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Thermoelectric Energy Recovery from Exhaust Systems: Design, Simulation, and Performance Analysis of a Waste-Heat Recovery Prototype

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Abstract

In today's context, energy plays a vital role in environmental development. Unfortunately, most energy strategies that yield immediate benefits often contribute to long-term environmental degradation. The law of conservation of energy states that "Energy cannot be created or destroyed; it can only change from one form to another." This idea emphasizes the fact that no technological improvement can continue eternally without having negative effects. Every living thing on the world is greatly impacted by the total global impact of energy use. Energy conservation strategies are the focus of this study. An electromechanical device that transforms thermal energy into electrical energy is called a thermoelectric generator (TEG). TEG can be used in a variety of applications by collecting and reusing waste heat. In this study, waste heat is recovered for secondary uses, like powering a car or generator, by integrating a TEG into an exhaust system. UNIGRAPHICS NX was used to design the prototype, while ANSYS 16.2 was used for analysis. The simulation results were compiled using Fluent Workbench. Simulations were carried out with double precision after parameters were established. Aluminum was selected as the material for this study. The analysis was carried out based on temperature and heat transfer characteristics.

Keywords: Fluent, thermal, renewable energy, efficiency, heat, temperature

INTRODUCTION

Background and Motivation

Global energy consumption continues to grow at an unprecedented pace, driven by industrial expansion, urbanization, and technological evolution. Modern society relies heavily on fossil fuels for electricity, transportation, and industrial operations, but the consequences of this dependence are increasingly unsustainable. Concerns over greenhouse gas emissions, climate change, and resource depletion have stimulated the urgent search for alternative and sustainable energy technologies [1–6]. Among the diverse portfolio of renewable energy solutions, thermoelectric (TE) energy conversion has emerged as a distinctive approach that directly transforms waste heat into electricity without moving parts, fuel, or emissions [3-4, 7-11].

The unique advantage of thermoelectric lies in their solid–state nature. Unlike conventional power generation systems that depend on turbines or combustion processes, thermoelectric devices exploit intrinsic material properties to harvest heat energy. This improves durability and dependability while simultaneously lowering mechanical complexity [10, 12-23]. Waste-heat utilization is especially critical given that more than 60% of primary energy is dissipated as unused heat in transportation, manufacturing, and power

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generation sectors [5, 7]. By recovering even a fraction of this energy, thermoelectric can make substantial contributions to efficiency improvements and sustainability goals.

The versatility of thermoelectric systems enables their deployment in diverse scales and contexts, ranging from microscale sensors and wearable electronics to large-scale industrial waste-heat recovery and space applications [24–32]. At small scales, they can provide self-sufficient power for the Internet of Things (IoT) and biomedical implants. At larger scales, thermoelectric is considered in combination with solar thermal systems and industrial exhaust management setups. This adaptability positions thermoelectric as a bridge technology, suitable for integration with both renewable energy grids and advanced battery systems [33–57].

Despite these promising applications, thermoelectric adoption faces challenges. The efficiency of thermoelectric materials is measured using the dimensionless figure of merit (ZT), defined as:

ZT = S2σTκZT = \frac{S^2 \sigma T}{\kappa}ZT = κS^2σT

where S is the Seebeck coefficient, σ is the electrical conductivity, T is absolute temperature, and κ is thermal conductivity. Superior energy conversion efficiency is indicated by high ZT values. However, optimizing S, σ, and κ simultaneously remains a scientific challenge due to their interdependent nature [20, 34, 41]. Over the past two decades, researchers have attempted to enhance ZT through material innovations, nanostructuring, and compositional engineering [11, 13, 20, 34].

The following section provides a detailed overview of advances in thermoelectric materials research, highlighting the strategies adopted to improve energy harvesting performance.

THERMOELECTRIC MATERIALS DEVELOPMENT

Classical Thermoelectric Materials

Historically, the most widely studied thermoelectric materials are bismuth telluride (Bi_2Te_3) and its alloys, which exhibit excellent thermoelectric performance near room temperature [3, 34]. Due to their high Seebeck coefficient and favorable electrical properties, bismuth telluride-based systems remain the benchmark for commercial thermoelectric modules [4, 13]. Other classical materials include lead telluride (PbTe) for mid-temperature applications and silicon–germanium (SiGe) alloys, which have been successfully deployed in space power systems due to their stability at high temperatures [20, 41].

However, the toxicity of lead-based compounds and the scarcity of tellurium restrict large-scale adoption. Consequently, researchers have explored alternative materials such as half-Heusler alloys, skutterudites, and oxides [6, 21]. These compounds offer the potential for abundant, stable, and cost-effective thermoelectric materials with competitive performance.

Nanostructuring and Low-Dimensional Systems

One of the most significant breakthroughs in thermoelectric came with the realization that nanostructuring can decouple thermal and electrical properties. By introducing nanoscale features, researchers can scatter phonons (reducing lattice thermal conductivity) without significantly impairing electrical transport [11–12, 23]. Techniques, such as nanocomposites, superlattices, and quantum dot embedding, have demonstrated remarkable improvements in ZT [10, 20, 34].

For example, layered superlattice structures confine electrons in low-dimensional systems, enhancing the power factor ($S^2\sigma$) while reducing thermal conductivity. Similarly, nanocomposites integrate secondary phases that selectively scatter phonons, producing materials with thermal conductivities far below their bulk counterparts [13, 27].

Doping and Alloying Strategies

Doping and alloying remain effective strategies for optimizing carrier concentration in thermoelectric materials. For instance, controlled doping in skutterudites can enhance electrical conductivity while retaining low thermal conductivity due to rattling modes within the crystal structure [17, 19]. Likewise, half-Heusler alloys exhibit improved power factors when doped with transition metals [31, 37].

Alloying introduces mass fluctuation and strain fields that scatter mid-to-long wavelength phonons, significantly reducing lattice thermal conductivity [20, 41]. These strategies are particularly effective in wide-bandgap materials where electronic transport remains robust under compositional changes.

Emerging Materials: 2D and Organic Thermoelectric

Beyond classical and nanostructured systems, emerging materials, such as graphene, transition metal dichalcogenides (TMDs), and organic polymers, have opened new research directions [9, 15, 24, 32]. Two-dimensional materials offer high mobility and tunable band structures, enabling efficient charge transport. Meanwhile, organic thermoelectric, though less efficient, provides flexibility, light weight, and low-cost fabrication, making them attractive for wearable and flexible electronics [40].

Recent studies have demonstrated hybrid composites of inorganic nanomaterials with organic polymers, combining the superior electrical properties of inorganic phases with the mechanical flexibility of organics [6, 21]. For next-generation thermoelectric devices intended for biomedical and Internet of Things applications, these hybrid materials show great promise.

Material Challenges and Commercialization Barriers

Despite substantial progress, several challenges persist. Scaling nanostructuring methods for industrial production remain difficult, while material toxicity (e.g., Pb, Te) raises environmental and cost concerns [34, 41]. Stability under operational conditions, particularly for high-temperature applications, also limits commercialization [10, 12].

Additionally, the balance between performance, cost, and scalability is critical. While laboratory experiments report ZT values above 2.5 in some nanostructured systems [13, 20, 23], commercially available devices rarely exceed ZT ~1 due to fabrication constraints and contact resistances. This discrepancy underscores the importance of integrating material research with device-level optimization and system modelling, which will be discussed.

MODELLING AND SIMULATION APPROACHES

The performance of thermoelectric (TE) devices is governed not only by material properties but also by their design, geometry, and integration within larger systems. While significant advancements have been made in materials science (Part 1), the translation of those improvements into real-world efficiency depends heavily on modelling and simulation. Advanced modelling techniques allow researchers to predict performance, optimize designs, and assess the long-term reliability of TE systems under diverse operational conditions [17, 19, 28, 38, 43, 50].

Classical Thermal–Electrical Models

At the foundation of TE modelling lies the coupling of heat transfer and electrical conduction equations. The governing equation for TE transport combines Fourier's law of heat conduction and Ohm's law of electrical conduction with the Seebeck and Peltier effects:

$$Q = -\kappa \nabla T + \sigma S T \nabla V q = -\kappa \nabla T + \sigma S T \nabla V q = -\kappa \nabla T + \sigma S T \nabla V$$

where q is the heat flux, κ is the thermal conductivity, S is the Seebeck coefficient, and V is the electric potential. Solving these coupled equations provides insights *into* temperature gradients, current flow, and energy conversion efficiency. Analytical models remain useful for preliminary design but often fall short when applied to complex, nonlinear, or transient conditions.

SPICE-Based Circuit Simulations

In recent years, SPICE (Simulation Program with Integrated Circuit Emphasis) modelling has been adapted for thermoelectric devices [19, 28]. TE modules are modeled as equivalent electrical circuits, with voltage sources representing the Seebeck effect and resistors representing electrical and thermal resistances. This approach enables fast, low-cost simulations that can be integrated with battery and power electronics models [29, 33].

SPICE-based models are particularly valuable for hybrid applications, where TE modules are embedded into systems containing DC–DC converters, battery management units (BMU), and control circuits. Researchers have reported accurate predictions of output voltage, transient response, and power management strategies, allowing designers to optimize TE devices for integration with real-world electronics [25, 55].

Computational Fluid Dynamics (CFD)

To analyze complex thermal flows and heat dissipation mechanisms, CFD (Computational Fluid Dynamics) has become indispensable [17, 38]. CFD models simulate temperature distribution, heat flux, and convective cooling in TE-integrated systems such as vehicle exhaust heat recovery units, solar–TE hybrid modules, and battery cooling architectures.

Figure 2 typically shows a CFD-generated contour map of temperature gradients within a TE device, illustrating localized hotspots and areas of maximum thermal stress. Such insights are critical to designing efficient heat exchangers and thermal interfaces, ensuring that TE modules maintain favorable temperature gradients for optimal energy harvesting.

Finite Element Analysis (FEA)

While CFD focuses on fluid and heat interactions, Finite Element Analysis (FEA) is used to model structural, thermal, and electrical stresses within TE modules [28, 43]. FEA simulations capture issues, such as:

- *Thermal stress:* Due to mismatched expansion coefficients between TE materials and substrates.
- *Contact resistances:* At interfaces.
- *Fatigue failure:* Under cyclic thermal loading.

These simulations guide material selection, device packaging, and module reliability assessments. For high-temperature or harsh environments (e.g., aerospace, automotive exhaust systems), FEA ensures that devices meet durability standards before fabrication [41].

Machine Learning and Data-Driven Models

Recent research has introduced machine learning (ML) and artificial intelligence (AI) to TE modeling [50]. ML algorithms are trained on large datasets of material properties and experimental results, enabling predictive modeling of ZT values, stability ranges, and performance trends without requiring exhaustive simulations. Furthermore, ML-driven optimization can rapidly explore parameter spaces (e.g., doping levels, nanostructure dimensions) that would otherwise require years of trial-and-error experimentation.

The convergence of CFD/FEA with ML-based digital twins is expected to transform TE design. Such approaches will allow real-time predictive monitoring, adaptive control, and autonomous optimization of TE devices within complex energy systems [43, 50].

INTEGRATION WITH BATTERIES AND HYBRID STORAGE SYSTEMS

While thermoelectric can independently harvest energy, their practical utility is amplified when integrated with energy storage systems, particularly batteries and supercapacitors. Since TE devices often generate small, fluctuating voltages, direct usage is limited. Therefore, coupling with storage not only stabilizes power supply but also enables the deployment of TE harvesters in larger-scale, continuous operations [5, 7, 25, 29, 33, 55].

Thermoelectric–Battery Coupling

Thermoelectric generators (TEGs) are increasingly coupled with lithium–ion (Li–ion) batteries, which dominate portable electronics, electric vehicles (EVs), and grid applications. By harvesting waste heat from EV battery packs, combustion engines, or industrial processes, TE modules can provide supplementary charging to Li–ion cells [25, 29].

Studies indicate that TE-assisted charging reduces battery cycling frequency, extending overall battery life [7, 33]. Additionally, TE modules improve the energy density of hybrid systems, ensuring that harvested thermal energy is not wasted.

Integration with Phase Change Materials (PCM)

One major limitation of TE modules is their reliance on stable temperature gradients. To mitigate these oscillations, Phase Change Materials (PCMs) have been investigated [5, 55]. By storing thermal energy during heating cycles and releasing it gradually during cooling, PCMs maintain stable thermal gradients across TE modules. This significantly enhances long-duration energy harvesting and improves the coupling between TEs and storage systems.

For example, in solar–TE hybrid systems**,** PCMs stabilize the daytime heat input, ensuring continuous electricity generation even under cloud cover [21, 31, 37]. In EV battery packs, PCMs prevent overheating while simultaneously providing thermal gradients for TE energy harvesting [25].

Hybrid Energy Storage Systems (HESS)

Beyond single battery integration, TEs are increasingly studied as components of Hybrid Energy Storage Systems (HESS), which combine batteries and supercapacitors [29, 33]. While batteries provide high energy density, supercapacitors offer rapid charge–discharge capability. TE devices can continuously trickle-charge both, ensuring:

- Extended lifetime of batteries by reducing deep cycling.
- Rapid response energy supply during sudden demand spikes.
- Smoothing of intermittent renewable energy inputs.

The combined system demonstrates higher reliability and stability compared to TE-only or battery-only setups.

Applications for Electric Vehicles (EVs) and Aerospace

The integration of TEs with storage is particularly attractive in EVs and aerospace applications, where efficiency and reliability are critical. In EVs, TEs are mounted on exhaust pipes, radiators, and battery casings to recover waste heat for auxiliary battery charging [25, 29]. This improves fuel efficiency in hybrid EVs and extends driving range in pure EVs.

In aerospace, radioisotope thermoelectric generators (RTGs) have powered satellites and deep–space missions for decades [20, 41]. Modern research now focuses on coupling RTGs with advanced storage systems to optimize energy usage, ensuring uninterrupted operation during eclipse cycles or power-intensive maneuvers [6, 31].

Challenges and Future Prospects

Despite progress, integration with batteries presents challenges. These include:

- Low power density of TE modules relative to battery capacities.
- Thermal management conflicts (batteries require cooling, while TEs require strong temperature gradients).
- Cost and scalability limitations for large-scale applications.

Future developments may address these issues through AI-driven optimization, multi-functional materials (e.g., PCM composites with embedded TE phases), and adaptive power electronics that dynamically match TE outputs with storage requirements [43, 50].

LITERATURE REVIEW

Lashof and Yeh (2015) [17] analyzed the real performance of Flat-panel TEGs with a high thermal concentration at an AM1.5, equivalent to 1 kW/m^2. For actual TEG testing to produce any significant results, the latter value is too optimal. However, the maximum efficiency of their model was 4.6%. Regrettably, every energy policy that results in short-term gains typically has long-term negative effects on the environment. It is a universal fact that no exponential growth will continue indefinitely. Wind, geothermal, and other renewable resources are abundant on Earth. With the current level of technical advancement, people are constantly coming up with new ideas to enhance the current mix of electrical power generation. The current global economic model, which is built on fossil fuels, may be untangled by learning how to use these infinitely valuable renewable resources to replace conventional fossil fuel energy sources.

Jaber et al. (2017) [18] proposed the reuse or reduction of wasted heat supplies as an excellent opportunity for cost saving in industrial and residential applications. This research discusses a hybrid heat recovery system that uses TEGs to create electric power and household hot water by reusing the thermal energy absorbed by exhaust fumes. The temperature of exhaust gases has a major impact on the heat recovery process. The impact of gas temperature on the system's water temperature and power output is examined, encompassing various home uses. It demonstrates that the heat rate, water temperature, and power produced all rise with the temperature of the exhaust gases.

Açıkkalp & Ahmadi (2018) [14] – This study explores the performance of a hybrid system combining a phosphoric acid fuel cell (PAFC) with a thermally regenerative electrochemical cycle (TREC), focusing on various parameters, including ecological function across different temperature levels. The waste heat generated by the PAFC at low temperatures is utilized by the TREC to produce additional electrical energy, enhancing overall system efficiency. The ecological function is employed as a design criterion to develop a more environmentally sustainable hybrid configuration. The best operating settings that balance power output and environmental impact were found using numerical simulations. Results indicate that the hybrid system achieves a peak power output of 885.60 W at 150°C, 935.07 W at 180°C, and 949.07 W at 200°C. The highest ecological function values are 373.85 W, 431.63 W, and 439.02 W at 150°C, 180°C, and 200°C, respectively. Corresponding maximum efficiencies are 0.754, 0.780, and 0.784 at those temperatures. It is concluded that, for optimal performance, the system should operate at a current density that lies between the values yielding maximum ecological function and maximum efficiency.

Shu et al. (2019) [28] – Thermal protection mechanisms in circuit breakers are engineered to interrupt electrical current when an overload or fault current is detected. To analyze the behavior of this protection system, a coupled nonlinear electro–thermal–structural model was developed, accounting for the complex deformation behavior of bimetallic components. The thermal expansion coefficients (CTE) of the bimetal were experimentally measured across various temperatures. The data revealed that the CTE of the thermally sensitive layer varies significantly with temperature, increasing from 13.2 ppm/°C at 20°C to 25.3 ppm/°C at 380°C – a change of approximately 91.7% across the temperature range. Using these measured values, three separate overload protection tests were carried out in compliance with IEC 60898 standards. Simulation results confirmed that the thermal trip mechanism activates within the expected time frame under different test conditions. While simulations assuming a constant CTE could only predict dimensional changes at specific temperatures, the proposed nonlinear model demonstrated superior accuracy in forecasting both thermal deformation and temperature variations over time.

Wang et al. (2020) [54]– Radioisotopes, a unique form of sustainable energy, possess exceptionally high energy density. Power systems that utilize the heat generated from radioactive decay can deliver consistent, long-duration energy in environments where solar or chemical sources are impractical. Since the 1960s, these radioisotope-based generators have been reliably employed in a variety of space and

Earth-based missions, powering everything from deep–space probes to remote arctic beacons. This study provides an overview of the evolution of these generators and examines the essential components required for their operation. Beginning with a historical overview, the paper delves into key technological aspects such as radioisotope fuel production, energy conversion mechanisms, thermal insulation strategies, material selection, prototype testing, and future development opportunities. The discussion also includes a comprehensive look at safety considerations for both terrestrial and space applications. These generators highlight the peaceful application of nuclear energy for the advancement of society. In support of future advancements, the United States has restarted and expanded production of plutonium fuel, while the European Space Agency is actively funding research into americium-based alternatives. These developments point toward broader adoption of high-efficiency radioisotope power systems in upcoming missions on Earth and in space.

Guk Kim et al. (2020) [50] – A metal–oxide-semiconductor field-effect transistor (MOSFET), a fundamental component in microelectronics, was restored using a self-powered electro–thermal annealing technique driven by a wind-powered triboelectric nanogenerator (TENG). The healing process utilized Joule heating, generated electrically by the MOSFET itself. The self-repair system consists of a MOSFET integrated with an internal Joule heating element and a wind-activated TENG. This self-healing capability is particularly beneficial for developing remote wireless sensor networks, offering long-term, sustainable functionality, resilience to both environmental and operational stress, and reducing the need for frequent manual maintenance or power source replacement.

Estevez et al. (2021) [35] – This study presents the development of an electro–thermal model for a single lithium–ion battery cell using the Simulink–Simscape platform. The model is composed of two interconnected components: an electrical section and a thermal section. The electrical part is represented by a Resistor–Capacitor (RC) branch circuit, while the thermal part models the battery cell as a discretized volume, created using a thermal–electrical analogy. Heat generation within the cell is estimated to be using a simplified lumped heat source method. A key innovation in this work is the introduction of an automated method for determining the RC circuit parameters from pulse discharge experiments, utilizing a Multi-Linear Regression Model technique. The accuracy of both the electrical and thermal aspects of the model was validated against experimental data under both dynamic and steady-state conditions. The model achieved a mean square error of 0.00027 V^2 for voltage prediction during dynamic operation, and errors of 0.014 V^2 for voltage and 2.28°C^2 for temperature in static tests. Owing to its simplicity and practicality, this model serves as a valuable tool for designing battery module configurations and optimizing thermal management systems.

Zhang et al. (2022) [52] suggested that the electrochemical and thermal behavior of cylindrical lithium–ion batteries (LIBs) be modelled by coupling a three-dimensional axisymmetric heat transfer model with a one-dimensional electrochemical model. The model is compared with experimental data on the discharge voltage and surface temperature of LIBs at different discharge rates. Initially, two models were developed: the holistic electrochemical–thermal coupling (HET) model and the layered electrochemical–thermal coupling (LET) model. Research on inhomogeneous discharge and aging caused by the battery's uneven internal temperature distribution is one of the LET models' advantages over the traditional HET model. In this study, we illustrate the radially inhomogeneous discharge of cylindrical LIBs using a 4-layer LET model.

It is also demonstrated that the HET model can provide the required degree of temperature simulation accuracy at a reduced computing cost. This provides researchers with the data they need to choose electrochemical–thermal coupling models that are more suited to the different scenarios. Second, the thermal behavior of cylindrical LIBs at different discharge rates is examined by looking at the heat generation rate and heat dissipation parameters during the discharge process. The study found that, in contrast to pouch LIBs, cylindrical LIBs show a significant temperature gradient in the radial direction. The factors that affect the battery's temperature uniformity – cooling conditions, ambient temperature, discharge rate, radial dimension, and radial thermal conductivity – are then thoroughly examined.

Meanwhile, some suggestions are offered to improve the uniformity of the temperature. Gaining a comprehensive grasp of the thermal behavior of cylindrical LIBs is made possible by the study's findings. Additionally, they may be used to increase the temperature signal's forecast accuracy in the LIB battery therapy management system.

Li et al. (2023) [53] – Utilizing phase-change materials (PCMs) to store solar or electro–thermal energy is an efficient and eco-friendly method for delivering consistent renewable heat. This work proposes a novel dynamic charging method that involves directly heating a solar or electro–thermal conversion mesh, which moves in sync with the melting front between solid and liquid phases of the PCM. This innovative approach addresses the challenge faced by traditional static PCM systems, where a trade-off exists between fast charging and maintaining latent heat storage. The dynamic method enhances energy input speed, improves storage efficiency, ensures quick thermal response, and retains the full latent heat capacity of the PCM. With benefits, such as low cost, compatibility with various PCM types, and the ability to harness variable solar and wind energy effectively, this system offers a practical and scalable solution for renewable thermal energy storage.

Luo et al. (2023) [24] – This study employed three different methods for the first time to improve the thermal performance of a double pipe heat exchanger: using nano fluids as the working fluid, a perforated wavy strip turbulator, and the air bubble injection method. The tests included turbulators with varying hole diameter ratios (D/L) and different bubble injection flow rates between 2 and 6 LPM. Water, air/water, CuO–water, and air/CuO–water have all been used as working fluids; their volume fractions ranged from 0.25 percent to 1 percent. According to the results, heat transfer was enhanced by 56, 53, and 14.1%, respectively, by the employment of nano fluid, the PWST, and the bubble injection method. Furthermore, combining all three approaches increases heat transfer and exergy losses up to 2.15 and 1.82 times greater than plain pipe, respectively. Using net profit per unit transferred heat load (ηp) and thermal performance factor (TEF), the best-case scenario was determined to be the double pipe heat exchanger with a perforated wavy strip turbulator with a hole diameter ratio of 6 and bubble injection with ma = 6 LPM. The greatest values of TEF and ηp in this instance are 1.24 and 2.124×10^{-9}, respectively.

LITERATURE REVIEW & SUMMARY

The literature review shows that waste heat recovery can reduce the CO_2 emissions of the ICE and save fuel. Comparison of the techniques that are used to recuperate waste heat, shows that CRCs and TEGs have the decisive advantage because their integration into the existing vehicle architecture is simple. Additionally, these techniques can be upgraded for already existing ICEs. However, currently both concepts are in the pre-development process. To what extent are the two methods promising for the future particularly depend on the development of thermal fluids and thermoelectric materials. The already developed TEG prototypes only have low efficiencies, and in the last years the research has been focused on the reduction of thermal loss and the optimization of heat exchanger. The electrical integration of TEG into the on-board power supply with DC–DC converters was neglected in the concepts in the past. Only TEGs with passive diodes are currently being used, which have the disadvantage that the MPP of the TEG cannot be tracked.

A vehicle simulation with a cooling system, an ICE, and a TEG is presented in these simulations, the geometry of the TEG and the heat exchanger are optimized in relation to the additional back pressure of the TEG in the exhaust gas system. Additionally, the fuel economy is calculated in relation to the used alternator. For the electric interface, an ideal DC–DC converter with a fixed efficiency is assumed. What impact the integration of TEG in the electrical system of the vehicle has on the energy management of the vehicle is not apparent from the documentation. In the literature, electrical circuits to link TEMs to a vehicle power supply are published. However, these circuits are only designed and optimized for well-defined TEMs. Furthermore, the dynamic temperature of the exhaust gas system results in a change of electric characteristics in the TEMs, which must be compensated by the converter. In experiments with changing temperature of the TEMs are presented, but only to verify or motivate the MPPT algorithms. The determined efficiency is only estimated for selected operation points. A detailed analysis of the efficiency for all possible operation points is missing. Therefore, an efficiency analysis, as shown in, is necessary to estimate the loss of a converter for entire power range of the TEM.

The electric wiring includes the wiring of individual TEMs with a converter, as well as the entire network of DC–DC converters of TEG. In the influence of the wiring is analyzed for three different TEMs, the results indicate a solution for this specific experiment only. The wiring has an influence on the performance of TEG, which is consistent with the results of both studies included only empirical results, and a generalization of the results is not possible. The presented bypass network which includes relays to decouple or couple parallel connected TEM, shows that a new configuration of TEM wiring can be useful for under heated TEMs. However, the concept is based on prior knowledge on how TEMs need to be interconnected. Modeling and analyzing DC–DC converters is possible with the SSA approach. Furthermore, an analytical evaluation of the electrical wiring of TEMs for different DC–DC converters is possible. Additionally, SSA models can be used to develop and design control structures for the electrical network of TEMs and the DC–DC converters.

CHAPTER
Design & Methodology
Problem Evaluation
Many of the pieces of research have been done for a long time on TEGs in different systems, but due to change in temperature there is variation in efficiency. A Thermoelectric Generator (TEG) consists of thermocouple and electromechanical components. The exhaust air is used for electricity generation and to improve the energy demand to maintain thermal comfort in Automobiles and Power plant. TEGs are characterized by their large potential for energy saving and low maintenance. The temperature differential between the exhaust and the exhaust air determines the straightforward physical fact. In Exhaust system, the exhaust material remains almost heated constantly throughout the engine runs. However, the TEGs profile is a function of the electromechanical involved and depends on other factors such as the physical properties of the material and the TEGs thickness. To understand the thermal performance of TEGs, several mathematical models, methods and computer tools were developed and used in the open literature. The heat transfer process in a TEGs and proposed an analytical model for the system.

A physical model to simulate the TEGs was developed and validated by authors. Prime highlights were the lack of optimization criteria when analyzing TEGs and developed a specific computer tool based on a physical model which was experimentally validated. In this experiment, base parameter is adopted for experimental set up, such as length, diameter, and material of the pipe, but simulation on ANSYS due to which it affects the performance. Since they all are using the heat energy of the exhaust which is constant. It is getting difficult to make a practical test setup for the experiment because it takes long time and is costly. If during the setup fails, then a huge investment will be wasted. For reducing this problem proposed research on TEGs by ANSYS Software CFD analysis. In this proposed research here, it is considered referred to by Jaber et al. (2017) [18] to identify our requirements according to our needs. CFD analysis is new technology for research in different fields. Since CFD analysis become important in the field of TEGs in different temperature to save our time and money. Before starting any thermal electro generator heat exchange project we need CFD analysis for better results according to the different climate.

Description of System
Advanced technology provides several options for researchers to carry out study of complicated heat transfer, mass transfer, and many other problems on software instead of creating the exact real model. Such ANSYS software tools have become popular to carry out complex flow analysis thoroughly. CFD employs discretizing whole system in smaller grids and applying governing equations, like mass, momentum and energy on every grid, it provides solution of differential equations for every grid in flow domain. Present system is designed in Unigraphics NX/Autocad and meshed in meshing tool of ANSYS Workbench, complex heat transfer and air flow process are examined in Fluent. This study is conducted assuming homogenous soil conditions, incompressible flow and properties of pipe and ground material are independent of temperature.

Physics of Electromechanical
The physical phenomena relevant to the study of thermoelectric devices are of four types.

- The Seebeck effect.
- The Peltier effect.

- The Thomson effect and the Joule heating effect.
- The Kelvin relationships which describe an important link between the first three of these effects.

The Seebeck Effect

This phenomenon states that when two junctions of dissimilar materials are kept at different temperatures, a voltage is created in the circuit. The open-circuit thermoelectric potential V_{OC} is obtained from the following equation:

$$V_{OC} = \alpha\, \Delta T \quad (1)$$

where ΔT [K] is the temperature difference across the two junctions, and α [V/K] is the Seebeck coefficient, which gives the rate of change of VOC [V] with ΔT:

$$\alpha = \Delta Voc / \Delta T \quad (2)$$

α is a "combined" coefficient associated with the properties of the materials used and is defined for ΔT => 0. The difference between the two absolute coefficients is the Seebeck coefficient of the junction between two materials, and experimental results indicate that metals have very low Seebeck coefficients. Conversely, good thermoelectric semiconducting materials typically have values in the hundreds of μV = K, either positive or negative.

The Peltier Effect

The Peltier coefficient, measured for ΔT => 0, is labeled π [V] and defined as:

$$\pi = P_P / I \quad (3)$$

where PP is the heat-transfer rate from the junction, and I is the direct current owing in the circuit. The magnitude of the heating or cooling that takes place at the intersection of two dissimilar materials is indicated by the Peltier coefficient, which has voltage dimensions.

The Thomson Effect

The heat absorbed by the conductor when the current flow toward the higher temperature is:

$$P_T = {}_T\, I \Delta T \quad (4)$$

where the Thomson coefficient is represented by [V/K]. The Thomson coefficient is a characteristic of a single conductor, whereas the Seebeck and Peltier coefficients are defined for junctions between two conductors.

The Kelvin Relationships

The Peltier coefficient is related to the Seebeck coefficient by the following relationship:

$$\pi = \alpha T j \quad (5)$$

where Tj is the temperature at the junction. The assumption of reversibility seems to be valid because this result is extensively supported by experimental evidence. Equation 6 provides a straightforward method for calculating π and enables the rewriting of Equation 5 as:

$$\pi = \alpha I T j \quad (6)$$

The Thomson coefficient is related to the Seebeck coefficient by the following relationship:

$$_{T} = T_{AVG\ T}\, d\alpha/dT \qquad (7)$$

where T_{AVG} is the average temperature of the material.

SOFTWARE & METHODOLOGY

ANSYS software simulation is being carried out to study the concept. The thermal parameters and methodologies are mentioned in Table 1. Major challenges include thermal conductivity and device efficiency. ANSYS 16.2 software is engaged, fluent workbench is selected for simulations. Fluent is also known as CFD (computational fluid dynamics). A software-based model is developed on UNIGRAPHICS NX and further simulated in ANSYS Fluent. Aluminum metal is considered as cylinder. To accurately model and build complex and dynamic thermoelectric systems, which frequently experience thermal transients, it is crucial to comprehend the behavior of thermoelectric devices during thermal and transients. A model for modeling dynamic thermoelectric systems is presented in this chapter. The section offers the transient solution to the one-dimensional heat conduction equation with internal heat generation and dynamic exchanges of heat through the hot and cold sides. The suggested analytical solution is then included into a computer-aided model that properly simulates the thermal actual thermoelectric power generating system. This model considers the dynamic relations between the numerous thermal masses and the most essential thermoelectric phenomena happening in a generalized thermoelectric system. A comparison between software model and previous model is being followed.

Table 1. Parameters of Model TEG heat exchanger System used in our simulation.

	Parameter	Unit	Values
Radius	rt,i	m	0.049
Radius	rt,o	m	0.050
Length of the tank	L	m	1
Radius	rw,i	m	0.158
Radius	rw,o	m	0.0160
Convection heat transfer coefficient	hw	W/m^2K	300
Convection heat transfer coefficient	ha	W/m^2K	50
Convection heat transfer coefficient	Hg	W/m^2K	80
Thermal conductivity	kt	W/mK	401
Thermal conductivity	kwall	W/mK	80
Thermal conductivity	kTeg	W/mK	1.4
Number of items	Nteg	Pieces	99
Temperature	Ta	Deg C	25
Thickness of the TEG	e	m	0.005
Power/ Temp Change	P/delT	W/K^2	0.0002
Area	A Teg	m^2	0.0031

Source: Jaber et al. (2017) [18].

In previous study, Jaber et al. [18], the parameters of the geometry are being adopted. The dimension is mentioned in Table 1. The model geometry is developed is a working software is a 3-dimentional model. The layer of TEG is mounted and assembled in the model. Figure 1 shows the 3D model attached with TEG layer. Equations (1) to (17) are the base equations of a TEG.

DESIGN PARAMETERS FOR SIMULATION

As previous research: "Effect of Exhaust Gases Temperature on the Performance of a Hybrid Heat Recovery System" by Author Hassan Jaber et al. (2017) by Elsevier (Science Direct) [18]. The given worked experimentally, for the same research present method a FLUENT analysis is carried out, for the study the base parameters were adopted for simulation. A new geometry was developed based on above-mentioned paper a circular tube attached with TEG is introduced. All the dimensions are in mm. The dimension is mentioned in Table 1. The model geometry is developed on Unigraphics NX. The model is 3-Dimentional; its each section is drawn for further simulation. The Layer of TEG is attached in the figure itself. Figure 1 shows the 3D model attached with TEG layer.

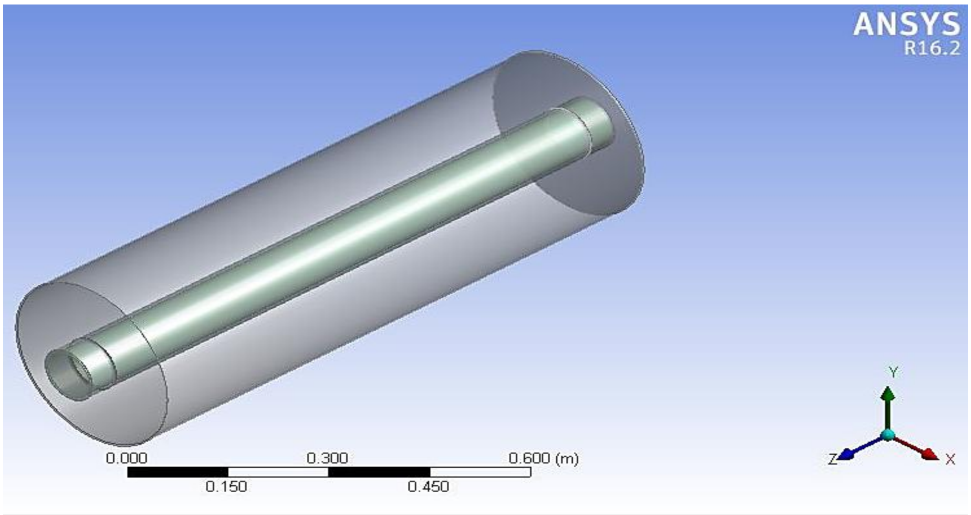

Figure 1. Geometry developed for analysis reference by Jaber et al. (2017) [18].

$$Rg = \frac{1}{hg(2\pi(rt,i-e)L)} \tag{8}$$

$$Rteg = \frac{\ln\left[\frac{rti}{rt,i-e}\right]}{2\pi KtegL} \tag{9}$$

$$Rp = \frac{\ln\left[\frac{rt,o}{rt,i}\right]}{2\pi KtL} \tag{10}$$

$$Rconv,w-p = \frac{1}{hw(2\pi rt,oL)} \tag{11}$$

$$Rconv,w-p = \frac{1}{hw(2\pi rw,iL)} \tag{12}$$

$$Rwall = \frac{\ln\left[\frac{rw,o}{rw,i}\right]}{2\pi KwL} \tag{13}$$

$$Rair = \frac{1}{ha(2\pi rw,oL)} \tag{14}$$

$$T(n) = T(n-1) - q.R(n) \tag{15}$$

$$P_{1Teg} = \left(\frac{P}{\Delta T2}\right)_{ref} ref\Delta T^2 P_{1Teg} \tag{16}$$

$$P_{Total} = N_{tegP_{1Teg}} \tag{17}$$

where A is the Area [m^2], H is the Convection heat transfer coefficient [W/m^2.K], HHRS s the Hybrid heat recovery system, Q is the Heat transfer rate [W], L is the Length of the tank [m], N is the Number of items, P is the Power produced [W], R is the Radius [m], Ta is the Temperature [°C], K is the Thermal conductivity [W/m.K], R is the Thermal resistance [K/W] and e is the Thickness of the TEG [m]. *Tg,i*, *TH*, *TC*, *Tp,o*, *Tw*, *Twall,i*, *Twall,o* and *Ta* are the temperature of exhaust gases, hot, cold, outer pipe wall, water, inner tank wall, outer tank wall, and ambient air temperature, respectively. Additionally, Rg, RTEG, Rp, Rconv, w-p, Rconv, w-w, Rwall, and Rair represent the thermal resistance of internal gas convection in pipes, conduction in TEGs, conduction in pipe walls, convection between water and pipes, convection between water and cylindrical tank walls, conduction in cylindrical tank walls, and convection of tanks with air, respectively. The convection heat coefficients of exhaust gases, water, and air are denoted by hg, hwand, and ha, respectively. The conduction coefficients of the TEG, tube wall, and tank wall are denoted by kTEG, kt, and kw, respectively. Additionally, rt, i, rt, o, rw, i, rw, o, and L represent the inner and outer radii of the tube and the water tank, respectively, as well as the tank's length. The TEGs' thickness is denoted by e.

Research Technique

As previous research: "Effect of Exhaust Gases Temperature on the Performance of a Hybrid Heat Recovery System" by Author Hassan Jaber et al. (2017) by Elsevier (Science Direct) [18], the given worked experimentally, for the same research present method a FLUENT analysis, is carried out.

For validation we need:

- To investigate the temperature difference and performance characteristics.
- Using the UNigraphics NX software to simulate and its dimensions of previous study.
- Aluminum material is used for result simulation having velocity of exhaust to be 1 m/s.
- For validation, we will further compare the results with previous research and our established research standards for validation.

CHAPTER

Results & Discussions

Discussion on Problems

Various factors are being studied and analyzed in CFD workbench of ANSYS software. The pipe's substance will be considered for this system's study. The material of the pipe to be utilized with the system for CFD analysis can be chosen in a variety of ways. It is difficult to repair the pipe frequently since it must be taken for CFD study and buried below. As the installation has been for decades, the pipe's material selection is important while taking care of the heat transfer.

Relevant Studies Are Being Carried Out

- Material Selection.
- Tube Material.
- Aluminum

Heat & Mass transfer the fundamental requirement is material selection. Aluminum is considered as a material. High thermal Conductivity, resistant to corrosion by liquids. The system is a one-time investment process; hence research is carried out on it. With references it makes a simulation work on Performance of TEGs Cooling of Air, by using Aluminum. The air was driven through the pipe and circulated throughout it using an air velocity range of 1 m/s. The simulation then begins, considering that the blower has been turned on and that air is passing through the pipe until it reaches a steady state. The velocity at the intake and outflow can be computed.

The total cooling and heating have been calculated for flow velocity of 1 m/s by the following equations:

- For Thermal Heat transfer

$$Qc = mCp\ (T\ inlet - T\ outlet) \quad (18)$$

where
- m = mass flow rate of air through the pipe.
- Cp = specific heat capacity of air.
- T inlet = inlet temperature of air.
- T outlet = outlet temperature of air.

Coefficient of performance (COP) of the system has been calculated from the following expression:

$$COP = m\ Cp\ (T\ inlet - T\ outlet)/T\ Input \quad (19)$$

- Measurement can be performed under quasi-steady conditions, and manual control were used to over ride the automatic control.
- It will be considered as a closed system

The main objective of the CFD study will be to investigate the transient behavior of simple TEGs system used in continuous heating mode and compare its thermal performance with TEGs operating under steady state condition (if the temperature of reuse of surrounding heat) in terms of derating factor.

RESULTS & ITS DISCUSSIONS

The results are based on 100°C (373K) inlet temperature of air. During analysis, Exhaust Air was the fluid medium, and Aluminum was the solid tube material. Present TEG's model is validated by comparing the results of simulation with the results of Jaber et al. (2017) [18], temperature of Exhaust air inlet is taken similar as the results of Table 2. The result of simulation came in close agreement with the previous research; thus, this model is considered appropriate for performing in depth analysis. Research: "Effect of Exhaust Gases Temperature on the performance of a Hybrid Heat recovery System" by Author Hassan Jaber et al. published in 2017 by Elsevier Ltd. Based on previous study, the geometry is followed and ANSYS software using Fluent workbench is engaged for the simulation of the results. Some values used in the analysis are as follows:

Table 2. Computed results based on pressure & temperature model TEG obtained at 100°C (373K) inlet temperature to the range of exhaust air.

Parameter	Units	Min Value	Max Value
Static temperature	K	300.0002	373
Total temperature	K	305.0298	372.9999
Relative total temperature	K	305.0298	372.9999
Wall temperature	K	0	352.2576
Total Enthalpy	j/Kg	6924.032	75331.73
Entropy	j/Kg	57.24993	259.7217
Total Energy	j/kg	–75790.81	–7383.112
Internal Energy	j/Kg	–75790.81	–7383.611

Figures 2–7 showed the Static Temperature, Energy, Total Enthalpy.

Validation of Simulation

In the case of a TEG, simulation validation involves cross-checking the outputs of computational models against experimental findings to confirm their precision and dependability. The Seebeck effect, in which a temperature gradient across thermoelectric materials generates a voltage, is the basis for how TEGs operate. During simulation, key material properties, such as thermal conductivity, electrical resistance, and the Seebeck coefficient, are used to replicate actual performance under different temperature conditions.

Validation ensures that simulated values like voltage output, thermal profiles, and efficiency align well with real-world data. This process is essential for improving the design, reducing potential inaccuracies, and ensuring the TEG functions effectively in real-world applications like energy recovery from waste heat and power generation in remote areas. The same analysis would be carried out at using simulation in ANSYS software to validate research Methodology being adopted. For Designing of simulation model will need software for result output. As further study, result output is found on ANSYS Software, and of its workbench Computational Fluid Dynamics (CFD Fluent) (Figures 8–10).

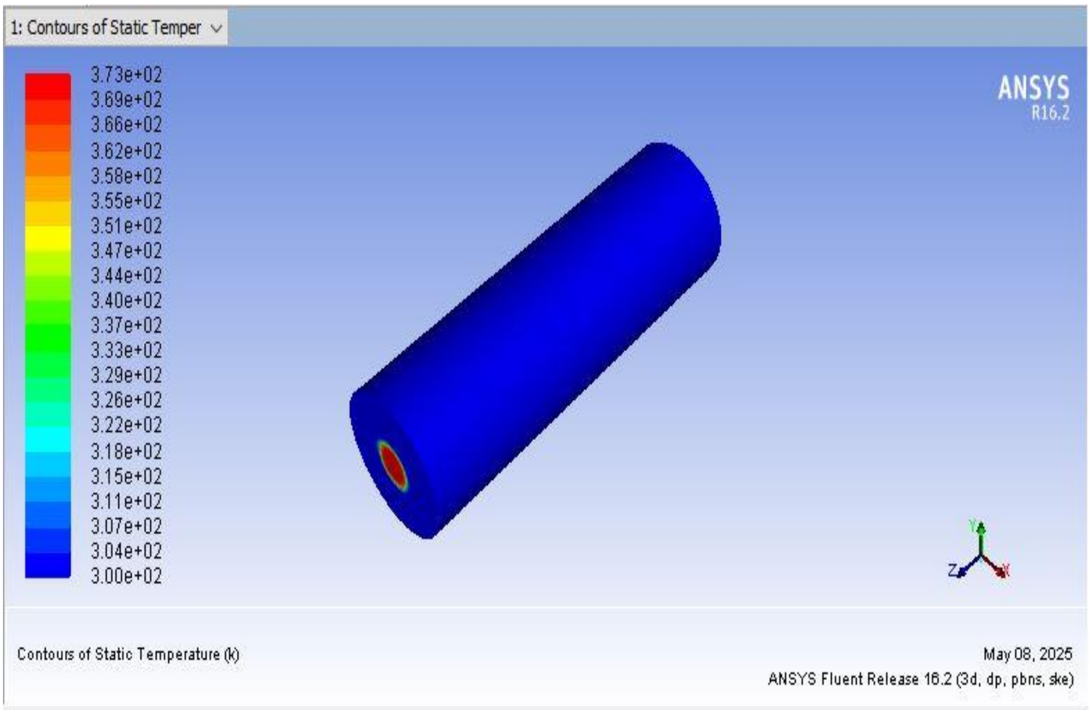

Figure 2. Result contour of static temperature.

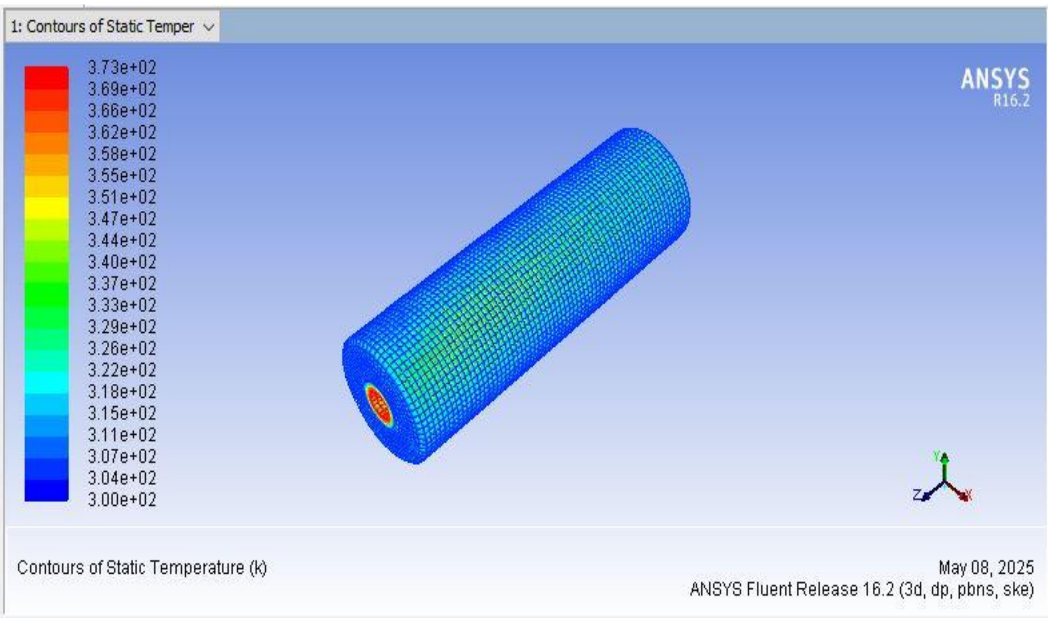

Figure 3. Result contour of static temperature streamline.

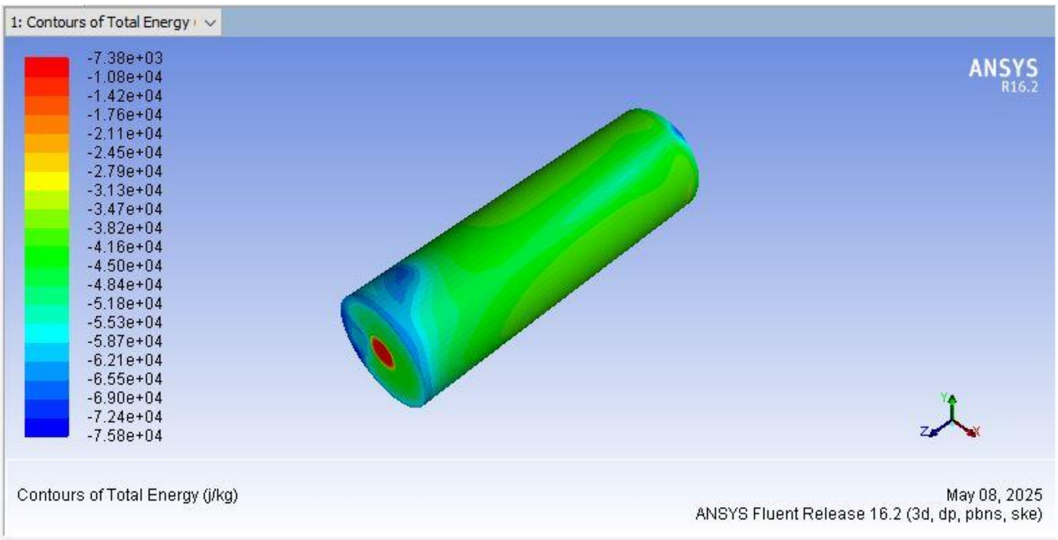

Figure 4. Result contour of total energy.

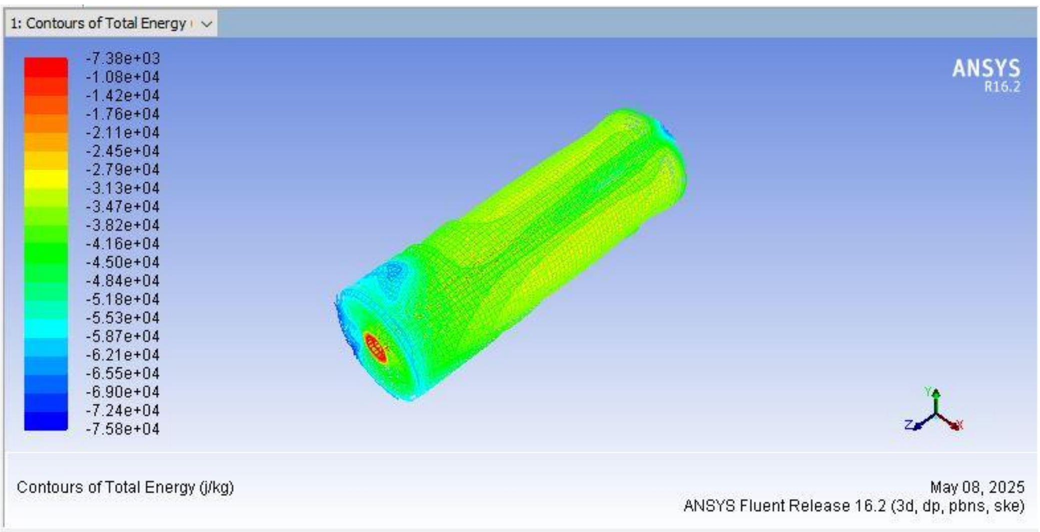

Figure 5. Result contour of total entropy streamline.

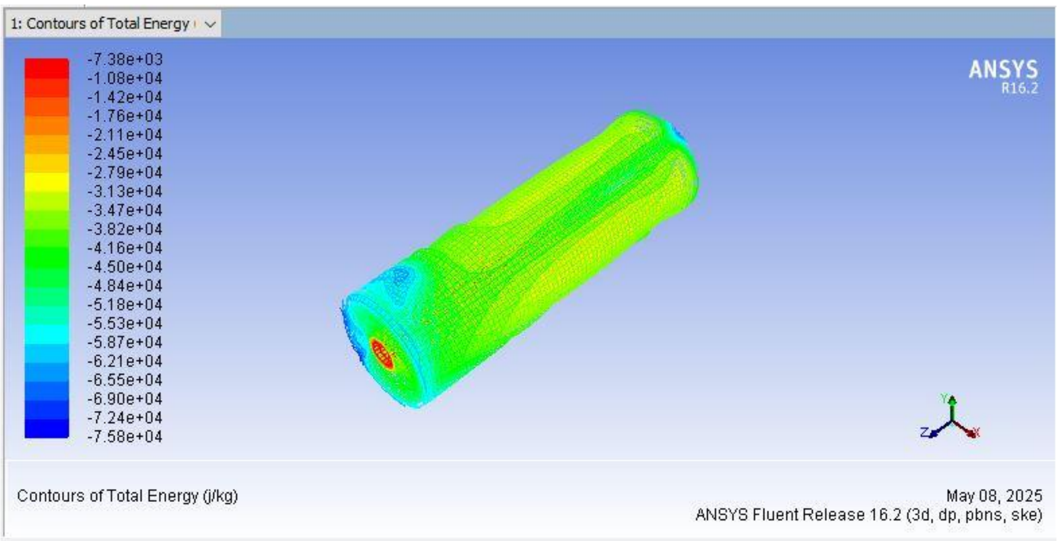

Figure 6. Result contour of total enthalpy streamline.

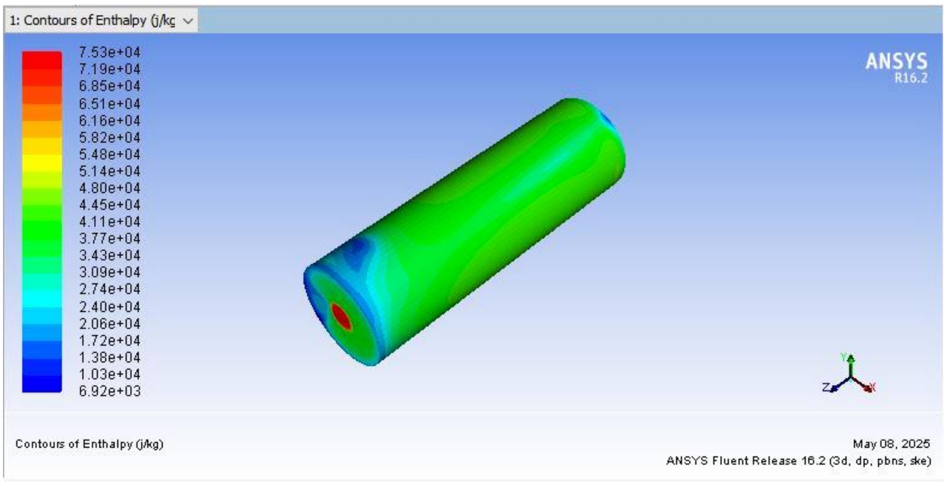

Figure 7. Result contour of total enthalpy.

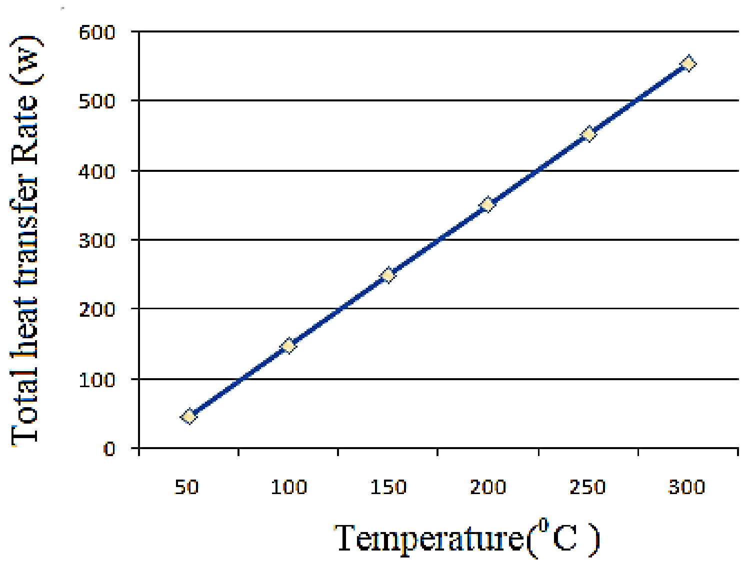

Figure 8. Graph result solution of inlet–outlet based on total transfer rate (w).

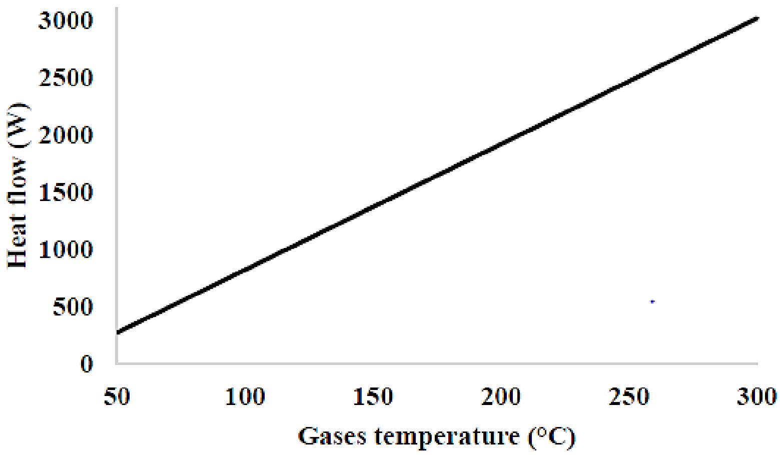

Figure 9. Graph Result solution of effect of exhaust gases temperature on heat rate (W) (Jaber et al.) [18].

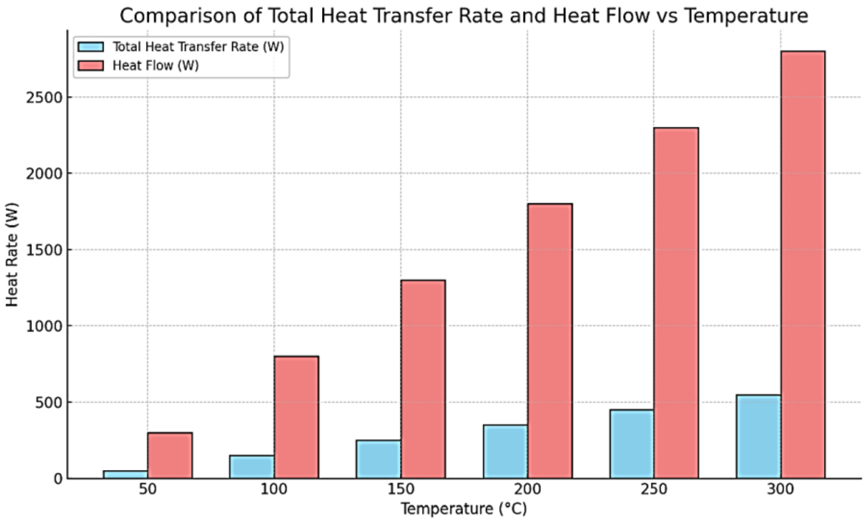

Figure 10. Comparative graph bar chart result solution of effect of exhaust gases temperature on heat rate (W) with the obtained results (Jaber et al.) [18].

CONCLUSIONS

The various authors carried out experiments related to the TEG. According to the above authors, some conclusions are left by the researchers for the following scope.

- Efficiency is an important selection and design criterion for a DC–DC converter.
- The temperature dynamic of the waste heat leads to a dynamic variation of the electrical operation points of a TEM.
- For the electrical efficiency analysis of a DC–DC converter, a loss model has been derived.
- This model can be used to compare different converter topologies. Furthermore, it might serve as a guideline to optimize efficiency. Experimental results are presented for a DC–DC converter prototype.
- The The DC–DC converter's transfer functions are influenced by a TEM's electric properties. To guarantee the stability of the intended feedback control, this influence must be considered throughout the controller's design.
- In general, the electrical states and component electrical parameters determine a converter's loss.
- To improve the efficiency in relation to the electrical characteristics of the TEM, loss optimization has been done.
- Measurement findings demonstrate that optimization boosted the converter's efficiency.
- The specifications of the TEMs' time-varying voltage sources with series resistors are determined by the exhaust gas system's temperature distribution and actual temperature.

This work delivers an idea to use renewable energy.

A novel transient heat transfer analysis method was introduced.

Thermoelectric modules that work based on the principles of Seebeck theory were picked for both technical and economic reasons to achieve the mission at hand.

To potentially recover waste heat, TEGs can be competitively coupled to the plant exhausts. Thermoelectric modules are incredibly small, despite their seemingly high cost. Hence, Software simulation is required before installations. Requires expertise people for installations.

CHAPTER
Future Work

After studying all research papers, it is found that there are many scopes available for further research. Some future directions are given below.

- The necessary components, like thermoelectric material, heat exchangers, and DC–DC converters, have been studied in detail.
- The aim of this thesis is to research the electrical integration of a TEG system in the on-board power supply.
- This includes the analysis of the electrical components, the interaction of the TEG with the on-board power supply and the TEG during a driving cycle.
- The focus of this thesis lies on the methodological analysis and the assessment of the electrical interface without any restrictions on used TEMs.

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