NEW CONCEPTS AND ADVANCED STUDIES IN MECHANICAL ENGINEERING

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Editor
Prof. Dr. İSMET SEZER

New Concepts and Advanced Studies in Mechanical Engineering

Design: All Sciences Academy Design
Published Date: October 2025
Publisher's Certification Number: 72273
ISBN: 978-625-5794-57-4

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CONTENT

Waste Heat Recovery in Internal Combustion Engines: A Comprehensive Analysis of Thermoelectric Generator Systems

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ABSTRACT

This study comprehensively evaluates the thermoelectric generator (TEG) systems used for waste heat recovery in internal combustion engines (ICE). Currently, only 25–40% of the fuel in internal combustion engines can be converted into mechanical work, while a large portion of the remainder is lost as waste heat. The most significant part of these losses is transferred to the atmosphere through exhaust gases with temperatures ranging from 300 to 700 °C. Thermoelectric generator systems provide a more feasible alternative in the automotive sector compared to methods like ORC and Kalina cycle due to their ability to convert heat directly into electricity through the Seebeck effect, their lack of moving parts, quiet operation, and modular structures. Experimental findings in the literature show that with the integration of thermoelectric generators, power generation of a few watts can be achieved in small-scale engines, while levels reaching kilowatts can be attained in heavy vehicles. Thus, while an improvement of 2-10% in fuel consumption can be achieved, a reduction of 6-12% in CO2 emissions can also be obtained. However, there are limitations such as low efficiency (3-5%), the use of expensive materials, pressure losses, and thermal management challenges. In recent years, nanostructured materials, graphite-based solutions, and hybrid energy systems (TEJ + ORC) have shown promising results in overcoming these limitations. As a result of this study, the thermoelectric generator technology holds potential for use as an additional energy source in hybrid/electric vehicles, to meet the increasing energy demand in autonomous vehicles, and in aerospace applications. Particularly, it is expected to spread more rapidly in commercial transportation and heavy vehicles from an economic standpoint.

Keywords: Thermoelectric, generator, waste heat, internal combustion engines

INTRODUCTION

Today, energy efficiency and sustainability constitute one of the most critical research areas in the automotive industry. In the global transportation sector, where internal combustion engines (ICE) are still widely used, only 25–40% of fuel is converted into useful mechanical work, with the remainder lost due to friction and heat losses. Approximately 35–40% of these losses are transferred to the atmosphere via exhaust gases, while 25–30% are dissipated through engine cooling systems (Burnete et al., 2022). Therefore, exhaust gases are the largest source of waste heat in internal combustion engines, and recovering this energy is of great importance in terms of both improving fuel economy and reducing greenhouse gas emissions.

Various technologies have been developed in the literature for waste heat recovery. Although methods such as the Organic Rankine Cycle (ORC), Kalina cycle, and turbo-compounding have been widely studied, the complex designs, high costs, and additional maintenance requirements of these systems limit their application in the automotive sector (Chammam et al., 2023; Sohrabi et al., 2023). In contrast, thermoelectric generators (TEGs) stand out as a promising alternative for automotive applications due to their ability to convert heat directly into electricity based on the Seebeck effect, their lack of moving parts, silent operation, modular structure, and low maintenance requirements (Burnete et al., 2022; Lan et al., 2025).

When examining the thermal properties of exhaust gases, it is observed that the temperature range is mostly between 300–700 °C, which is a suitable range for thermoelectric materials to operate effectively (Ramírez-Restrepo et al., 2021). Therefore, numerous experimental studies have tested TEG integration in different engine types, ranging from small-displacement diesel engines (Ramírez-Restrepo et al., 2021) to hydrogen-fuelled buses (Oh et al., 2024), petrol-powered passenger cars (Esen et al., 2025) to heavy-duty vehicles (Li et al., 2025). Findings indicate that the electrical power generated can range from a few watts (around 17 W in small-scale systems) to hundreds of watts and even reach kilowatt levels in some heavy-duty vehicle applications.

However, there are also some technical challenges facing TEG applications in the automotive sector. First, high temperature gradients must be maintained in a sustainable manner, and a homogeneous temperature distribution must be preserved between modules. Otherwise, thermoelectric modules may overheat and fail or operate at low efficiency. To address this issue, the integration of highly conductive materials such as graphite plates has increased temperature homogeneity and improved power generation by more than 40% (Lan et al., 2025). Another critical issue is minimising pressure losses in the exhaust line, as pressure drops can negatively affect engine performance. Therefore, optimisation efforts are intensively ongoing in the designs of heat exchangers and modules (Zhang et al., 2024; Ni et al., 2024).

The advantages of TEG technology are not limited to fuel economy. It can also make significant contributions in terms of emission reduction. Various experimental studies have shown that CO_2 emissions can be reduced by 6–12% with TEG systems (Orjuela-Abril et al., 2024). Furthermore, studies conducted on engines using biodiesel have reported that TEG integration has positive effects not only on energy gain but also on combustion characteristics (Karabulut, 2025). Such findings indicate that thermoelectric technology can provide a broader sustainability contribution when used in conjunction with alternative fuels.

Given global energy transition targets and increasingly stringent emission standards, the automotive industry's interest in TEG continues to grow. The European Union's carbon-neutral transport targets, US Environmental Protection Agency (EPA) regulations, and sustainable mobility policies in Asian countries have made waste heat recovery a strategic priority (Burnete et al., 2022). In this context, TEG systems replacing alternators in the future or being used as an additional energy source in hybrid/electric vehicles are among the research areas that the sector is focusing on.

Consequently, thermoelectric energy recovery from automotive exhaust waste heat is a topic that has been addressed multidimensionally in the existing literature through different engine types, material solutions, and system designs, but it is still a subject with engineering problems to be solved. In this review article, the fundamentals of the thermoelectric effect and the materials used will first be introduced; then, waste heat sources and existing technologies in the automotive industry will be examined; finally, TEG applications in different engine types, experimental studies, and optimisation approaches will be evaluated. After discussing the economic and environmental impacts and future research areas, a general evaluation and recommendations will be presented in the Conclusion section.

2. FUNDAMENTALS OF THE THERMOELECTRIC EFFECT

2.1. Seebeck, Peltier, and Thomson Effects

There are three main effects underlying thermoelectric phenomena: the Seebeck, Peltier and Thomson effects. These effects were discovered in the 19th century and are used in many areas today, from energy production to cooling (Asaduzzaman et al., 2023).

The Seebeck effect was discovered in 1821 by Thomas Seebeck. When there is a temperature difference between two different conductors or semiconductors, an electrical potential difference, known as the thermoelectric potential, arises due to the movement of electrons and holes. This forms the basis of thermoelectric generators. The open-circuit voltage is expressed by the following formula (Sok & Kusaka, 2023):

$VOC = \alpha \times \Delta T = \alpha \times (Thot - Tcold)$

Here;

- α: Seebeck coefficient (Volt/Kelvin)
- ΔT: Temperature difference (Kelvin)
- VOC: Open-circuit voltage (Volt)

The Peltier effect was discovered by Jean Peltier in 1834. When an electric current passes through the junction of two different materials, heat is absorbed or released. This amount of heat is directly related to the Peltier coefficient (Asaduzzaman et al., 2023):

$QP = \pi \times I$

According to the Kelvin relationship:

$\pi = \alpha \times T$

Therefore:

$QP = \alpha \times T \times I$

Here;

- π: Peltier coefficient (Volt)
- I: current (Amperes)
- T: Temperature (Kelvin)

The Thomson effect was defined by Lord Kelvin in 1851. When an electric current passes through a conductor and there is a temperature gradient, additional heat dissipation or cooling occurs (Asaduzzaman et al., 2023).

$QT = \tau \times I \times \Delta T$

Here;

- τ: Thomson coefficient (Volt/Kelvin)
- I: current (Amperes)
- ΔT: temperature difference (Kelvin)

The Kelvin relation relates the Thomson coefficient to the Seebeck coefficient:

$\tau = T \times (d\alpha/dT)$

Thus, the Thomson effect actually arises from the temperature dependence of the Seebeck coefficient.

2.2. Performance Indicators of Thermoelectric Materials

The most fundamental indicator used to evaluate the efficiency of thermoelectric materials is the dimensionless performance factor ZT (Sok & Kusaka, 2023; Esen et al., 2025):

$$ZT = (S^2 \times \sigma \times T) / k$$

Here;

- S: Seebeck coefficient (Volt/Kelvin)
- σ: Electrical conductivity (Siemens/metre)
- T: Absolute temperature (Kelvin)
- k: Thermal conductivity (Watt/metre-Kelvin)

A high-performance thermoelectric material must have a high Seebeck coefficient and electrical conductivity, as well as low thermal conductivity. Bi2Te3 materials currently used commercially have a ZT ≈ 1 value at conditions close to room temperature. New-generation materials developed using nanotechnology have reported ZT > 2 values (Toker, 2025; Huang et al., 2024).

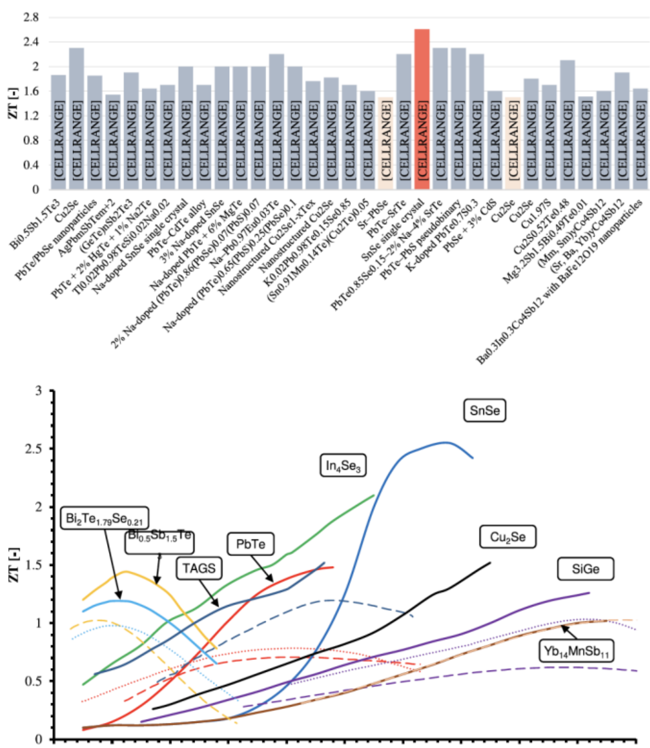

Figure 1: Temperature-dependent ZT values of different thermoelectric materials (Burnete et al., 2022).

2.3. Material Classes Used

- Bismuth Telluride (Bi_2Te_3): Provides high performance at room temperature (ZT ≈ 1). However, it loses its stability at high temperatures.
- Lead Telluride (PbTe): It is highly efficient in the 500–900 K range, but its toxic properties are a disadvantage (Asaduzzaman et al., 2023; Toker, 2025).
- Skutterudites: Possess low thermal conductivity due to voids in their crystal structures. Can be used at temperatures between 600–900 K.
- Silicon-Germanium (SiGe) alloys: Resistant above 900 K, used in space applications and heavy vehicles.
- Nanocomposites: Boron-doped polymers and graphene-based materials offer high ZT values, enabling the development of more efficient, flexible, and lightweight modules (Asaduzzaman et al., 2023; Toker, 2025).

2.4. Thermoelectric Module and System Structure

A thermoelectric generator system used in automotive applications typically consists of four components (Esen et al., 2025; Ramírez-Restrepo et al., 2021):

1. Heat exchanger: Collects heat from exhaust gases.
2. Thermoelectric modules: Generate electricity between the hot and cold surfaces.
3. Cooling unit: Prevents the modules from overheating, typically using liquid cooling.
4. Electrical circuit integration: Energy is regulated and transferred to the battery via DC-DC converters.

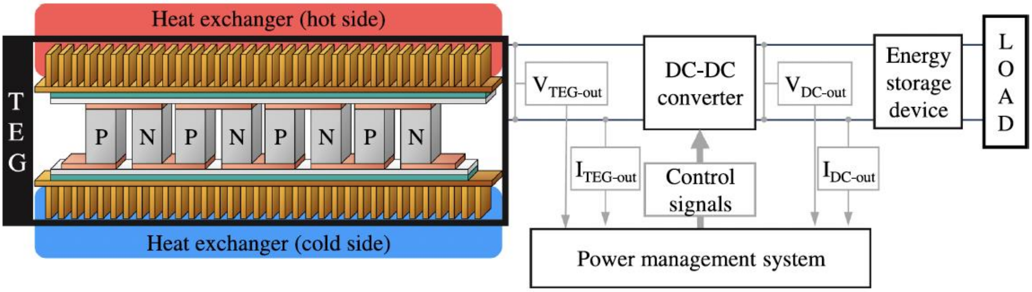

Figure 2: General schematic and basic components of a typical automotive thermoelectric generator (TEG) system (Burnete et al., 2022, p. 13).

2.5. Limitations of thermoelectric technology

- Low efficiency (3–5% range) (Sok & Kusaka, 2023; Gürbüz et al., 2022).
- Use of high-cost materials (Sok & Kusaka, 2023; Gürbüz et al., 2022).
- Thermal management challenges (Sok & Kusaka, 2023; Gürbüz et al., 2022).
- Mechanical durability issues (Sok & Kusaka, 2023; Gürbüz et al., 2022).
- Heat leakage problems: power losses of up to 11% (Zhang et al., 2024).

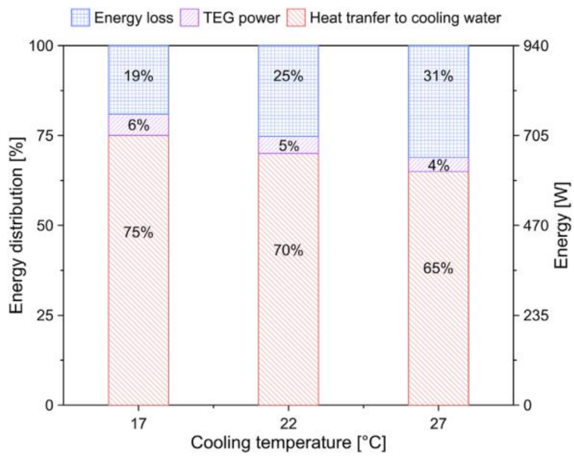

Figure 3: Schematic representation of energy flow distribution and losses in a thermoelectric generator system (Ramírez-Restrepo et al., 2021, p. 10).

3. WASTE HEAT SOURCES IN AUTOMOTIVE APPLICATIONS

3.1. Energy Losses in Internal Combustion Engines

In internal combustion engines (ICE), only approximately 25–35% of the chemical energy of the fuel can be converted into useful mechanical work. The remaining 65–70% is lost as waste heat (Burnete et al., 2022). A large portion of these losses is transferred to the atmosphere via exhaust gases and engine cooling systems.

- Loss via exhaust gases: 35–40%

• Loss through the cooling system: 25–30%
• Friction, radiation, and other losses: approximately 5%

This distribution makes the exhaust line one of the most important sources for energy recovery. Furthermore, the temperature range of exhaust gases varies between 300–700 °C. These temperature values are suitable for the effective operation of thermoelectric materials (Ni et al., 2024; Li et al., 2025).

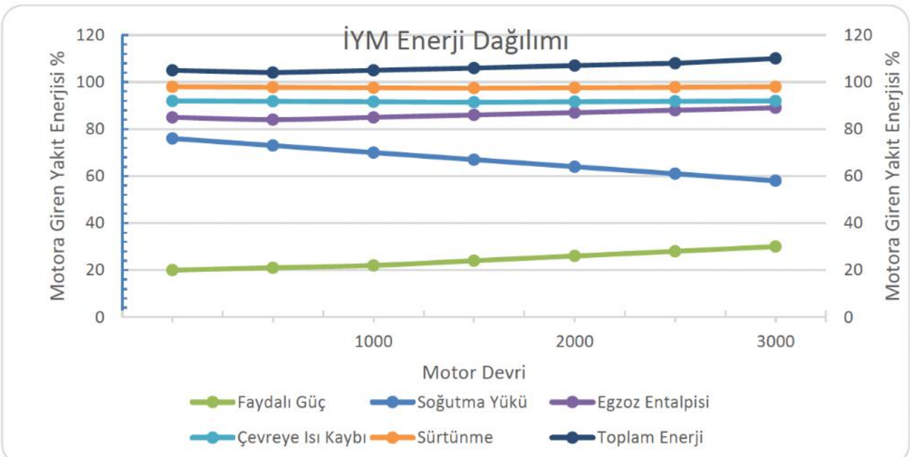

Figure 4: Distribution of energy flows in a typical internal combustion engine depending on engine speed (Karabulut, 2025, p. 63).

3.2. Thermal Properties of Exhaust Gases

The properties of exhaust gases vary depending on the type of engine used, the type of fuel, the engine load, and the operating conditions. Generally, in passenger car engines, the exhaust gas temperature ranges from 400–600 °C, while in heavy-duty and diesel engines, it can reach up to 700 °C (Ni et al., 2024).

The flow rate of exhaust gases is also important. The flow rate increases at high engine loads, which means that more heat is transferred to the exhaust line. However, pressure losses can also occur in the exhaust line. Therefore, during the integration of thermoelectric generators into the exhaust line, a balance must be struck between heat transfer and pressure loss (Chen et al., 2023; Ni et al., 2024).

3.3. Waste Heat Recovery Technologies

Various methods have been developed for waste heat recovery in the automotive industry:

- Organic Rankine Cycle (ORC): The heat from the exhaust gas is transferred to an organic fluid, which expands to drive a turbine and produce mechanical work. Although highly efficient, it is a complex and heavy system (Sohrabi et al., 2023).
- Kalina Cycle: Similar to ORC, but uses an ammonia-water mixture. It provides better efficiency at high temperatures, but the system is more complex and costly (Sohrabi et al., 2023).
- Turbo-Compounding: Exhaust gas energy is transferred directly to the crankshaft via a turbine. It can increase fuel efficiency but requires modification of the engine's mechanical structure.
- Thermoelectric Generators (TEGs): These generate electricity directly using the Seebeck effect. Their simple structure, lack of moving parts, silent operation, and modularity make them one of the most suitable solutions for the automotive sector (Burnete et al., 2022).

3.4. Integration with Post-Exhaust Systems

Today**,** catalytic converters (DOC), diesel particulate filters (DPF), and SCR systems are widely used in automotive exhaust systems. These systems alter the temperature and flow of exhaust gases (Li et al., 2023; Tarhan, 2025).

For example, thermoelectric generators integrated into diesel particulate filters (DPF) provide both thermal recovery and additional energy for regeneration (Li et al., 2023). In addition, the exhaust gas recirculation (EGR) line is also a potential heat source. However, temperatures here are lower than at the exhaust outlet.

Therefore, when integrating TEGs in automotive applications, the focus is not only on the exhaust outlet but also on intermediate points such as the DPF, catalytic converter, and EGR lines (Asaduzzaman et al., 2023; Burnete et al., 2022).

4. THERMOELECTRIC GENERATOR (TEG) APPLICATIONS IN AUTOMOTIVE EXHAUST SYSTEMS

4.1. System Components

An automotive TEG system consists of several main components:

• Heat exchanger (hot-side heat exchanger): Collects the high-temperature heat carried by the exhaust gas. Its design targets high thermal conductivity and minimum pressure loss. Aluminium or steel is typically used as the material.

• Thermoelectric modules (TEM): Consist of p-type and n-type semiconductor pairs. They are connected in series-parallel to obtain the desired voltage and current values.

• Cooling system (Cold-side heat exchanger): Liquid cooling (water or coolant) or air-cooling systems are used to prevent the modules from overheating. The effectiveness of the cooling directly affects the performance of the TEG.

• Electrical integration: The electrical power obtained from the modules is usually regulated via DC-DC converters. Thus, the energy produced is either stored in the vehicle battery or fed directly into the electrical systems (Esen et al., 2025).

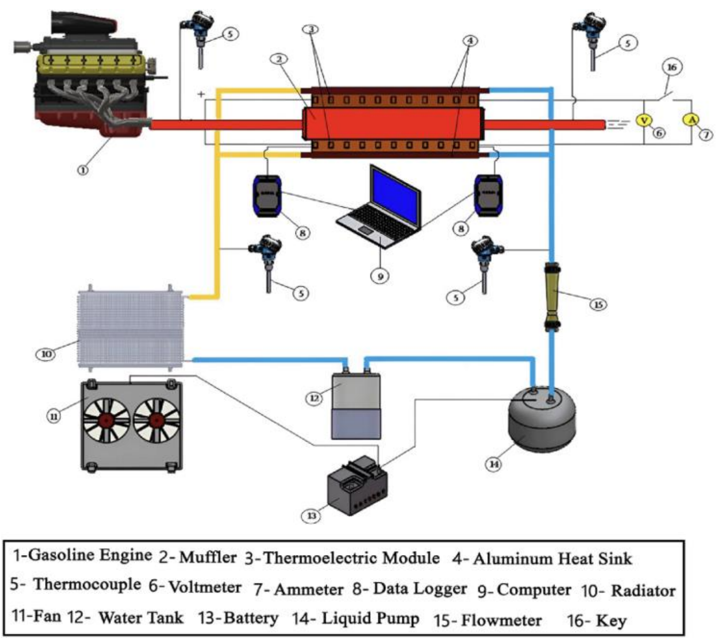

Figure 5: Schematic representation of a typical automotive thermoelectric generator system: exhaust line, thermoelectric modules, cooling block, closed-loop liquid cooling, radiator, fans, pump, and power management components (Esen et al., 2025, p. 6).

4.2. Design Parameters

The success of TEG systems depends on several critical parameters:

- Temperature gradient: The Seebeck effect is directly dependent on the temperature difference. Therefore, creating the maximum temperature difference in the exhaust line is a priority for system efficiency.
- Module placement: The placement of the modules determines the heat flow and temperature distribution. If the placement is not appropriate, a temperature difference occurs between the modules and the overall efficiency decreases (Zhang et al., 2024).
- Pressure losses: Heat exchangers integrated into the exhaust line can cause a pressure drop in the exhaust flow. This negatively affects engine performance. Therefore, the heat exchanger design must be optimised considering both heat transfer and flow aerodynamics.
- Material selection: Due to the high temperature and corrosive nature of exhaust gases, durable materials should be preferred in heat exchangers. Similarly, it is important that thermoelectric modules are resistant to high temperatures (Ni et al., 2024).

4.3. Applications by Vehicle Type

Petrol engines: Experimental studies conducted on petrol cars have reported that small-scale TEG prototypes can generate around 17 W of electricity. These studies demonstrate that TEG can be practically applied, particularly in low-volume engines (Esen et al., 2025; Abdelghany et al., 2023).

Diesel engines: Since exhaust gas temperatures are higher in diesel engines, TEG systems can generate more power. Studies have shown that TEG systems integrated into diesel engines can produce hundreds of watts of electricity (Ni et al., 2024; Sok & Kusaka, 2023).

Biodiesel applications: TEG integration in engines using biodiesel affects not only electricity generation but also combustion characteristics. Cleaner combustion and lower emission values have been reported in such applications (Karabulut, 2025).

Heavy vehicles: TEG integration in trucks and buses has enabled electricity generation up to 1 kW. This amount is sufficient to power a large portion of the vehicle's electrical systems (Li et al., 2025; Ramírez-Restrepo et al., 2021).

Hydrogen and hybrid vehicles: TEG systems are used as an additional energy source in hydrogen engines and hybrid vehicles, providing significant support, especially when combined with regenerative energy systems (Oh et al., 2024).

4.4. Performance Evaluations

Experimental studies in the literature show that the electrical power generated by TEG systems can range from a few watts to kilowatt levels.

- In small prototype systems: Power generation between 3–20 W (Gürbüz et al., 2022; Esen et al., 2025; Sok & Kusaka, 2023).
- In medium-sized passenger vehicles: Power production between 50–200 W (Ni et al., 2024; Sok & Kusaka, 2023).
- In heavy-duty vehicle applications: Power generation of 1 kW and above (Li et al., 2025; Ramírez-Restrepo et al., 2021).

In terms of fuel economy, TEG integration can achieve fuel savings of 2–10 per cent (Orjuela-Abril et al., 2024). In terms of emissions, a 6–12 per cent reduction in CO_2 emissions has been reported.

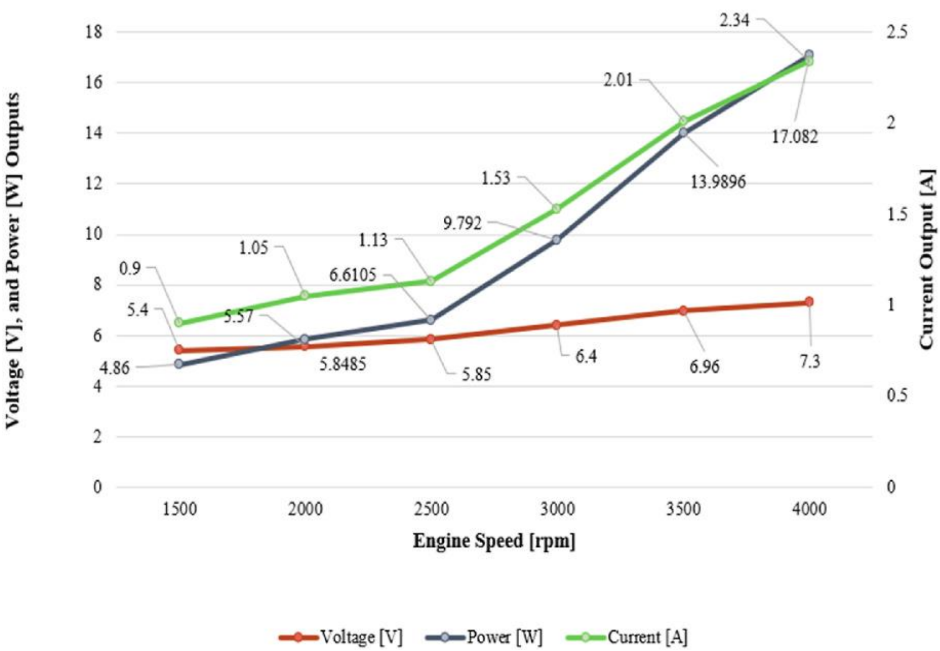

Figure 6: Comparison of power outputs from thermoelectric generator systems in different engine types: power and voltage variations depending on engine speed for petrol engine applications (Esen et al., 2025, pp. 13–14).

5. THERMOELECTRIC MATERIAL AND TECHNOLOGY DEVELOPMENTS

5.1. Nano-Structured Materials

The performance of thermoelectric generators largely depends on the properties of the materials used. Traditional materials have been unable to exceed a certain efficiency limit for many years, leading to an increased focus on nano-structured materials in recent years.

Nanostructures allow electrons to move freely while restricting the propagation of phonons (heat-carrying vibrations). This reduces the thermal conductivity of the material while maintaining its electrical conductivity. Thus, the ZT coefficient increases significantly.

For example, it has been reported that adding nanoparticles to Bi2Te3-based materials increases the ZT value to 1.5 levels. Carbon nanotube and graphene additives have been effective in raising ZT values above the 2 level due to their high surface area and high electron mobility (Toker, 2025).

5.2. Graphite-Based Materials

Recent studies indicate that graphite-based materials can be used to increase the high-temperature stability of thermoelectric modules. Although graphite has high thermal conductivity, it is effective in homogenising temperature distribution when combined with certain composite structures.

Graphite plates extend the life of the modules by ensuring more balanced temperature differences between the modules integrated into the exhaust line. Furthermore, experimental results have shown that electricity production can increase by up to 40% in graphite-based systems (Lan et al., 2025; Huang et al., 2024).

5.3. DPF Integrated Thermoelectric Systems

The diesel particulate filter (DPF) is a mandatory component for emission control in modern diesel vehicles. Research has shown that integrating thermoelectric generators with DPFs can support both electricity generation and DPF regeneration.

Thermoelectric modules placed on the DPF convert the heat of the exhaust gases into electricity while also providing additional energy for the regeneration process required to burn the soot accumulated in the filter. In such hybrid systems, power generation levels of 200–300 W have been reported using modules with high ZT values (Li et al., 2023).

5.4. Hybrid Solutions: ORC + TEG Systems

TEG systems alone face low efficiency issues in the automotive sector. Therefore, intensive work is being done on hybrid integration with technologies such as ORC (Organic Rankine Cycle).

In hybrid systems, part of the exhaust gas is transferred to the ORC cycle, while TEG modules are used at points where the high temperature difference is more suitable. This combines the advantages of both technologies. Optimisation studies show that total energy efficiency in such hybrid systems can exceed 20% (Chammam et al., 2023).

5.5. Heat Loss and Insulation Problems

One of the most significant factors reducing the performance of TEG systems is heat leakage. Heat leakage occurs, particularly due to air gaps between the modules. Experimental studies have revealed that this situation reduces total power production by 11% (Zhang et al., 2024).

Therefore, in recent years, the vertical placement of modules, the sealing of gaps with thermal insulation materials, and the use of special cooler designs have been proposed. This has made it possible to minimise heat loss and increase total efficiency by 5–10% (Huang et al., 2024; Chen et al., 2023).

6. ECONOMIC AND ENVIRONMENTAL ASSESSMENTS

6.1. Cost-Benefit Analysis

One of the main obstacles to the widespread adoption of thermoelectric generators in the automotive sector is their high cost. Semiconductors such as Bi_2Te_3, PbTe, and skutterudite used in TEG modules are rare and expensive materials. Additionally, heat exchangers, cooling systems, and power electronics components required for system integration also increase the total cost.

Studies show that the cost of a TEG system integrated into a medium-sized passenger car is in the range of several thousand dollars, but it can achieve fuel savings of 3–5 per cent per year (Sohrabi et al., 2023). This extends the payback period to an average of 4–6 years.

However, this period is shorter for heavy goods vehicles and commercial fleets. This is because vehicles with high mileage consume more fuel and therefore the economic value of fuel savings is greater. For this reason, it is predicted that the first widespread applications of TEG systems will be in high fuel consumption vehicles such as heavy goods vehicles and buses (Sohrabi et al., 2023; Orjuela-Abril et al., 2024).

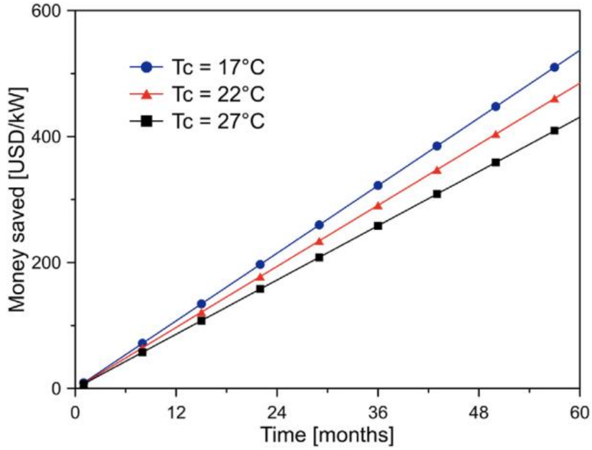

Figure 7: The impact of TEG usage on economic savings at different cooling temperatures (Ramírez-Restrepo et al., 2021, p. 14).

6.2. Environmental Contributions

The integration of thermoelectric generators into the automotive sector provides significant benefits not only economically but also environmentally. Converting waste heat from the exhaust system into electricity directly reduces fuel consumption and consequently lowers greenhouse gas emissions.

Experimental studies show that CO2 emissions can be reduced by 6–12 per cent in vehicles equipped with TEG systems (Orjuela-Abril et al., 2024). Furthermore, applications in engines using biodiesel have shown that TEG integration leads to cleaner combustion characteristics and additional reductions in particulate emissions (Karabulut, 2025).

However, positive effects are not always observed. For example, some applications in natural gas engines have reported a 9–10% increase in NOx emissions (Orjuela-Abril et al., 2024). This is due to TEG systems altering exhaust gas temperature profiles. Therefore, to fully realise the environmental benefits, TEG systems must be optimised in conjunction with post-treatment units.

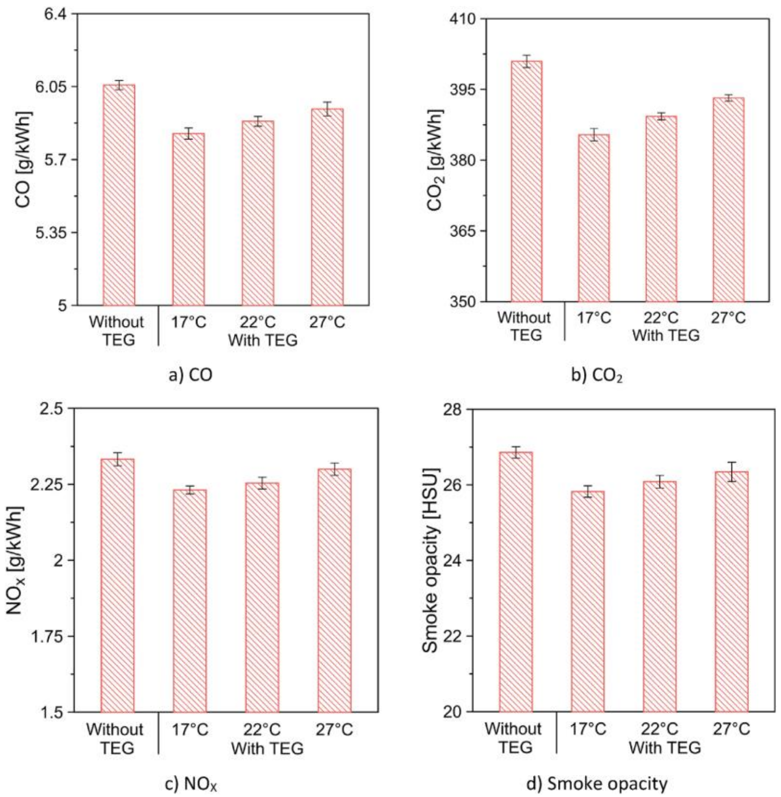

Figure 8: Effect of TEG integration on CO_2 and NOx emissions: Comparison of engines with and without TEG (Ramírez-Restrepo et al., 2021, p. 12).

6.3. Regulation and Policy Framework

One of the most important factors that will pave the way for the wider use of TEG technology in the automotive industry in the future is emissions regulations.

- European Union: As part of its carbon-neutral transport goal, the sale of new internal combustion engine vehicles is planned to be banned by 2035. In this process, technologies that provide energy efficiency for hybrid and alternative fuel vehicles are being supported.
- USA (EPA): The Environmental Protection Agency has introduced stricter fuel economy and emission standards for light and heavy vehicles. This is directing manufacturers towards energy recovery solutions.
- Asian Countries: Countries such as China and Japan are making significant investments in TEG research in line with energy efficiency

and emission reduction targets. In China, there are government incentives for TEG integration, particularly in electric and hybrid buses. These policies indicate that TEG systems will become increasingly prevalent in hybrid and heavy-duty vehicle applications, if not immediately, then in the short term (Orjuela-Abril et al., 2024; Burnete et al., 2022).

7. FUTURE PERSPECTIVES AND RESEARCH AREAS

7.1. TEG Applications in Hybrid and Electric Vehicles

In the future, the automotive industry is expected to shift entirely towards electric and hybrid vehicles. In this transformation, TEG technology, while not a primary energy source, can play a critical role as a secondary energy recovery system.

As internal combustion engines still exist in hybrid vehicles, it is possible to contribute to battery systems by generating electricity from waste heat in the exhaust line. This reduces both fuel consumption and the battery's charging load. In fully electric vehicles, TEG systems do not have a direct exhaust source; however, it is anticipated that they can be used in battery heat management, motor control units, and the evaluation of secondary heat sources (Oh et al., 2024).

7.2. Autonomous Vehicles and High Energy Requirements

It is predicted that autonomous vehicles will have much higher energy requirements in the future. Sensors, radars, lidar systems, and the need for continuous data processing demand much more electrical energy than traditional vehicles.

In this context, TEG systems can be used as a supplementary energy source in autonomous vehicles. Simulation studies show that 5–10% of an autonomous vehicle's energy demand can be met by TEG. Although this percentage may seem small, it can make a significant contribution to fuel economy and battery endurance in long-distance transport (Li et al., 2025).

7.3. Aviation and Space Applications

One of the future research areas for TEG technology is the aviation and space industry. Since exhaust temperatures are extremely high in hypersonic systems such as scramjet engines, it has been reported that thermoelectric generators could utilise these temperatures to produce power at levels of hundreds of kilowatts (Lan et al., 2025).

Furthermore, long-lasting TEG systems have been developed for space vehicles using high-temperature-resistant materials such as SiGe. Some radioisotope thermoelectric generators (RTGs) used by NASA have been in operation for over 40 years. Work is ongoing to adapt such technologies for automotive applications.

7.4. Multi-Energy Recovery Systems

In the future, TEG technology is expected to be used in conjunction with other energy recovery systems rather than on its own. In particular, hybrid solutions are emerging, where the Organic Rankine Cycle (ORC) converts part of the exhaust heat into work using turbines, while the remaining part is converted into electricity using TEG modules.

Thanks to these systems, total efficiency can exceed 20%, and fuel economy in vehicles can be improved by more than 10% (Chammam et al., 2023).

7.5. Compact and Modular Designs

Another focus of future research is reducing the size and weight of TEG systems. Currently, TEG systems are still large and costly. However, new-generation sandwich-type TEG devices offer both greater compactness and higher power density thanks to their modular structures.

For example, a recent study reported achieving a power density of 19.8 kW/m^3 in a sandwich-type multilayer TEG device (Ni et al., 2024). Such designs will facilitate automotive integration and accelerate the transition to mass production.

CONCLUSION

This study comprehensively evaluated thermoelectric generator (TEG) systems used for waste heat recovery in internal combustion engines. The investigations revealed that a significant portion (60–70%) of the fuel energy in engines is lost as heat and that this loss offers considerable potential for recovery, particularly through the exhaust line.

TEG systems stand out as one of the most applicable technologies in the automotive sector due to their simple structure, lack of moving parts, silent operation, and modular characteristics. Experimental studies show that it is possible to generate electricity at the level of a few watts in small-scale prototypes and at the kilowatt level in heavy vehicles. As a result, fuel consumption can be reduced by 2–10 per cent and CO_2 emissions can be reduced by 6–12 per cent. However, there are some technical and economic barriers to the widespread adoption of TEG technology. Maintaining high temperature gradients, minimising pressure losses, preventing heat leakage problems, and developing more economical alternatives to high-cost materials are emerging as priority research areas. In recent years, nanostructured materials, graphite-based solutions, and hybrid energy systems (TEG + ORC) have shown promising results in overcoming these problems.

Looking ahead, the use of TEG systems as an additional energy source in hybrid and electric vehicles, meeting the high electrical demands of autonomous vehicles, and the possibility of integration into aerospace applications increase the strategic importance of the technology. Furthermore, stricter global emission standards and energy efficiency targets make TEG applications particularly attractive in commercial transport.

Consequently, although TEG systems are still in the development phase, they will play a significant role in the transformation of the automotive industry as an innovative technology that contributes to both energy efficiency and environmental sustainability. With future material developments, system optimisations, and cost-reduction efforts, TEG technology is expected to become more widely adopted on a larger scale.

REFERENCES

Abdelghany, E. S., Mohamed, E. S., & Sarhan, H. H. (2023). Exhaust heat recovery performance analysis of a bi-fuel engine integrated with a TEG kit. *Case Studies in Thermal Engineering, 49,* 103288. https://doi.org/10.1016/j.csite.2023.103288

Asaduzzaman, M., Ali, M. H., Pratik, N. A., & Lubaba, N. (2023). Exhaust heat harvesting of automotive engines using thermoelectric generators. *Energy Conversion and Management: X, 19,* 100398. https://doi.org/10.1016/j.ecmx.2023.100398

Burnete, D., Gheorghiu, A., Muntean, N., & Radu, C. (2022). Review of thermoelectric generation for internal combustion engine waste heat recovery. *Progress in Energy and Combustion Science, 92,* 101017. https://doi.org/10.1016/j.pecs.2022.101017

Chammam, W., Kairouani, L., & Ben Nasrallah, S. (2023). Hybrid ORC–TEG systems for waste heat recovery: Performance and optimization. *Energy Conversion and Management, 289,* 117245. https://doi.org/10.1016/j.enconman.2023.117245

Chen, W., Li, Y., & Wang, Z. (2023). Multidisciplinary design optimisation of a power generation system based on TEG. *Chemical Engineering Science, 266,* 118211. https://doi.org/10.1016/j.ces.2023.118211

Esen, H., Kaya, E., & Demir, A. (2025). Experimental analysis of exhaust energy recovery performance of an internal combustion engine with TEG. *Energy, 281,* 129035. https://doi.org/10.1016/j.energy.2025.129035

Gürbüz, H., Akçay, H., & Topalcı, Ü. (2022). Experimental investigation of a novel thermoelectric generator for exhaust waste heat recovery in SI engines. *Applied Thermal Engineering, 216,* 119122. https://doi.org/10.1016/j.applthermaleng.2022.119122

Huang, Y., Zhou, L., & Deng, X. (2024). Thermal flow and thermoelectricity characteristics in a sandwich flat-type TEG device. *Energy, 278,* 128754. https://doi.org/10.1016/j.energy.2024.128754

Karabulut, M. (2025). *Application of a thermoelectric generator in a diesel engine using biodiesel and examination of its performance characteristics* (Doctoral thesis). Marmara University.

Lan, Z., Zhang, Y., & Huang, J. (2025). Graphite plates for enhanced high-temperature stability and thermal uniformity in TEG systems. *Energy, 280,* 129001. https://doi.org/10.1016/j.energy.2025.129001

Li, H., Wu, J., & Zhang, C. (2025). Optimising thermoelectric energy recovery from petrol engines. *Case Studies in Thermal Engineering, 68,* 105765. https://doi.org/10.1016/j.csite.2025.105765

Li, Y., Chen, H., & Zhou, Q. (2023). Performance analysis of diesel particulate filter integrated with TEG. *Energy, 263,* 125423. https://doi.org/10.1016/j.energy.2023.125423

Ni, H., Zhao, L., & Sun, Q. (2024). Numerical investigations on a thermoelectric generator based on diesel engine exhaust. *Energy, 282,* 129045. https://doi.org/10.1016/j.energy.2024.132815.

Oh, S., Ko, K., & Kim, J. (2024). Development of thermoelectric exhaust energy recovery system for a hydrogen ICE bus. *Energy Conversion and Management, 300,* 118006. https://doi.org/10.1016/j.enconman.2023.118006

Orjuela-Abril, S., Torregroza-Espinosa, A., Garrido-Yserte, R., Hernández-Comas, B., & Duarte-Forero, J. (2024). Evaluation of an integrated electric power generation system using natural gas engines and thermoelectric generators for hydrogen production. *Thermal Science and Engineering Progress, 47,* 102284. https://doi.org/10.1016/j.tsep.2023.102284

Ramírez-Restrepo, Á., Correa, M. Á., & López, M. E. (2021). Experimental study of the potential for thermal energy recovery with TEG in small diesel engines. *Heliyon, 7*(11), e08493. https://doi.org/10.1016/j.heliyon.2021.e08493

Sohrabi, A., Asgari, N., Imran, M., & Shahzad, M. W. (2023). Comparative energy, exergy, economic, and environmental (4E) analysis of Kalina cycles integrated with thermoelectric generators. *Energy Conversion and Management, 291,* 117320. https://doi.org/10.1016/j.enconman.2023.117320

Sok, R., & Kusaka, J. (2023). Experimental and modelling analysis on thermoelectric heat recovery in next-generation diesel engines. *Applied Thermal Engineering, 219,* 119530. https://doi.org/10.1016/j.applthermaleng.2022.119530

Tarhan, N. (2025). *Investigation of electricity generation from flue gases using thermoelectric generators with heat spreaders of different materials and sizes* (Master's thesis). Bingöl University.

Toker, R. A. (2025). *A new polymer-borophen nanocomposite-based thermoelectric generator module that converts waste heat into electrical energy* (Master's thesis). Maltepe University.

Tural, H. (2024). *Electricity production from exhaust and flow analysis using a thermoelectric generator system in a petrol-powered car* (Master's thesis). Kocaeli University.

Zhang, F., Liu, T., & Xu, Y. (2025). Performance analysis of a scramjet engine integrated with thermoelectric converters. *Renewable Energy, 213,* 1410–1425. https://doi.org/10.1016/j.renene.2025.02.011

Zhang, J., Wu, S., & Li, P. (2024). The impact of heat leakage through air gaps on thermoelectric generator performance. *Green Energy and Environment, 9*(1), 34–45. https://doi.org/10.1016/j.gee.2024.01.004

Selective Laser Sintering (SLS): A High Precision Additive Manufacturing Process

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INTRODUCTION

Selective Laser Sintering (SLS) is a cutting-edge Additive Manufacturing technology that has gained significant attention in recent years due to its ability to produce complex, customized parts with a wide range of materials, including polymers, metals, and ceramics. This technique involves the use of a laser to selectively fuse and consolidate powder particles in a layer-by-layer process, allowing for the creation of intricate geometries that are not easily achievable through traditional manufacturing methods[1-3].

SLS is an additive manufacturing method that uses the technique known as Powder Bed Fusion (PBF). The procedure is said to resemble SLA-type production. While SLA solidifies resin, SLS typically uses Nylon 11 or Nylon 12 thermoplastic material powders for solidification. A CAD model created in a computer environment is transferred to the SLS machine. Once the process starts, the lower build platform begins heating. This platform maintains the polymer powders at a temperature close to their melting point, facilitating the work of the laser beam responsible for solidification. A basic schematic representation of the SLS printer is presented in Figure 1.

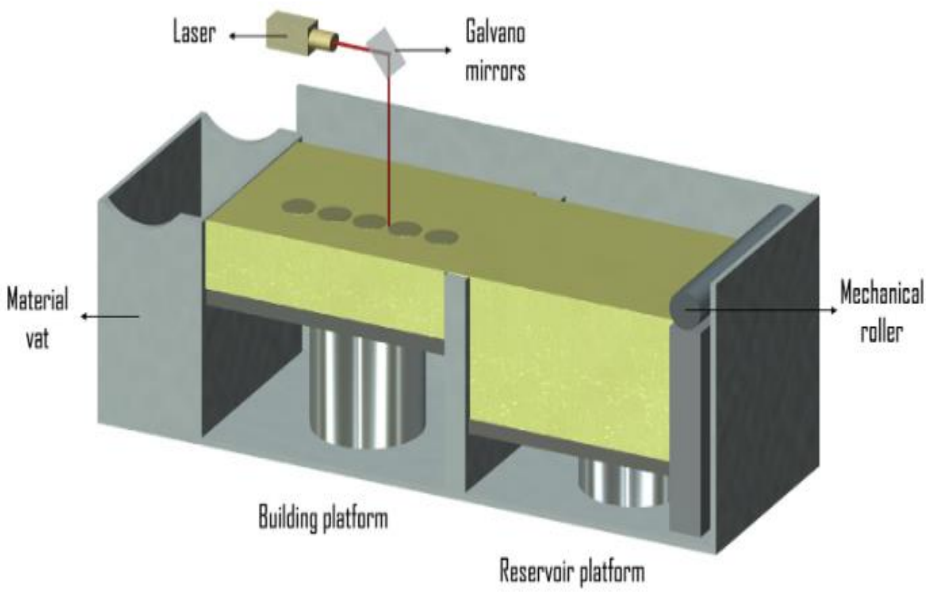

Figure 1. Selective Laser Sintering Printer[4]

WORKING PRINCIPLE

In the SLS process, 3D parts are built layer by layer by following the sequence of powder layering, laser sintering, and re-powder layering[5,6]. A diagram illustrating these production steps is presented in Figure 2. Here, the powder feed piston moves upward before each layer is sintered, and the recoating roller spreads the powder homogeneously across the surface. Subsequently, the CO_2 laser beam passes through lenses and is reflected onto the surface of the spread powder via a galvanometer mirror. As a result, the polymer powders, reaching their melting point, solidify where the laser beam strikes. Afterward, the build piston moves one layer down, and the powder is supplied again by the powder feed piston and spread across the surface by the recoating roller, continuing the process in the same manner. Once all layers are completed, the part is produced in 3D form.

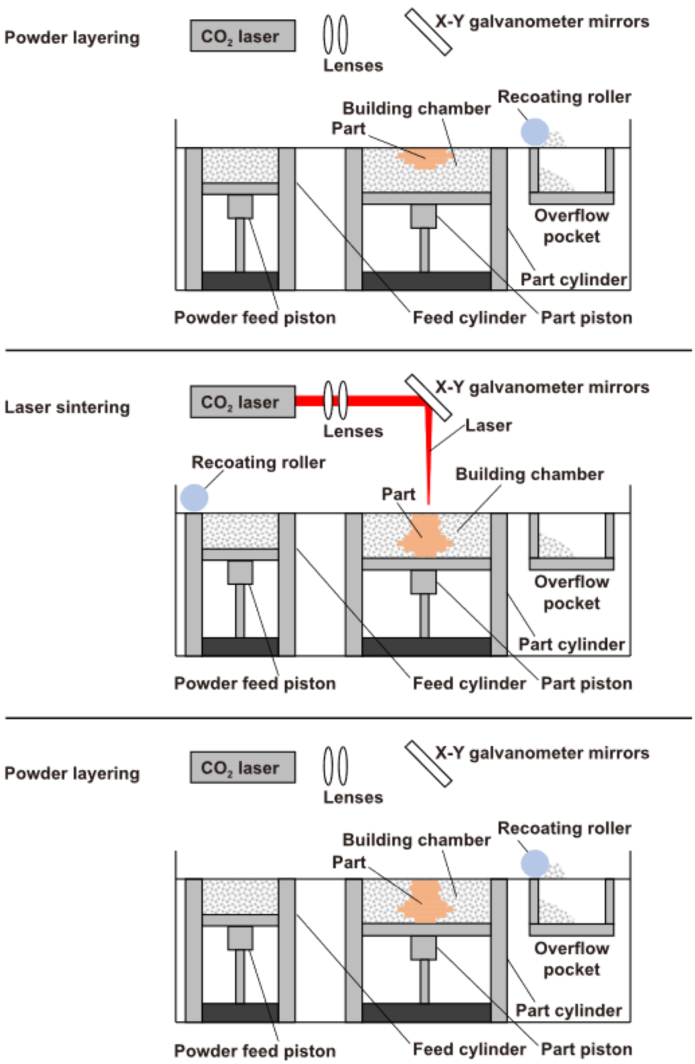

Figure 2. Selective Laser Sintering Process Scheme[7]

In Figure 3, the build chamber of the SLS machine is demonstrated. If details about the production process are to be provided: The heated powders are then selectively solidified layer by layer, starting from the base layer of the desired part, at a thickness of approximately 50-200 microns. The laser on the device, guided by a system of mirrors and motors, projects onto the specific points of each layer of the CAD model that need to solidify. The thermoplastic powders, already at a certain temperature, reach their melting point upon contact with the laser and sinter to form the designated layer of the part. Layers are successively created in this manner to build the complete part.

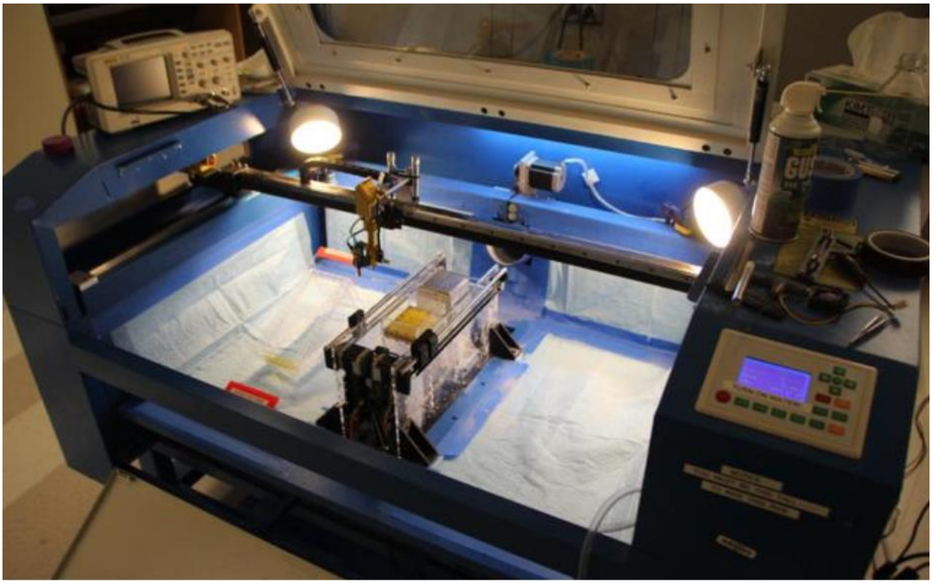

Figure 3. Build chamber of the SLS Machine[16]

Non-sintered powders surrounding the part remain in place, acting as a natural support structure. As layers are completed, the build platform lowers to allow the deposition of a new layer of powder, which is subsequently sintered. This process continues until the part is fully constructed. This approach enables the fabrication of complex structures with minimal material waste, as the un-sintered powder can be recycled and reused. After the procedure, the production chamber is allowed to cool.

Finally, the unsintered polymer powders surrounding the part are cleaned and reclaimed for future use, revealing the manufactured part. Depending on the desired surface quality, the part may undergo finishing processes such as sandblasting, polishing, painting, or coating. The timescale of the SLS process is presented in Figure 4.

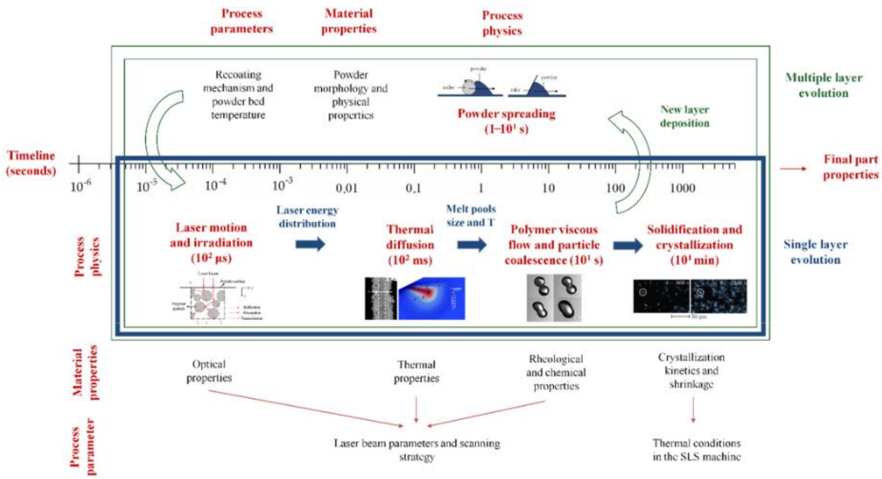

Figure 4. Timescale of the different physical phenomena involved in the SLS process, powder requirements for effective sintering, and relevant process parameters.[8]

The working principle of SLS involves the selective melting of a powder bed using a laser beam, followed by the deposition of a new layer of powder and the repetition of the process until the final part is complete.

One of the key advantages of SLS is its design flexibility, as it allows for the creation of complex geometries, internal structures, and integrated features that would be challenging or even impossible to manufacture using traditional methods. In addition, SLS can be used to process a wide range of materials, including polymers, reinforced and filled polymers, metals, and ceramics, further expanding its range of applications[9].

Laser-based Additive Manufacturing processes, such as Selective Laser Melting and Laser Engineered Net Shaping, have also played a significant role in the development of metallic products through Additive Manufacturing. These processes, while similar to SLS, involve the direct melting of metal powders using a laser to create near-net-shape components with stable properties[12]. Compared to traditional manufacturing techniques, these laser-based processes can offer improved design flexibility, reduced material waste, and enhanced opportunities for customization.

The widespread adoption of SLS and related laser-based Additive Manufacturing technologies has led to ongoing research and development efforts to address various challenges, such as improving process stability, enhancing part quality, and expanding the range of available materials. These advancements are expected to further drive the growth and application of SLS and related technologies in the future.

MATERIALS USED IN SLS PRODUCTION

SLS technique has been widely adopted in various industries, including aerospace, automotive, and medical, due to its ability to produce high-performance parts with customized properties[10,11]. SLS is compatible with a wide range of materials, enabling diverse applications[13,14]. In this technique, the following materials are commonly used, and their descriptions are provided below: nylon (PA11, PA12), glass-filled nylon, aluminum-filled nylon, TPU (thermoplastic polyurethane), polystyrene, and metal powders such as stainless steel or titanium.

Common Materials for SLS

Polyamide 12 (Nylon 12):

The most commonly used polymer in SLS due to its excellent balance of strength, flexibility, and chemical resistance. Can be used in functional prototypes, medical devices, automotive parts, and consumer products. Low water absorption, good thermal stability, and durability are the fundamental mechanical advantages of PA12 materials.

Polyamide 11 (Nylon 11):

Derived from renewable resources (castor oil) and offers higher elasticity compared to PA 12. Finds applications in medical implants, prosthetics, and flexible parts. High impact resistance, excellent ductility, and eco-friendliness are the basic mechanical advantages of PA11 materials.

PA 6 (Nylon 6):

Offers superior mechanical strength and thermal resistance but is less commonly used due to higher melting temperatures. It is commonly applied in high-performance engineering parts and industrial applications. Provides high stiffness and wear resistance in products.

Glass-Filled Nylon:

This material contains glass fibers for enhanced rigidity and dimensional stability. Can be used in automotive housings, fixtures, and aerospace parts. Has mechanical properties like increased stiffness and reduced flexibility.

Carbon-Fiber-Filled Nylon:

Infused with carbon fibers to provide higher strength-to-weight ratios. Finds applications in lightweight structural components in aerospace and motorsports. Provides excellent tensile strength and thermal stability.

Thermoplastic Polyurethane (TPU)

Known for its rubber-like elasticity and high impact resistance. Mostly used in flexible prototypes, seals, gaskets, and footwear. High elongation at break, good abrasion resistance, and excellent flexibility are the main mechanical advantages of this material.

Polypropylene (PP)

A lightweight and chemically resistant polymer used in SLS. Can be used in areas including; fluid-handling components, packaging, and automotive interiors. Low density, good fatigue resistance, and high chemical inertness is the important mechanical properties of PP material.

Polystyrene (PS)

A less common SLS polymer, typically used for applications requiring high rigidity. Can be used to produce disposable items, packaging, and prototyping. Provides mechanical properties like high stiffness and low cost, but brittleness is the disadvantage of this material.

Polyether Ether Ketone (PEEK) and High-Performance Polymers

Advanced engineering polymers used for high-temperature and high-strength applications. It is commonly applied in aerospace, medical implants, and electronics. Provides exceptional thermal and chemical resistance, biocompatibility (in medical-grade variants).

SLS MACHINE TYPES

Industrial SLS Machines

- Overview:
    - These are large-scale machines designed for high-volume production and complex geometries.
    - They are used primarily in industries like aerospace, automotive, and medical devices.
- Features:
    - Large build volumes, enabling the production of multiple parts simultaneously.
    - Advanced thermal control systems for consistent sintering.

- Multi-laser systems for faster production speeds.

- These types of machines enable the production of large-sized, complex geometry samples with high speed and high dimensional accuracy. The primary application sectors are aerospace, automotive, and medical devices. They allow simultaneous production of large-scale and diverse parts. Advanced thermal control systems ensure consistent sintering. To achieve high-speed production, they are equipped with multi-laser systems. An example of an industrial SLS machine is shown in Figure 5.

Figure 5. Industrial SLS Machine[17]

Compact SLS Printers

- Overview:
    - Compact and affordable machines designed for small businesses, educational purposes, or personal use.

- Features:
    - Smaller build volumes compared to industrial machines.
    - Lower power lasers, typically optimized for polymers like Nylon (PA 12).
    - Easier to use with simplified software interfaces.

These compact and affordable machines are designed for small businesses, educational purposes, or personal use as can be seen in Fig. 6. They feature smaller build volumes compared to industrial machines and utilize lower-power lasers, typically optimized for polymers such as Nylon (PA 12). Additionally, their simplified software interfaces make them user-friendly and accessible for a wide range of applications.

Figure 6. Desktop SLS Machine[18]

High-Performance SLS Machines

- Overview:
    - Machines with advanced features for creating high-precision and high-performance parts.
    - Often used for aerospace or medical applications requiring specific material properties.

- Features:
    - Multi-laser or high-power laser systems for rapid production.
    - Ability to process advanced composites (e.g., carbon-fiber-filled or glass-filled nylons).
    - Integrated post-processing capabilities in some systems.

These machines, equipped with advanced features, are designed for creating high-precision and high-performance parts, often used in aerospace and medical applications requiring specific material properties. An example of SLS machines used in this context is presented in Figure 7. They feature multi-laser or high-power laser systems for rapid production, the ability to process advanced composites such as carbon-fiber-filled or glass-filled nylons, and integrated post-processing capabilities in some systems. Additionally, these machines can have automated interfaces and optimized accessories that reduce cycle times and ensure operational build times lasting several days, making them highly efficient for demanding production environments.

Figure 7. High Performance SLS Machine[19]

Metal SLS Machines (DMLS Variants)

- Overview:
    - While SLS typically refers to polymer sintering, metal-based machines use a similar process known as Direct Metal

Laser Sintering (DMLS) or Laser Powder Bed Fusion (LPBF).

- Suitable for aerospace, automotive, and biomedical applications.

- Features:
  - High-power lasers for sintering metal powders.
  - Requires advanced cooling systems and controlled atmospheres (e.g., inert gases like Argon).
  - High precision for producing metal prototypes and functional components.

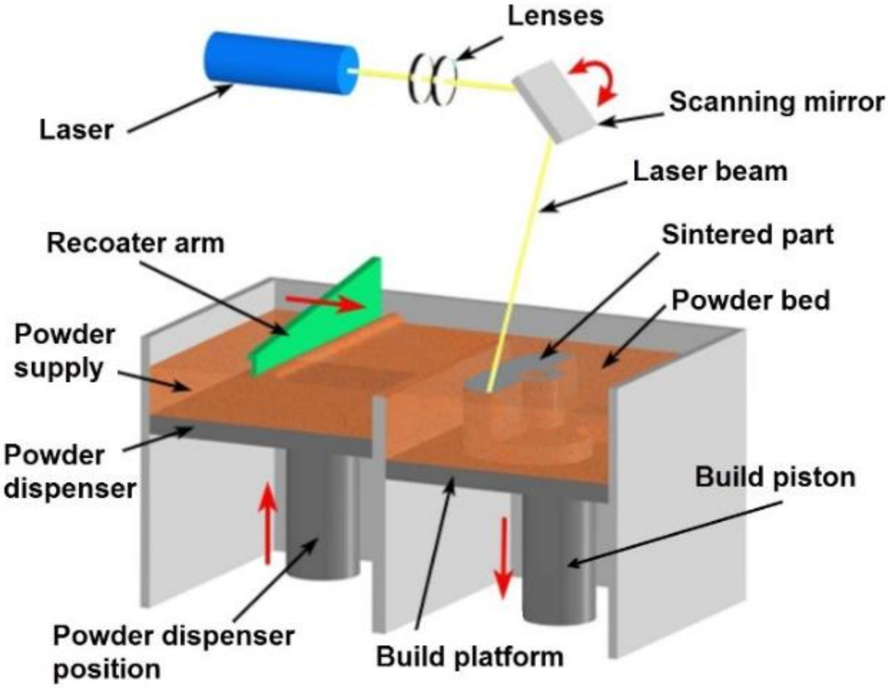

Figure 8. Schematic diagram of DMLS process [15]

Customizable and Modular SLS Machines

- Overview:
  - Designed for scalability and customization to meet specific production needs.
  - Often used in research or specialized industries.

- Features:
    - Modular components for upgrading build volume or material capacity.
    - Open material platforms, allowing the use of third-party powders.
    - Research-focused machines enable parameter tweaking.

Customizable SLS machines, specifically tailored for rapid prototyping in small-to-medium enterprises, are designed to balance performance, cost, and usability. An example of a customizable SLS machine is shown in Figure 9. Typically featuring a limited build volume, this type of SLS machines is ideal for producing smaller parts quickly and efficiently while being optimized for faster cycle times to enable rapid design iterations.

Figure 9. Customizable SLS Machine[20]

Available in various configurations, from educational setups to high-temperature-capable systems, they often include modular components that allow users to upgrade or customize features like build platforms or laser systems. Their user-friendly interfaces and open material platforms provide flexibility for experimenting with different powder materials, making them a versatile and cost-effective solution for prototyping and small-scale production. This adaptability makes them particularly appealing to industries seeking to minimize costs while maintaining high-quality output.

KEY CONSIDERATIONS WHEN CHOOSING AN SLS MACHINE

- Build Volume**:** Large volumes are ideal for industrial-scale production, while smaller ones suit prototyping.
- Material Compatibility**:** Ensure the machine supports the desired polymer, composite, or metal powders.
- Speed and Efficiency**:** Multi-laser systems and advanced thermal controls improve productivity.
- Cost**:** Desktop SLS machines are more budget-friendly, while industrial systems involve higher upfront and operational costs.

The type of SLS machine you choose depends on the specific application, material requirements, and production scale.

Advantages of SLS Production

The advantages of production using the SLS method can be listed as follows:

Design Freedom: Allows for complex geometries and intricate details, enabling the production of parts that would be difficult or impossible to create using traditional manufacturing methods. This makes it ideal for lightweight structures, internal channels, and customized components.

No Supports Needed: The unsintered powder surrounding the part acts as a natural support structure during printing, eliminating the need for additional support materials. This reduces post-processing time and allows for more efficient use of material and design space.

Material Efficiency: Many SLS powders, especially PA 12 can be collected and reused in subsequent prints, minimizing material waste and reducing overall production costs. This makes SLS both economical and environmentally friendly.

Wide Material Range: SLS supports a variety of polymers such as PA 11, PA 12, TPU, and composites, allowing customization for specific industry needs including automotive, aerospace, medical, and consumer products.

Durability: Produces strong and functional parts with excellent mechanical properties, making them suitable for end-use applications, prototypes, and components that require high strength and wear resistance.

Challenges in SLS Production

The challenges of production using the SLS method can be listed as follows:

Surface Finish: Parts often have a rough and grainy texture due to the powder-based process, requiring additional post-processing such as sanding, polishing, or coating to achieve smoother and more visually appealing surfaces.

Powder Degradation: Repeated thermal exposure during the printing process can cause changes in the chemical and physical properties of the powder, reducing its quality and limiting the amount that can be reused in future builds.

Material Costs: High-quality powders used in SLS are often more expensive than those in other additive manufacturing methods, which can increase overall production costs, especially for large-scale or frequent printing.

Machine Costs: SLS machines are generally more expensive than other 3D printing technologies due to their advanced components, high-powered lasers, and precise temperature control systems, making the initial investment significantly higher.

RESULTS AND CONCLUSION

Selective Laser Sintering (SLS) has emerged as one of the most robust and versatile additive manufacturing technologies, offering a unique combination of geometric freedom, mechanical integrity, and material efficiency. Its layer-by-layer sintering approach enables the fabrication of complex internal features, lightweight lattice structures, and customized components that would be challenging—if not impossible—to produce via conventional manufacturing techniques.

A major strength of the SLS process lies in its material portfolio, which continues to expand with the development of high-performance polymers, composites, and bio-compatible alternatives. Particularly notable is the recyclability of polyamide-based powders such as PA 12, which contributes significantly to waste reduction and resource efficiency. Nevertheless, challenges such as powder degradation due to repeated thermal cycling and the need for surface post-processing remain areas of active investigation and technological refinement.

In parallel, advancements in machine architecture, laser systems, and thermal control mechanisms are contributing to increased process stability and reduced operational costs. These improvements are making SLS more accessible not only to large-scale industrial manufacturers but also to small and medium enterprises seeking rapid prototyping and end-use part production. Furthermore, the incorporation of artificial intelligence (AI) and machine learning algorithms is enabling intelligent process optimization—ranging from real-time parameter tuning to predictive maintenance—thus enhancing reliability and repeatability across production cycles.

The potential applications of SLS are rapidly diversifying. In the medical domain, it facilitates the creation of patient-specific implants and prosthetic devices with precise anatomical compatibility. In the aerospace and automotive sectors, the technology supports the production of lightweight, high-strength parts that meet stringent performance standards. Meanwhile, the consumer goods industry is increasingly utilizing SLS for the manufacture of individualized products, such as custom footwear, eyewear, and wearable devices.

Looking ahead, the evolution of SLS is expected to be driven by continued innovation in materials science, hardware miniaturization, and digital design workflows. As mass customization becomes a central paradigm in modern manufacturing, SLS stands out as a key enabler due to its ability to efficiently transition from digital models to fully functional, application-ready components without the need for tooling.

In conclusion, Selective Laser Sintering represents not only a mature technology for current industrial needs but also a strategic foundation for the future of smart and sustainable manufacturing. Its convergence with digital technologies and data-driven design promises to unlock new capabilities, making it an indispensable asset in the next generation of advanced production systems.

REFERENCE

[1] D. L. Bourell, P. Vallabhajosyula, B. Stevinson, S. Chen, and J. J. Beaman, "Rapid Manufacturing Using Infiltration Selective Laser Sintering," in *Volume 1: Advanced Energy Systems; Advanced and Digital Manufacturing; Advanced Materials; Aerospace*, Haifa, Israel: ASMEDC, Jan. 2008, pp. 173–178. doi: 10.1115/ESDA2008-59084.

[2] Sanjeet. Chandra, "Trends in Selective Laser Sintering in Biomedical Engineering," *IJETER*, vol. 8, no. 1, pp. 54–59, Jan. 2020, doi: 10.30534/ijeter/2020/10812020.

[3] B. Xiao and Z. Ye, "Selective Laser Sintering: Processing, Materials, Challenges, Applications, and Emerging Trends," *J. Adv. Therm. Sci. Res.*, vol. 11, pp. 65–99, Dec. 2024, doi: 10.15377/2409-5826.2024.11.4.

[4] A. Awad, F. Fina, A. Goyanes, S. Gaisford, and A. W. Basit, "3D printing: Principles and pharmaceutical applications of selective laser sintering," *International Journal of Pharmaceutics*, vol. 586, p. 119594, Aug. 2020, doi: 10.1016/j.ijpharm.2020.119594.

[5] H. M. Yehia, A. Hamada, T. A. Sebaey, and W. Abd-Elaziem, "Selective Laser Sintering of Polymers: Process Parameters, Machine Learning Approaches, and Future Directions," *JMMP*, vol. 8, no. 5, p. 197, Sept. 2024, doi: 10.3390/jmmp8050197.

[6] J. Kruth, P. Mercelis, J. Van Vaerenbergh, L. Froyen, and M. Rombouts, “Binding mechanisms in selective laser sintering and selective laser melting,” *Rapid Prototyping Journal*, vol. 11, no. 1, pp. 26–36, Feb. 2005, doi: 10.1108/13552540510573365.
[7] W. Han, L. Kong, and M. Xu, “Advances in selective laser sintering of polymers,” *Int. J. Extrem. Manuf.*, vol. 4, no. 4, p. 042002, Dec. 2022, doi: 10.1088/2631-7990/ac9096.
[8] F. Lupone, E. Padovano, F. Casamento, and C. Badini, “Process Phenomena and Material Properties in Selective Laser Sintering of Polymers: A Review,” *Materials*, vol. 15, no. 1, p. 183, Dec. 2021, doi: 10.3390/ma15010183.
[9] N. Raghunath and P. M. Pandey, “Improving accuracy through shrinkage modelling by using Taguchi method in selective laser sintering,” *International Journal of Machine Tools and Manufacture*, vol. 47, no. 6, pp. 985–995, May 2007, doi: 10.1016/j.ijmachtools.2006.07.001.
[10] S. Kumar and S. Pityana, “Laser-Based Additive Manufacturing of Metals,” *AMR*, vol. 227, pp. 92–95, Apr. 2011, doi: 10.4028/www.scientific.net/AMR.227.92.
[11] Y. A. Gueche, N. M. Sanchez-Ballester, S. Cailleaux, B. Bataille, and I. Soulairol, “Selective Laser Sintering (SLS), a New Chapter in the Production of Solid Oral Forms (SOFs) by 3D Printing,” *Pharmaceutics*, vol. 13, no. 8, p. 1212, Aug. 2021, doi: 10.3390/pharmaceutics13081212.
[12] W. Guoqing, H. Yingzhou, Z. Weinan, S. Chenguang, and H. Hongsong, “Research Status and Development Trend of Laser Additive Manufacturing Technology,” in *2017 4th International Conference on Information Science and Control Engineering (ICISCE)*, Changsha: IEEE, July 2017, pp. 1210–1213. doi: 10.1109/ICISCE.2017.251.
[13] M. Schmid, A. Amado, and K. Wegener, “Polymer powders for selective laser sintering (SLS),” presented at the PROCEEDINGS OF PPS-30: The 30th International Conference of the Polymer Processing Society – Conference Papers, Cleveland, Ohio, USA, 2015, p. 160009. doi: 10.1063/1.4918516.
[14] B. Özbay Kisasöz, İ. Tütük, E. Koç, S. S. Karabeyoğlu, and A. Kisasöz, “Seçici lazer sinterleme yöntemiyle üretilen PA 12 matrisli seramik takviyeli kompozitlerin aşınma davranışının incelenmesi,” *Gazi Üniversitesi Mühendislik Mimarlık Fakültesi Dergisi*, vol. 39, no. 2, pp. 1029–1036, Nov. 2023, doi: 10.17341/gazimmfd.1207967.
[15] M. Marrey, E. Malekipour, H. El-Mounayri, and E. J. Faierson, “A Framework for Optimizing Process Parameters in Powder Bed Fusion (PBF) Process Using Artificial Neural Network (ANN),” *Procedia Manufacturing*, vol. 34, pp. 505–515, 2019, doi: 10.1016/j.promfg.2019.06.214.
[16] “OpenSLS - An Open Source Project Creates a Sub-$15K Selective Laser Sintering 3D Printer” *3DPrint.com | The Voice of 3D Printing / Additive Manufacturing*, Jun. 03, 2014. https://3dprint.com/5104/opensls-sls-3d-printer/
[17] “EOS Formiga P396 SLS Printer” *3dprint-uk.co.uk*, 2025. https://www.3dprint-uk.co.uk/eos-formiga-p396-sls-printer/ (accessed Sep. 18, 2025).
[18] “Fuse 1+ 30W: Compact Selective Laser Sintering (SLS) 3D Printer” *Formlabs*, 2025. https://formlabs.com/asia/3d-printers/fuse-1/ (accessed Sep. 18, 2025).

[19] "EOS P 500 - For Industrial Scales" *EOS GmbH*, 2025. https://www.eos.info/polymer-solutions/polymer-printers/eos-p-500#key-features (accessed Sep. 18, 2025).

[20] "403P Series" http://www.songyi.net, "403P Series | Farsoon Technologies," *Farsoon-gl.com*, 2020. https://www.farsoon-gl.com/products/403p-series (accessed Sep. 18, 2025).

Thermodynamic Analysis, Design and Applications of Pulsejet Engines

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ABSTRACT

This section comprehensively examines the thermodynamic principles, design dynamics and modern application areas of pulsejet engines. While Pulsejet engines attract attention with their simple structures that do not contain moving parts, they pose difficulties in terms of analysis due to their complex operating mechanisms based on discontinuous combustion and acoustic resonance. Section comprehensively examines the thermodynamic principles, dynamic design and modern application areas of pulsejet engines. While Pulsejet engines attract attention with their simple structures that do not contain moving parts, they pose difficulties in terms of analysis due to their complex operating mechanisms based on discontinuous combustion and acoustic resonance. The basic operating principle is based on a thermoacoustic feedback loop that produces thrust through periodic combustion explosions.

Keywords – Pulsejet, Thermodynamic, Jet Engine, Engine Design

INTRODUCTION

Pulsejet engines have the simplest mechanical structures in aviation history. They are among the most complex propulsion systems in terms of their operating principles. Their basic operating principle is based on generating thrust through periodically repeated combustion bursts. A striking feature of these engines is that, unlike gas turbines, they do not contain complex, high-precision parts such as moving compressors or turbines (Matveev, 2003). This mechanical simplicity makes them attractive for their low cost, high reliability, and ease of manufacture. The engine essentially consists of an air intake (usually a one-way valve system or a valveless design), a combustion chamber, and a long, straight exhaust pipe that creates a resonant effect (Heiser & Pratt, 1994).

Pulsejets are classified as "unsteady flow" engines due to their operating principles. This means that the flow characteristics within the engine (pressure, temperature, velocity) are not constant but rather change continuously and periodically with time. This makes their analysis much more complex than that of steady-flow engines like turbojets and ramjets. The operating cycle consists of four main stages:

- *Intake and Compression:* A fresh air and fuel mixture is drawn into the combustion chamber. As the intake valves close, the mixture begins to compress due to residual heat from the previous cycle.
- *Combustion:* The compressed mixture is ignited by a spark or by spontaneous ignition. This causes an immediate and violent increase in pressure and temperature.
- *Expansion and Exhaust:* High-pressure gases rapidly expand out the exhaust pipe. This expansion creates the primary force (thrust) that pushes the engine forward.
- *Exhaust-Intake Transition (Critical Phase):* The pressure wave emerging from the open end of the exhaust pipe is reflected as a "negative pressure wave" (rarefaction wave). When this wave returns to the combustion chamber, it reduces the pressure in the chamber below atmospheric pressure, creating a suction effect that allows the next batch of fuel-air mixture to enter the combustion chamber, restarting the cycle (Cumpsty, 2003). This self-sustaining cycle repeats tens or hundreds of times per second.

Germany in World War II. To today, they continue to exist in specialized applications such as experimental vehicles, micro unmanned aerial vehicles (UAVs), target drones, and thermoacoustic generators. Their main disadvantages are their low fuel efficiency (thermal efficiency is typically between 5% and 15%), their characteristic and extremely high noise levels (130-140 dB), and their relatively short service life due to the high thermal load (Gollahalli, 1990).

HISTORICAL DEVELOPMENT AND EVOLUTION

Pulsejet engines date back to early internal combustion engine experiments in the late 19th century. In 1906, Russian engineer "Karavodin" proposed the "Pulsating". He patented a device and he called the "Combustor" that used the principle of pulsating combustion. Similarly, Swedish inventor Martin Wiberg worked on early pulsejet-like systems. However, the maturation of pulsejet technology into a practical and reliable engineering product came in the 1930s with the pioneering work of German engineer Paul Schmidt. Schmidt developed an efficient design that effectively controlled mixture intake and exhaust using a spring-loaded flapper valve system (Schmidt, 1945).

The culmination of these German investigations, Argus “The Argus As 014” engine was developed in collaboration with the Motoren company and Schmidt. Measuring 2.7 meters in length and weighing approximately 75 kg, this engine produced 3.5–4.0 kN (approximately 350–400 kgf) of thrust. The engine's characteristic high frequency, rasping "sawing" sound made it easier for Allied forces to detect it from a distance. It was also extremely inefficient and was used largely as a psychological weapon (Lissaman, 1985).

In the postwar period, the rapid development of more efficient, quieter, and higher-speed turbojet engines pushed pulsejets out of mainstream aerospace and defense applications. However, due to their simplicity, high static thrust, and low cost, experimental and niche work never ceased. In the 1950s, Hiller Companies work on like Helicopters and Lockheed valveless pulsejet models. In the 21st century, pulsejets have regained traction thanks to advanced materials (high-temperature ceramics), precision manufacturing techniques, and advanced computer analysis methods (Computational Fluid Dynamics - CFD). Currently, their potential for use in hybrid systems (pulsejet-ramjet), compact propulsion systems for micro -UAVs and target drones, and thermoacoustic generators that generate electricity using industrial waste heat are being extensively investigated (Yang, 1991; Matveev, 2003).

THERMODYNAMIC FUNDAMENTALS AND ENERGY ANALYSIS

The thermodynamic analysis of a pulsejet engine differs fundamentally from that of a steady-state, steady-flow system such as the classical Brayton (gas turbine) or Rankine cycle. A pulsejet is modeled as an unsteady, open control volume because all properties at every point in the system, such as pressure, temperature, density, and mass flow rate, change continuously and rapidly throughout a cycle (Turns, 2012). This dynamic structure both complicates the analysis and explains the unique characteristics of the engine.

Energy Balance and Control Volume Analysis

The first law of thermodynamics (conservation of energy) is written as follows, considering a control volume for the pulsejet:

$$dE_{system} / dt = \dot{Q} - \dot{W} + \Sigma\, \dot{m}_{in} (h + V^2/2 + gz)_{in} - \Sigma\, \dot{m}_{out} (h + V^2/2 + gz)_{out}$$

In this equation:

dE_{system} / dt: The rate of change of energy within the control volume with respect to time.

$\dot{Q}$: The heat transfer rate to the system (added to the system by combustion).

$\dot{W}$: The speed of work done at the boundaries of the system.

$\Sigma\, \dot{m}_{in} (h + V^2/2 + gz)_{in}$: Energy (enthalpy, kinetic energy, potential energy) entering the control volume along with the mass.

$\Sigma\, \dot{m}_{out} (h + V^2/2 + gz)_{out}$: Energy released along with the mass leaving the control volume.

Pulsejet engines, the potential energy change is negligible. The term $\dot{W}$ is usually set to zero because there is no work done through a shaft; the only "useful work" done is the boundary work acting on the system boundaries (specifically the combustion chamber and exhaust walls) via the thrust of the exhaust gases, propelling the vehicle forward. $\dot{Q}$ is added to the system in large instantaneous quantities by the combustion process. With these simplifications, the energy balance is essentially expressed in terms of heat transfer, mass inflow and outflow, and their associated enthalpy and kinetic energy (Cumpsty, 2003).

Fluid Properties and Combustion Products

The gases formed because of combustion are a complex mixture consisting of components such as carbon dioxide (CO_2), water vapor (H_2O), nitrogen (N_2), excess oxygen (O_2) and, depending on combustion inefficiency, carbon monoxide (CO), nitrogen oxides (NOx), and unburned hydrocarbons (HC). In engineering calculations, this mixture is often assumed to exhibit ideal gas behavior and heat capacities are constant of the mixture (Glassman, 2014).

Cycle and Productivity Analysis

The pulsejet cycle cannot be described as a precise blend of ideal thermodynamic cycles (Otto, Diesel) because discontinuity and acoustic effects dominate. However, conceptually, it contains elements like heat addition (combustion) at constant volume and heat rejection at constant pressure. The actual cycle is fraught with irreversibilities (entropy generation) caused by flow friction, incomplete combustion, heat loss to the walls, and shock waves.

Thermal Efficiency (η_{th})

The overall efficiency of the engine in converting the chemical energy in the fuel into kinetic energy (work of thrust). It is defined approximately as:

$$\eta_{th} \approx (F \cdot V_0) / (\dot{m}_f \cdot LHV)$$

Here:

F: Measured thrust force (N)

V_0: Vehicle flight speed (m/s) Since this term is zero in the steady-state test ($V_0 = 0$), the thermal efficiency is also calculated as zero, which shows the limitation of this definition.

$\dot{m}_f$: Fuel mass flow rate (kg/s)

LHV: Lower Heating Value of Fuel (J/kg)

In practice, the thermal efficiency of pulsejet engines is typically in the 5% to 15% range, depending on design and operating conditions. This is significantly lower than that of modern gas turbines (over 25-40%) (Turns, 2012).

The primary reasons for this low efficiency are:

- *High Exhaust Temperature:* A significant portion of the energy is released through exhaust gases that are still at very high temperatures (800-1000°C).
- *Incomplete Combustion:* Combustion is inefficient due to the mixture of not becoming homogeneous in a short time and cold wall effects.
- *Heat Transfer Losses:* Intense heat transfer to the combustion chamber and exhaust pipe walls.

- *Turbulence and Friction Losses:* Friction caused by high-speed, turbulent flow.
- *Shock Losses:* Shock waves formed in supersonic flow regions cause loss by converting mechanical energy into heat (Lefebvre, 1999).

Table 1: Avarage Performance Data for a Typical Small-Scale Pulsejet Engine

Parameter	Symbol	Average or Typical Value	Unit
Exhaust Temperature	T_e	850	°C
Exhaust Exit Velocity	V_e	220	m/s
Suction Pressure (Average)	p_i	0.92 p_a (Sub- Atmospheric)	bar (relative)
Exhaust Pressure (Average)	p_e	1.05 p_a (Upper Atmospheric)	bar (relative)
Working Frequency	f	185	Hz
Impulse (Stationary State)	F	27	N
Fuel Flow (Kerosene)	$\dot{m}_f$	0.025	g/s
Total Efficiency (Estimated)	η_0	~8%	-

DETAILED ANALYSIS OF THE COMBUSTION PROCESS AND ENERGY CONVERSION

Pulsejet engines differ fundamentally from continuous combustion systems (such as those in gas turbines and rockets). Here, combustion is intermittent and periodic, occurring separately for each cycle. This means that there is a very limited timeframe for mixture preparation, ignition, and combustion to be completed (Gollahalli, 1990).

Combustion Chemistry and Stoichiometry

Depending on the fuel used, the stoichiometric reaction (the theoretical ideal rate for complete combustion) is expressed by the general formula. For example, for dodecane ($C_{12}H_{26}$), which represents kerosene or jet fuel, the stoichiometric reaction is:

$$C_{12}H_{26} + 18.5\ (O_2 + 3.76\ N_2) \rightarrow 12\ CO_2 + 13\ H_2O + 69.56\ N_2$$

However, the chemical reactions are incomplete because the combustion duration is extremely short (on the order of milliseconds) and the mixture is not always homogeneous. This leads to the presence of carbon monoxide (CO), unburned hydrocarbons (HC), and soot (carbon particles) in the exhaust emissions. Furthermore, the locally very high flame temperatures (1800-2200K) trigger the conversion of atmospheric nitrogen (N_2) to nitrogen oxides (NO, NO_2), referred to as thermal NOx (Turns, 2012). Pulsejets are generally operated with near-stoichiometric or slightly rich mixtures because lean mixtures reduce ignition reliability and flame stability.

Heat Release Rate (HRR)

It is one of the most critical parameters in the energy conversion of combustion. In a turbojet or ramjet, the HRR is relatively constant, while in a pulsejet, the HRR has a highly impulsive profile, rising and falling abruptly with time. The timing, shape, and magnitude of the HRR profile interact directly with the engine's resonant frequency and pressure waves. For optimum performance, maximum heat release must occur at or just before the moment when combustion chamber pressure also peaks. This synchronization is crucial for maximizing thrust and maintaining self-sustaining oscillations (Lefebvre, 1999).

Energy Conversion Chain and Losses

The energy flow and conversion in the system can be summarized as follows:

1. **Chemical Energy:** It is stored in the chemical bonds of fuel molecules.
2. **Thermal Energy:** It is released suddenly by the combustion reaction, sharply increasing the temperature and pressure of the combustion gases.

3. **Kinetic Energy and Pressure Work:** High-pressure gases rapidly expand outward from the exhaust pipe. In this process, the internal energy and pressure of the gases are used to accelerate them to high speeds (kinetic energy).

4. **Thrust (Change of Momentum):** The change in momentum of high-speed exhaust gases exerts a thrust force on the engine (and hence the vehicle to which it is attached) in the opposite direction (Newton's third law of motion).

The main energy losses in this process are:

- *Sensible Heat Loss:* The biggest loss is that the exhaust gases are still discharged at a very high temperature (usually 800-1000°C).

- *Heat Transfer to the Wall:* Continuous heat transfer occurs to the combustion chamber and exhaust pipe walls.

- *Chemical Loss:* Chemical energy remaining in the form of incomplete combustion products (CO, HC, soot).

- *Flow Losses:* Conversion of mechanical energy (pressure) into heat due to turbulence, friction and shock waves (Glassman, 2014).

ACOUSTIC RESONANCE, FREQUENCY CONTROL AND WAVE DYNAMICS

The pulsejet engine, and the key feature that distinguishes it from all other jet engines, is that it acts as an acoustic resonator. The exhaust pipe is essentially a "quarter-wave resonator" This means that the length of the pipe is critical for the resonance of acoustic waves, which determines the operating frequency of the engine (Matveev, 2003).

Dynamics of Pressure and Velocity Waves (The Pulsejet)

A pulsejet cycle is governed by the continuous reflection and interaction of pressure and velocity waves:

1. *Combustion and Forward Pressure Wave:* After a combustion stroke, a high-pressure wave (compression wave) travels down the

exhaust pipe. This pushes the exhaust gases out at high speed, creating most of the thrust.

2. *Reflection and the Negative Backward Pressure Wave:* When this forward pressure wave reaches the open end of the pipe, it is reflected as a "rareflection wave" (rareflection/negative pressure wave). Because the open end acts as a "free end" in acoustics, the pressure wave changes phase (the pressure becomes a node instead of an antinode) when reflected.

3. *Suction Effect:* When this negative pressure wave returns to the combustion chamber, it reduces the pressure in the chamber significantly below atmospheric pressure. This lower pressure creates a suction effect, which:

    - In valve engines: The flapper opens the valves and allows the next fuel-air mixture to enter the combustion chamber.
    - valveless engines: Triggers the intake of fresh air from both intake and exhaust.

4. *Reignition and Cycle Repetition:* The fresh mixture entering the combustion chamber is ignited either by hot residual gases from the previous cycle, a hot surface (hot pipe), or a spark (usually only at startup). The cycle then repeats itself until the engine is shut down.

This self-sustaining, energetically closed loop is called a “thermoacoustic feedback loop”. Heat energy (combustion) is converted into acoustic energy (pressure waves), which in turn organizes and schedules the next combustion event (Yang, 1993).

Sound Pressure Level (SPL) and Noise

Pulsejet engines are extremely noisy due to these violent, periodic pressure oscillations. SPL levels can easily reach around 130-140 dB(A). This level is not only painful to the human ear, carries the potential for permanent hearing damage, and makes the engine easy to detect in military applications. The noise spectrum is concentrated around the fundamental operating frequency and its harmonics.

COMPUTATIONAL FLUID DYNAMICS (CFD) SIMULATIONS

The complex, transient, turbulent, chemically reactive, and acoustically coupled nature of pulsejet engines makes it extremely difficult to fully understand and optimize through experimental means alone. Computational Fluid Dynamics (CFD) has become an indispensable tool for visualizing, quantifying, and understanding the physical phenomena within these engines (Anderson, 2016).

Modeling Process and Challenges

1. **Geometry and Mesh Generation:** The engine's 3D geometry (intake, combustion chamber, exhaust pipe) is created in CAD software. This geometry is overlaid with a mesh structure that divides the computational domain into millions of small cells (mesh/grid). In critical regions with high gradients, such as the combustion chamber and the beginning of the exhaust pipe, the mesh is significantly finer to increase solution accuracy.

2. **Boundary Conditions and Solver Settings:** The input (pressure input or mass flow input), output (pressure output), and wall conditions defining heat transfer and friction are determined. A transient solver is selected, and the time step is set small enough (milliseconds or less) to accurately capture high-frequency oscillations (≥50 Hz). This significantly increases computational cost.

3. **Physical Models:**

    - *Turbulence Model:* To model the turbulent nature of the flow, RANS (Reynolds -Averaged) models such as k-ε, k-ω SST are used. Navier-Stokes) models or the more advanced and accurate but much more computationally intensive LES (Large Input Simulation) models can be used.

    - *Combustion Model:* Eddy to model chemical reactions " Dissipation Model" (EDM) or " Flamelet Generated

Mixture-controlled or premixed combustion models such as " manifold " are used.

- *Acoustic Modeling:* Compressible flow solvers are used for accurate propagation of pressure waves.

Analysis and Benefits of CFD Results

When a simulation is run, all variables within the engine, such as pressure, temperature, speed, turbulent kinetic energy, and concentration of chemical species, are obtained as a function of time and space. This “sanitized experiment” data is used to:

- *Visualization:* See animations of how pressure waves propagate, reflect, and interact along a pipe.
- *Performance Estimation:* Calculating thrust and efficiency by integrating the velocity and temperature distribution in the exhaust.
- *Combustion Optimization:* Analyze combustion efficiency, heat release rate, and emissions.
- *Design Optimization:* Testing and optimizing the effect of different design variables (pipe length (L), combustion chamber volume, inlet cross-sectional area, valve design) on performance quickly and inexpensively without making a physical prototype (Yang, 1991).

PERFORMANCE ANALYSIS, THRUST CALCULATIONS AND EFFICIENCY METRICS

A pulsejet engine is measured and evaluated by primary impulse, specific impulse, power and various efficiency parameters.

Thrust Calculation

Thrust is calculated by the general thrust formula, considering the momentum change and pressure forces:

$$F = \dot{m} \cdot (V_e - V_0) + (p_e - p_0) \cdot A_e$$

Here:

- F: Total thrust force (N)

- $\dot{m}$: Total mass flow rate (air + fuel) (kg/s)
- V_e: Average gas velocity at the exhaust outlet (m/s)
- V_0: Inlet air speed (flight speed) (m/s)
- P_e: Average static pressure at the exhaust outlet (Pa)
- p_0: Atmospheric pressure (Pa)
- A_e: Exhaust outlet cross-sectional area (m^2)

Efficiency Metrics

- *Propulsive Efficiency (η_p):* The efficiency with which the engine converts the jet kinetic power into thrust useful for the aircraft. The general formula for jet engines is: $\eta_p = (2 \cdot V_0) / (V_e + V_0)$
  This formula shows that the closer the jet speed (V_e) is to the flight speed (V_0), the higher the thrust efficiency. Pulsejets have a high Ve (typically 400-600 m/s), so their thrust efficiency is very low at low speeds ($V_0 \sim 0$). As V_0 increases, η_p increases.
- *Thermal Efficiency (η_{th}):* As defined above, it is the efficiency of converting chemical energy in the fuel into jet kinetic energy.
  η_{th} = (Jet Kinetic Power) / (Fuel Energy Input Power)
- Total Efficiency (η_0): It is the ultimate indicator of the overall performance of the system and is the product of thermal efficiency and thrust efficiency:
  $\eta_0 = \eta_{th} \cdot \eta_p$

Pulsejet performance is optimized by operating the engine at its natural acoustic resonance frequency. Deviations from this frequency (due to temperature changes or fuel flow changes, for example) cause pressure wave synchronization, resulting in poor charging, inefficient combustion, and ultimately reduced thrust and efficiency.

APPLICATION AREAS, CURRENT RESEARCH AND FUTURE PERSPECTIVE

Pulsejet engines (simplicity, high thrust/weight, low cost) make them extremely suitable for certain niche and innovative applications:

- *Hybrid Pulsejet-Ramjet Systems:* Ramjet engines cannot operate efficiently at low speeds (typically Mach <0.5) because they cannot provide sufficient compression for self-sufficient operation. A pulsejet can be used as a " booster " during a vehicle's takeoff and initial acceleration. Once sufficient speed is reached (Mach 2-3), the ramjet is engaged, and the pulsejet is deactivated. This offers the potential to create a propulsion system with no moving parts, capable of operating from zero to hypersonic speeds.
- *Micro/Mini UAVs and Target Drones:* For small-sized, low-cost UAVs and target drones, pulsejets' high power-to-weight ratio and mechanical simplicity are a major advantage. They are particularly well-suited for single-use or reusable military reconnaissance and target systems.
- *Thermoacoustic Generators and Heat Recovery:* The pulsejet principle can be used to convert waste heat directly into useful acoustic energy and subsequently into electricity. Valveless Pulsejet designs offer the potential to utilize waste heat from industrial furnaces, cogeneration systems, or concentrated solar power systems to create a generator with no moving parts (a thermoacoustic engine). This is a highly reliable and low-maintenance energy conversion method.
- *Education and Research:* They are excellent and relatively inexpensive educational tools that provide students and researchers with practical, high-impact experiments in the fields of thermodynamics, fluid dynamics, combustion, acoustics, and control systems.

Future Perspective and Research Directions

Pulsejet technology is being shaped by research aimed at reducing its main disadvantages (low efficiency, high noise, short life) and expanding its range of applications:

- *Materials Science and Cooling:* Ceramic matrix composites (CMCs) and advanced superalloys that are resistant to high temperatures, thermal shock, and fatigue can extend engine life and improve efficiency by allowing higher combustion temperatures. Regenerative cooling techniques are also being actively researched.

- *Intelligent Control and Active Stabilization:* Actively controlled fuel injection (with fast-responding solenoid valves) and even variable-geometry exhausts can ensure that the engine maintains optimum resonance and mixture ratio at different speeds, altitudes and atmospheric conditions.
- *Optimization with Advanced CFD and Machine Learning:* High-fidelity simulations combined with AI and machine learning can lead to optimized designs (geometry, materials) that maximize efficiency and thrust, which are impossible to discover with traditional methods.
- *Alternative and Sustainable Fuels:* Hydrogen is a clean fuel option for pulsejets, offering high combustion efficiency, rapid flame speed, and zero carbon emissions. Sustainable biofuels and synthetic fuels are also being explored as alternatives to fossil fuels.
- *Noise Reduction Techniques:* Acoustic silencers, active noise control methods and optimizing exhaust geometry are being developed to reduce noise, one of the biggest handicaps of pulsejets.

9. CONCLUSION

Pulsejet engines are fascinating and paradoxical propulsion systems that combine engineering simplicity, high thrust density, and mechanical reliability with physical complexity, low efficiency, and high noise levels. While historically symbolized by the V-1 missile (V1 flaying bomb, these drawbacks have prevented them from finding a permanent place in general aviation. However, the operating principle of these engines represents a complex and dynamic combination of the first and second laws of thermodynamics, compressible fluid dynamics, chemical kinetics, and acoustics, making them extremely rich subject for academic and research purposes (Matveev, 2003; Turns, 2012).

Today, advanced computational methods (CFD), next-generation materials, and increasing niche application needs have rekindled interest in pulsejet technology. These simple yet powerful engines are likely to play an even more significant role in areas such as hybrid systems, micro-UAVs, target drones, and thermoacoustic energy conversion. Pulsejets stand as ongoing proof of how fundamental physical principles, despite their limiting shortcomings, can be translated into innovative and practical engineering solutions. As research leads to breakthroughs in efficiency and noise reduction, the potential of pulsejets in aerospace and energy technology may expand even further.

REFERENCE

Anderson, J. D. (2016). Fundamentals of aerodynamics (6th ed.). McGraw-Hill Education.

Cumpsty, N. (2003). Jet propulsion: A simple guide to the aerodynamic and thermodynamic design and performance of jet engines (2nd ed.). Cambridge University Press.

Glassman, I., & Yetter, R. A. (2014). Combustion (5th ed.). Academic Press.

Gollahalli, S. R. (1990). Combustion phenomena in pulsejet engines. Combustion Science and Technology, 70(1-3), 125–145. https://doi.org/10.1080/00102209008951607

Heiser, W. H., & Pratt, D. T. (1994). Hypersonic airbreathing propulsion. American Institute of Aeronautics and Astronautics.

Lefebvre, A. H., & Ballal, D. R. (2010). Gas turbine combustion: Alternative fuels and emissions (3rd ed.). CRC Press.

Liepmann, H. W., & Roshko, A. (2002). Elements of gasdynamics. Dover Publications.

Lissaman, P. B. S. (1985). Aerodynamic considerations of pulsejet propulsion. Progress in Aerospace Sciences, 22(2), 109–141. https://doi.org/10.1016/0376-0421(85)90002-5

Matveev, K. I. (2003). Pulsejet engines: Theory, design and optimization. Springer-Verlag.

Schmidt, P. (1945). Pulsejet engine development. Journal of Jet Propulsion, 15(5), 217–225.

Turns, S. R. (2012). An introduction to combustion: Concepts and applications (3rd ed.). McGraw-Hill.

Yang, V. (1991). Multi-dimensional analysis of pulsejet engines. AIAA Journal, 29(5), 752–759. https://doi.org/10.2514/3.10658

Yang, V. (1993). Thermoacoustic oscillations in pulsejet engines. AIAA Journal, 31(2), 294–301. https://doi.org/10.2514/3.11333