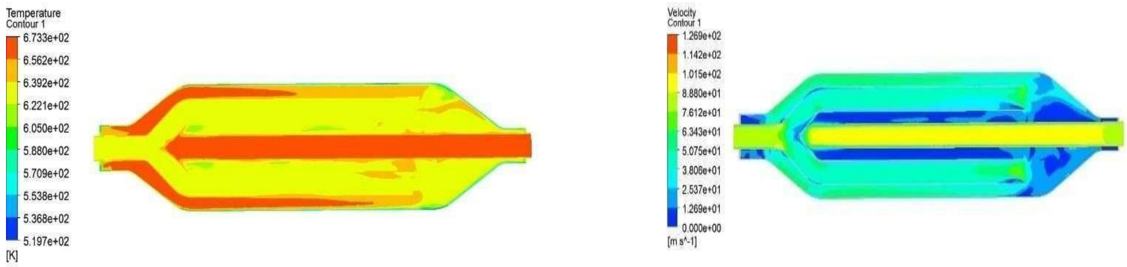
(a)Temperature field (b)Velocity field

Figure 2. Physical distribution in an empty cavity.



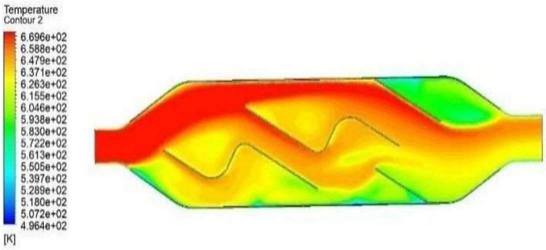
(a)Temperature field (b)Velocity field

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

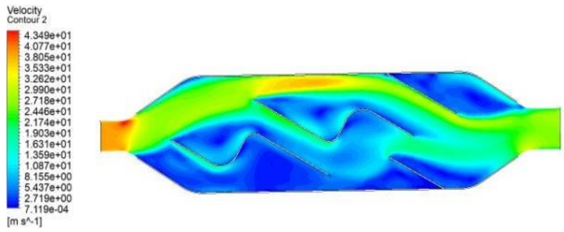


(a)Temperature field (b)Velocity field

Figure 4. Physical distribution of a pipe structure.

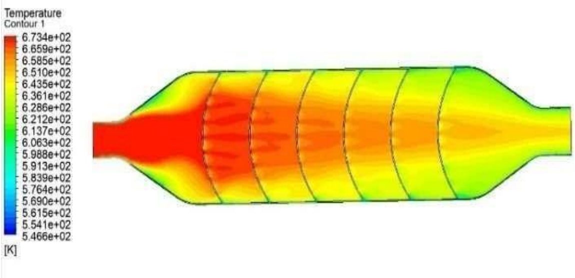


(a)Temperature field

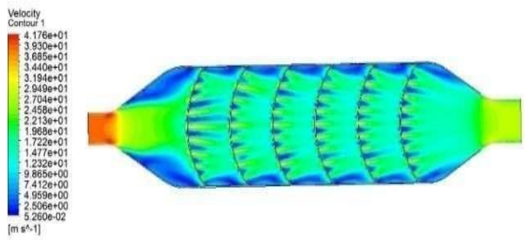


(b)Velocity field

Figure 5. Physical distribution of a Wavy fin plate.



(a)Temperature field



(b)Velocity field

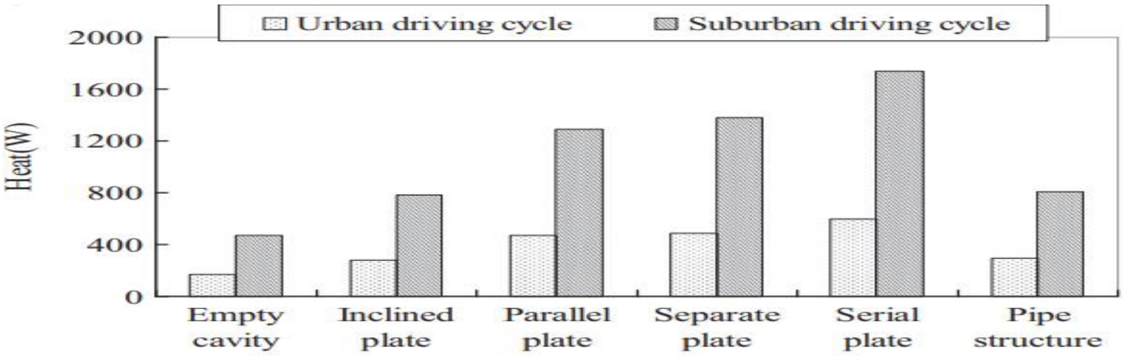
Figure 6. Physical distribution of an Obstruction type

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 ofheat 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 typeand 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 contains numerous plates that are stacked one on top of the other as opposed to the empty cavity.



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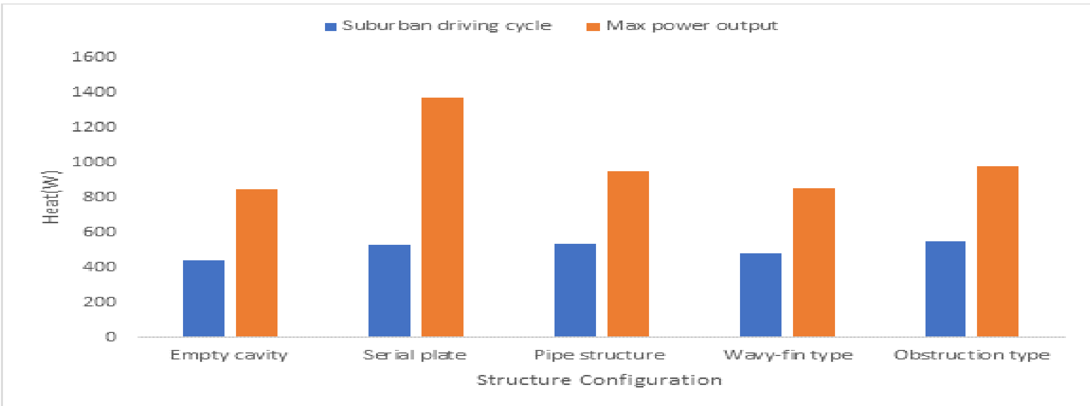
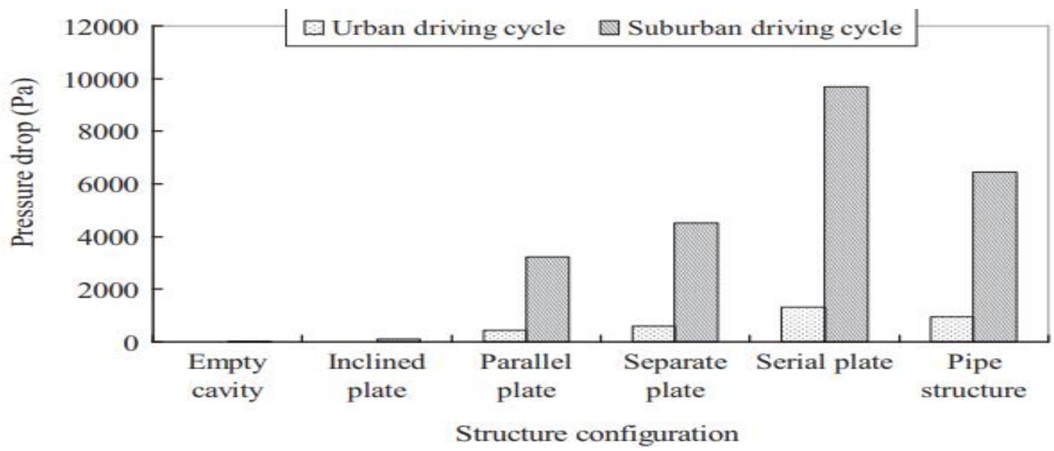


Experimental Results

Figure7 :Validation of results under different cycles(Heat Transfer rate)



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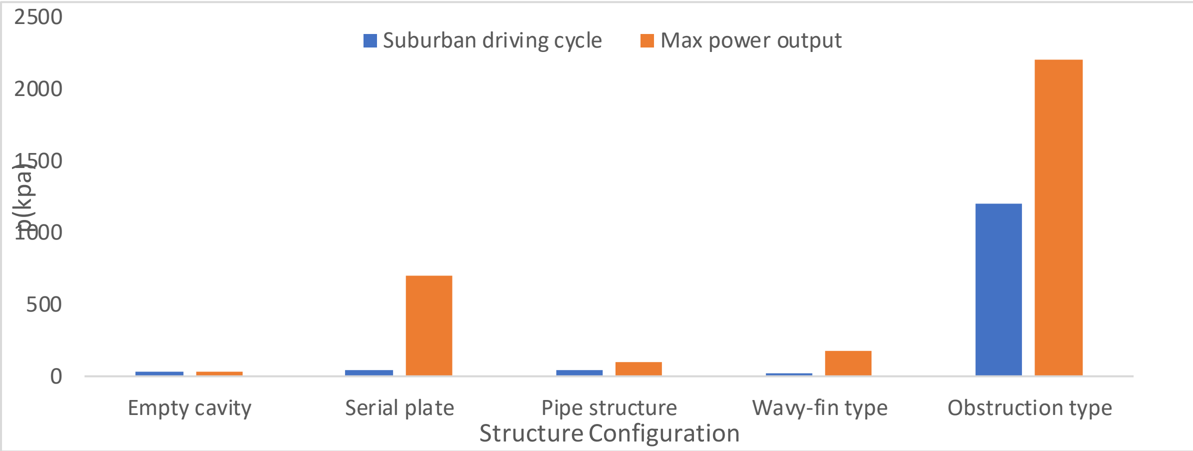
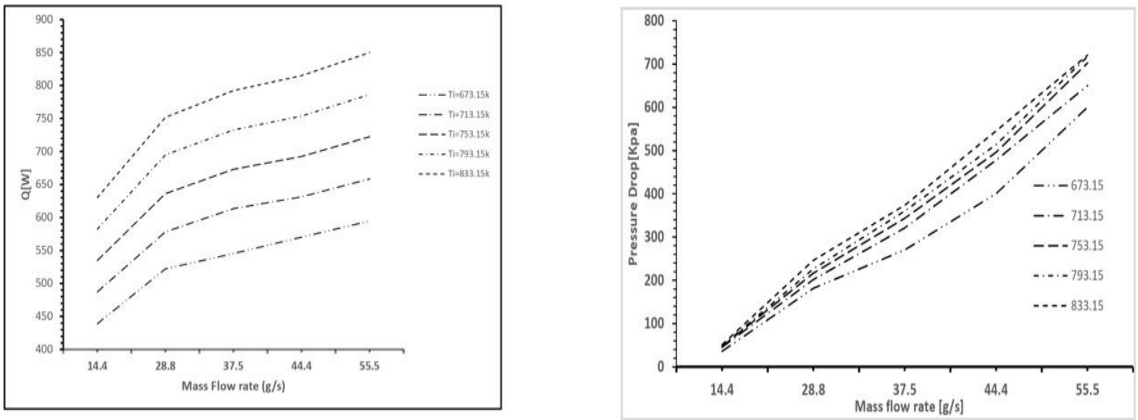


Experimental Results

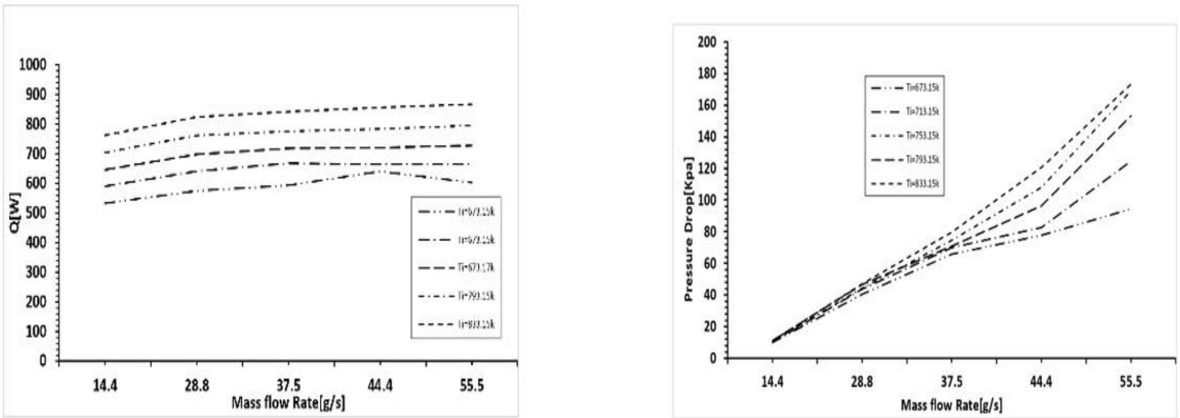
Figure 8: Validation of results under different cycles(Pressure Drop)

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.



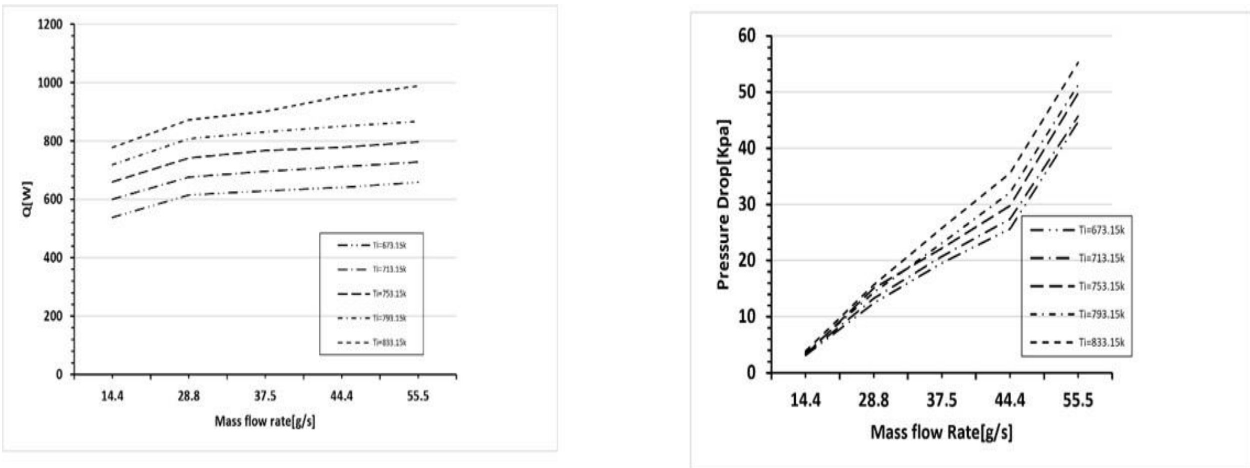
(a)Heat (b)Pressure Drop

Figure 9. CFD results for the Empty cavity structure.



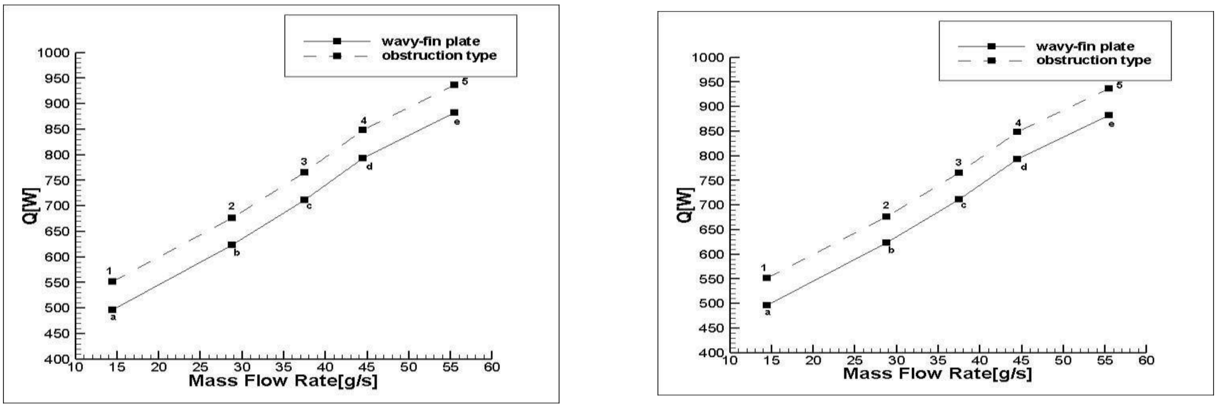
(a)Heat (b)Pressure Drop

Figure 10. CFD results for the Serial plate structure.



(a)Heat (b)Pressure Drop

Figure 11. CFD results for the Pipe structure



(a)Heat (b)Pressure Drop

Figure 12. 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.

How each structure Performs under varying 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 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.

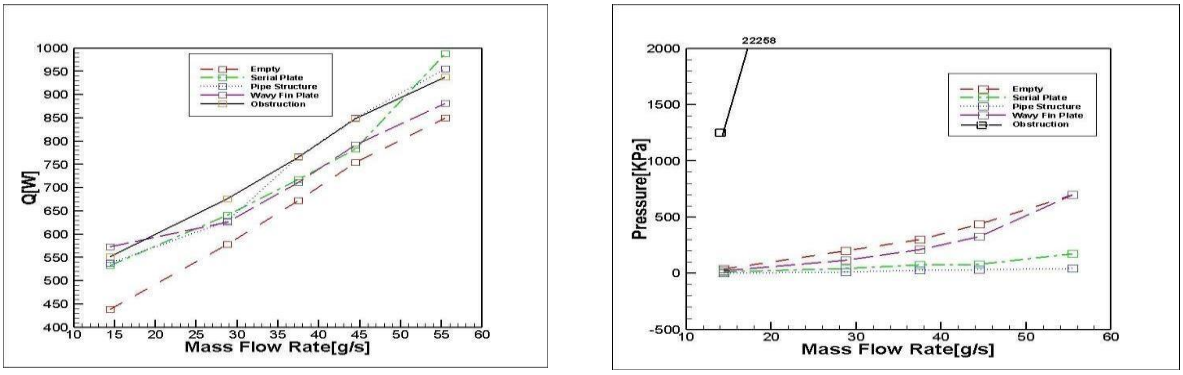


Figure 13. Comparison of five internal structures

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.

From figure 1, d; the wavy fin structure, characterized by a relatively simple geometry with fewer obstructions, our findings revealed a moderate heat release of 496 W. This was in line with our expectation that a simpler design would lead to moderate heat transfer. The pressure drop was also relatively low, amounting to 6.5 kPa, due to the structure's streamlined flow path. This aligned with our prediction of lower pressure drop compared to more complex configurations.

Figure 1, e; of the obstruction-type design, where exhaust followed a convoluted path through attenuation plates, our investigation unveiled a moderate heat extraction of 551 W, equivalent to 46.3% of the heat generated by the serial plate structure. This confirmed our prediction of heightened heat transfer due to increased gas interaction with the interior structure. However, the complex arrangement of attenuation plates resulted in a substantial pressure drop of 122 kPa, reflecting the anticipated pressure reduction due to intricate obstructions and increased heat transfer rates.

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.

4. FUTURE DIRECTIONS AND RESEARCH OPPORTUNITIES

- **Advancements in TEM development and characterization**

Transmission electron microscopy (TEM) has been a powerful tool for material characterization for many decades. In recent years, there have been several advancements in TEM development and characterization, which have expanded the capabilities of this technique. One of the most significant advancements in TEM development has been the development of aberration correctors. Aberration correctors can compensate for the spherical and chromatic aberrations that occur in TEMs, which can significantly improve the resolution and contrast of TEM images. Another important advancement inTEM development has been the development of in situ TEM techniques. In situ TEM allows researchers to observe materials in real-time as they are subjected to various stimuli, such as heat, pressure, or electric fields. This has enabled researchers to gain new insights into the behavior of materials under a variety of conditions. In addition to these advancements in TEM development, there have also been several advancements in TEM characterization techniques. For example, electron tomography can now be used to reconstruct 3D images of materials from TEM images. This has enabled researchers to study the 3D structure of materials in great detail.

- **Payback period and return on investment considerations**

The payback period and return on investment (ROI) of a TEM-based waste heat recovery system will vary depending on several factors, including the size of the system, the type of TEM used, the level of automation required, the cost of energy, and the amount of waste heat that can be recovered. However, in general, TEM-based waste heat recovery systems have a payback period of 3-5 years and an ROI of 10-20%. The payback period is the amount of time it takes for the energy savings from the system to offset the initial cost of the system. The ROI is the annual percentage of the initial cost of the system that is saved due to the energy savings. When considering the payback period and ROI of a TEM-based waste heat recovery system, it is important to consider all of the relevant costs and benefits. The costs include the initial cost of the system, the cost of operation and maintenance, and the cost of financing. The benefits include energy savings, the reduction in greenhouse gas emissions, and other environmental benefits.

It is also important to consider the risks associated with TEM-based waste heat recovery systems. The main risk is that the system may not perform as expected, which could lead to lower energy savings and a longer payback period. Overall, TEM-based waste heat recovery systems can be a cost-effective way to recover heat from waste streams and reduce energy consumption. However, it is important to carefully consider the costs, benefits, and risks of TEM-based waste heat recovery systems before deciding to install one.

Here are some tips for reducing the payback period and improving the ROI of a TEM-based waste heat recovery system

- Select the right size system for your needs. A system that is too large will be more expensive and will take longer to pay back.
- Choose a TEM that is specifically designed for waste heat recovery applications.
- Automate the system as much as possible to reduce operating costs.
- Consider financing options to reduce the upfront cost of the system.
- Properly maintain the system to ensure optimal performance.

By following these tips, you can maximize the benefits of a TEM-based waste heat recovery system reduce the payback period, and improve the ROI.

- **Energy savings estimation and environmental benefits**

  The energy savings that can be achieved with a TEM-based waste heat recovery system will vary depending on several factors, including the size of the system, the type of TEM used, the level of automation required, the cost of energy, and the amount of waste heat that can be recovered. However, in general, TEM-based waste heat recovery systems can achieve energy savings of 10-20%.

  For example, a TEM-based waste heat recovery system installed in a steel mill can recover heat from the waste gases produced during the steelmaking process. This heat can then be used to generate electricity or to heat other processes in the mill. A TEM-based waste heat recovery system installed in a power plant can recover heat from the exhaust gases of the power plant. This heat can then be used to generate more electricity or to heat buildings or other facilities. In addition to energy savings, TEM-based waste heat recovery systems can also provide several environmental benefits. By reducing the amount of waste heat that is released into the environment, TEM-based waste heat recovery systems can help to reduce air pollution and greenhouse gas emissions.

For example, a TEM-based waste heat recovery system installed in a cement plant can recover heat from the waste gases produced during the cement-making process. This heat can then be used to generate electricity or to heat other processes in the plant. Reducing the amount of waste heat released from the cement plant can help to reduce air pollution and greenhouse gas emissions. Overall, TEM-based waste heat recovery systems can provide several energy.

5.CONCLUSION

The numerical results suggest that the heat exchanger with the highest heat transfer rate has an excessively large pressure drop under the maximum power output condition. Therefore, there is a trade-off between heat transfer rate and pressure drop that needs to be considered when designing a heat exchanger for a TEG-based waste heat recovery system.This study highlights the importance of CFD modeling in designing and optimizing heat exchangers for TEG- based waste heat recovery systems. CFD modeling can be used to predict the heat transfer rate and pressure drop for different heat exchanger designs, which can help to identify the best design for a specific application.

Further research is needed to develop heat exchanger designs that can achieve high heat transfer rates while minimizing pressure drop. This will help to make TEG-based waste heat recovery systems more efficient and cost-effective.

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