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CFD Analysis of Exhaust Heat Exchangers in Automobile Thermoelectric Generators: A Review

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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

I. 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 See-Beck 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].

1.1 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.

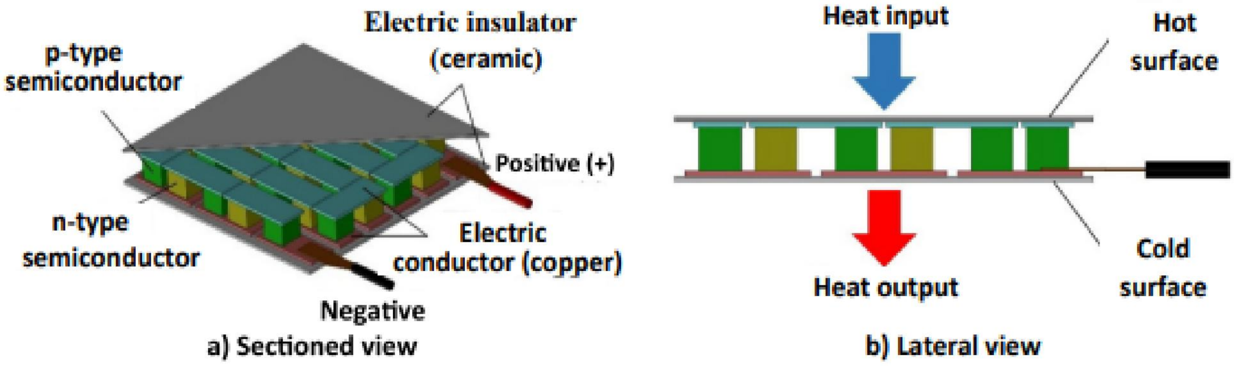

Figure 1 Thermo-electric module

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].

1.2 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.

1.3 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.

II. 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

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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.

III. EXPERIMENTATION AND 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].

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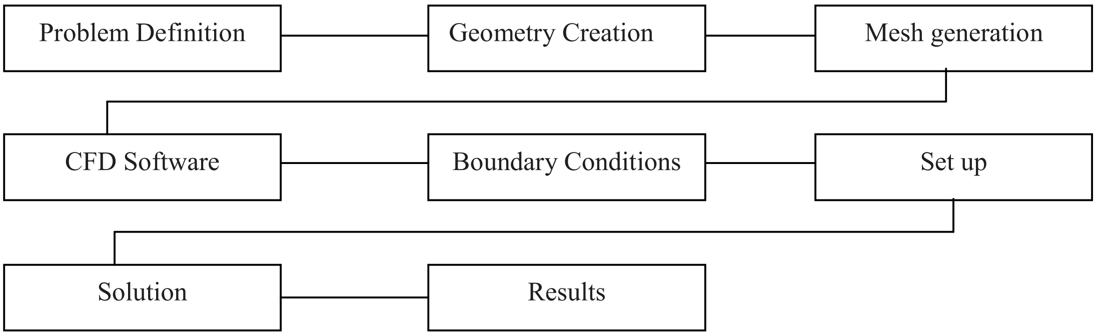

Problem Definition

Clearly define the objectives of your analysis, such as heat transfer efficiency, temperature distribution, or fluid flow behavior.

Introduction to Computational Fluid Dynamics (CFD):

Computational fluid dynamics (CFD) is a branch of engineering that exploits numerical methods and algorithms to simulate and analyze fluid flow and heat transfer phenomena. It plays a central role in understanding, predicting, and optimizing fluid behavior in various applications across industries. The CFD process typically includes several key steps:

- **Steps**: Create Geometry, Create Meshes, Define Configurations, Solve Governing equations, and interpret results.
- **Geometry**: The first step in CFD analysis is to create a virtual representation of the physical system, called geometry. This step involves identifying the boundaries, surfaces, and structures involved in the fluid flow. Accurate geometry is important for accurate simulation, and it can be created using specialized CAD (computer-aided design) software or directly in a CFD simulation environment.
- **Mesh:** Once the geometry is established, the next step is to create the mesh. Meshing involves dividing geometry into separate elements or cells, thereby creating a mesh. The quality of the mesh significantly affects the accuracy and efficiency of the simulation. Different meshing techniques, including structured, unstructured, and hybrid methods, are used depending on the complexity of the geometry and physics involved Setup: After meshing, the setup phase includes the determination of boundary conditions, initial conditions, and material properties.
- **Boundary conditions**: determine how the fluid interacts with the boundaries of the system. Initial conditions determine the initial state of the fluid, and material properties determine the behavior of the fluid under different conditions. This phase essentially prepares the virtual environment for the simulation.
- **Solution**: The focus of CFD lies in solving the equations that govern fluid dynamics, such as the Navier-Stokes equation. These equations describe the fundamentals that govern fluid flow, and their numerical solutions provide insight into the flow patterns, velocities, and pressures in the system. Numerical solvers, algorithms, and iterative methods are used to calculate the solution in discrete time steps.
- **Resul**t: The final step includes post-processing and interpretation of the results obtained from the simulation. Visualization tools help create contour diagrams, lines, and animations, providing a comprehensive understanding of fluid behavior. Engineers and researchers analyze these results to better understand system performance, identify potential problems, and optimize designs. Current discourse in this field.

3.1 Thermal performance analysis of TEM-based heat exchangers

Thermoelectric materials (TEMs) can be used to convert heat directly into electricity, making them a promising technology for waste heat recovery. TEM-based heat exchangers are particularly attractive for automotive applications, as they can be used to generate electricity from exhaust gas, which is a major source of waste heat in vehicles is a powerful tool that can be used to simulate the thermal performance of TEM-based heat exchangers. CFD simulations can be used to optimize the design of the heat exchanger and to predict its performance under different operating conditions.A recent study used CFD to investigate the thermal performance of an automobile thermoelectric generator's exhaust heat exchanger. The study found that the heat exchanger could generate a significant amount of electricity from the exhaust gas and that the performance of the heat exchanger was affected by several factors, including the design of the heat exchanger, the operating conditions, and the properties of the TEM material.The study also found that the CFD simulations were able to accurately predict the performance of the heat exchanger, which suggests that CFD can be used to design and optimize TEM-based heat exchangers for automotive applications.his work is to determine the heat transfer characteristics for a heat exchanger and the mass flow rates (only the hot fluid) in the inner tube at constant wall heat transfer coefficient to the surrounding. Analysis has been carried out for different structures of flow heat exchanger using ANSYS FLUENT software also the optimal conditions for heat transfer has been found based on Nusselt number and pumping power required, and the temperature and velocity contours at the outlets.The present work reviews existing exhaust heat exchangers and proposes several internal structures: an inclined plate, a parallel plate structure, a separate plate with holes, a serial plate structure, and a novel pipe structure. CFD models were developed with solid domains, liquid domains and fluid solid interfaces to compare the heat transfer and pressure drop for the 6 structures under the same working conditions. The numerical results suggest that the serial plate structure offers the highest heat transfer, while its pressure drop is excessively large under the maximum power output condition.

IV. FUTURE DIRECTIONS AND RESEARCH OPPORTUNITIES

4.1Advancements 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 in TEM 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.

4.2 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.

4.3 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 and environmental benefits. By recovering heat from waste streams, TEM-based waste heat recovery systems can help to reduce energy consumption, reduce air pollution, and reduce greenhouse gas emissions.

Here are some tips for estimating the energy savings and environmental benefits of a TEM-based waste heat recovery system:

- Identify the sources of waste heat in your facility.
- Determine the amount of heat that can be recovered from each source.
- Estimate the cost of energy.
- Estimate the reduction in air pollution and greenhouse gas emissions.

V. 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.

5.1 SUMMARY OF KEY FINDINGS

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 exchange configurations ranging from traditional setups to innovative structures introduced in the study. The examination commenced with the

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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 Fim Structure and the Obstruction-Type Design, both of which exhibited distinctive advantages. The Wavy Fin Structure offered a streamlined partlyvery 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 versatilityimpressive 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.

5.2 IMPLICATIONS FOR WASTE HEAT RECOVERY APPLICATIONS

The findings of a Computational Fluid Dynamics investigation of an automobile thermoelectric generator's exhaust heat exchanger have significant implications for waste heat recovery applications. By optimizing the design and performance of such heat exchangers, this research contributes to more efficient utilization of waste heat from automotive exhaust systems, thereby enhancing overall vehicle energy efficiency. This has the potential to reduce fuel consumption and greenhouse gas emissions, making it environmentally beneficial. Additionally, improved waste heat recovery can lead to enhanced thermal comfort and reduced wear and tear on vehicle components, ultimately impacting both sustainability and the operational costs of automobiles. Furthermore, advancements in this field may have broader applications in various industrial and renewable energy sectors, contributing to more sustainable and energy-efficient systems.

5.3 RECOMMENDATIONS FOR FUTURE RESEARCH AND DEVELOPMENT

The CFD investigation of the automobile thermoelectric generator (TEG) exhaust heat exchanger has several implications for waste heat recovery applications. First, the results show that the heat transfer rate between the exhaust gas and the thermoelectric modules can be improved by increasing the exhaust gas flow rate and temperature. This is important for waste heat recovery applications, where the exhaust gas temperature is typically relatively low. Second, the results show that the heat transfer rate can also be improved by increasing the thickness of the thermoelectric modules. However, this will also increase the weight and cost of the heat exchanger. Therefore, a trade-off must be made between heat transfer performance and cost. Third, the results show that the heat transfer rate decreases with increasing spacing between the thermoelectric modules. This is because the spacing between the thermoelectric modules creates a thermal resistance that inhibits heat transfer. Therefore, it is important to minimize the spacing between the thermoelectric modules to maximize heat transfer. Overall, the CFD investigation of the TEG exhaust heat exchanger provides valuable insights into the factors that affect heat transfer performance.

REFERENCES

[1]. Wahile, G. S., Malwe, P. D., & Kolhe, A. V. (2020). Waste heat recovery from the exhaust gas of an engine by using a phase change material. Materials Today: Proceedings, 28, 2101-2107.

[2]. 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.

DOI: 10.48175/IJARSCT-13143

[3]. Hilmin, M. N. H. M., Remeli, M. F., Singh, B., & Affandi, N. D. N. (2020). Thermoelectric power generation from vehicle exhaust gas with TiO2 nanofluid cooling. Thermal Science and Engineering Progress, 18, 100558.

[4]. He, M., Wang, E., Zhang, Y., Zhang, W., Zhang, F., & Zhao, C. (2020). Performance analysis of a multilayer thermoelectric generator for exhaust heat recovery of a heavy-duty diesel engine. Applied Energy, 274, 115298.

[5]. Su, C. Q., Wang, W. S., Liu, X., & Deng, Y. D. (2014). Simulation and experimental study on thermal optimization of the heat exchanger for automotive exhaust-based thermoelectric generators. Case Studies in Thermal Engineering, 4, 85-91.

[6]. Patil, D. S., Arakerimath, R. R., & Walke, P. V. (2018). Thermoelectric materials and heat exchangers for power generation–A review. Renewable and Sustainable Energy Reviews, 95, 1-22.

[7]. Huang, K., Li, B., Yan, Y., Li, Y., Twaha, S., & Zhu, J. (2017). A comprehensive study on a novel concentric cylindrical thermoelectric power generation system. Applied Thermal Engineering, 117, 501-510.

[8]. Ezzitouni, S., Fernández-Yáñez, P., Sánchez, L., & Armas, O. (2020). Global energy balance in a diesel engine with a thermoelectric generator. Applied Energy, 269, 115139.

[9]. BHUİYAN, M. R. A., MAMUR, H., ÜSTÜNER, M. A., & DİLMAÇ, Ö. F. (2022). Current and future trend opportunities of thermoelectric generator applications in waste heat recovery. Gazi University Journal of Science, 1-1

[10]. Tariq, H., Sajjad, R., Khan, M. Z. U., Ghachem, K., Ammar, A., Khan, S. U., &Kolsi, L. (2023). Effective waste heat recovery from engine exhaust using fin prolonged heat exchanger with graphene oxide nanoparticles. Journal of the Indian Chemical Society, 100(2), 100911.

[11]. Luo, D., Wang, R., Yu, W., Sun, Z., & Meng, X. (2019). Modeling and simulation study of a converging thermoelectric generator for engine waste heat recovery. Applied Thermal Engineering, 153, 837-847.

[12]. Bejjam, R. B., Dabot, M., Wondatir, T., & Negash, S. (2021). Performance evaluation of thermoelectric generator using CFD. Materials Today: Proceedings, 47, 2498-2504.

[13]. 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.

[14]. 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.

[15]. 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.

[16]. 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.

[17]. 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.

[18]. Liu, C., Deng, Y. D., Wang, X. Y., Liu, X., Wang, Y. P., & Su, C. Q. (2016). Multi-objective optimization of heat exchanger in an automotive exhaust thermoelectric generator. Applied Thermal Engineering, 108, 916-926.

[19]. Jaziri, N., Boughamoura, A., Müller, J., Tounsi, F., Mezghani, B., & Kouki, A. (2019, April). TC connectivities effect investigation in the LTCC-based thermoelectric generator for automotive waste heat recovery. In 2019 IEEE International Conference on Design & Test of Integrated Micro & Nano-Systems (DTS) (pp. 1-5). IEEE.

[20]. Hatami, M., Jafaryar, M., Ganji, D. D., & Gorji-Bandpy, M. (2014). Optimization of finned-tube heat exchangers for diesel exhaust waste heat recovery using CFD and CCD techniques. International Communications in Heat and Mass Transfer, 57, 254-263.

[21]. Ramos, J., Chong, A., &Jouhara, H. (2016). Experimental and numerical investigation of a cross flow air-to-water heat pipe-based heat exchanger used in waste heat recovery. International Journal of Heat and Mass Transfer, 102, 1267-1281.

[22]. Park, S., Woo, S., Shon, J., & Lee, K. (2017). Experimental study on heat storage system using phase-change material in a diesel engine. Energy, 119, 1108-1118.

[23]. TEG, T. Validation and Numerical Assessment of a Temperature-Controlled Thermoelectric Generator Concept aimed at Maximizing Performance under Highly Variable Thermal Load Driving Cycles.

[24]. 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.

[25]. 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.