Exhaust Gas Flow Study of Electric Turbo Compounding (ETC) to Determine the Potential Electrical Energy Recovery from Exhaust Emission

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***Abstract* – Electric turbo compounding (ETC) emerges as a pivotal energy recovery solution, seamlessly combining an advanced turbocharger with a high-speed generator to harvest electrical energy from exhaust gas dynamics. This research delves into the practical application of ETC in vehicles, employing a comprehensive approach blending simulation techniques with experimental validation. The investigative process involves meticulous data collection on vehicle muffler dimensions, subsequent device modelling based on this data, and rigorous flow simulations, followed by thorough analysis. The study's key findings highlight a noteworthy 9% increase in engine back pressure at 850 rpm, counterbalanced by a 7% reduction at 2000 rpm. Despite the integration of the ETC mechanism, electric current measurements remain consistently within the range of 1.4 to 1.6 amperes at 1200-2000 rpm. This research not only unveils the tangible effects of ETC on engine performance but also underscores its viability as an efficient energy recovery solution in the automotive sector, setting the stage for advancements in sustainable transportation.**

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1. Introduction

The Internal Combustion Engine (ICE) plays a crucial role in powering modern vehicles, yet a significant portion of the energy it generates goes unused [16]. Research indicates that the energy conversion efficiency of the combustion chamber ranges from 25% to 40%, leaving a substantial amount of heat energy wasted [19]. Cooling and lubrication structures contribute to additional energy losses, with friction accounting for 2% to 10% of energy waste. Despite advancements, the energy utilised to move the vehicle's wheels remains below 15% of the total energy produced [6], [18]. Previous studies, such as those employing the mechanical turbo compounding mechanism (MTC), have shown promise in increasing engine power and efficiency by harnessing exhaust gas flow [18]. However, challenges persist, as MTC absorbs only 25.7% of potential exhaust energy. Alternative approaches, like utilising exhaust gas heat for motorcycle battery energy, have demonstrated limited success [1], [15]. Meanwhile, research utilising a mechanical turbine mechanism has shown improvements in brake mean effective pressure at specific engine speeds [3]. This review underscores the need for further exploration to address the limitations of existing methods and identifies potential avenues for enhancing energy recovery systems in internal combustion engines.

The study's importance lies in addressing the considerable energy losses in vehicles, where only 12.6% of the total energy reaches the wheels, while the majority is wasted in engine loss, idling, accessories, and power transfer [6], [19].

Despite previous efforts in energy recovery, significant room for improvement remains in vehicle energy harvesting mechanisms. Various studies, including regenerative shock absorbers, aim to reuse wasted energy [12]. A critical aspect of increasing combustion engine efficiency involves recovering exhaust energy, with methods like turbocharging and turbo-compounding systems proposed for unexpanded gas energy recovery [7]. Turbo compounding, categorized into mechanical turbo compounding (MTC) and electric turbo compounding (ETC), has shown promise in generating mechanical and electrical energy, respectively. While MTC has demonstrated positive effects, ETC, when used, can reduce fuel consumption by 3% to 10%, offering potential benefits in meeting vehicle electrical energy demands [16]. Notably, ETC has predominantly been tested on diesel engines, and this study explores its impact on gasoline engines, contributing novel insights to the field of exhaust gas flow management.

This study investigates the impact of exhaust gases, both with and without the electric turbo compounding (ETC) mechanism, on changes in pressure, velocity, and temperature. The focus is on understanding the alterations in exhaust gas behaviour between engines equipped with ETC and those without. Unlike previous research, which did not delve into the ETC mechanism's influence on engine installation, our study aims to fill this gap by exploring the specific effects on exhaust gas flow. Turbo-compounding, a method employed to extract additional energy from exhaust gases, has shown promise in enhancing system productivity. Two types of turbocompounds, mechanical and electrical, differ in their utilisation of the obtained power. While mechanical turbo-compounds directly boost the vehicle's propulsion system, electrical turbo-compounds, like ETC, operate independently. ETC's distinct advantage lies in its ability to control turbine velocity separately from engine speed, reducing the risk of improper operation. Despite the fuel savings achieved by turbocompounds in aircraft and heavy-duty engines, challenges arise, such as increased exhaust back pressure affecting fuel consumption under low engine loads. This study aims to contribute valuable insights into the specific effects of ETC on exhaust gas dynamics, address gaps in existing research, and pave the way for future ETC developments.

Previous research on a 2 L diesel engine with series-turbo compounding demonstrated fuel consumption reduction specific to brakes but raised engine back pressure [9]. Another study showcased the potential of a turbo compounding unit coupled with an EGR valve, yielding an extra 14 kW of power [5], [10], [11].

Experiments with IVECO engines (3L) using different exhaust configurations revealed varying performance at different engine loads, with both systems capable of recovering power in the 2-2.5% range [8]. Comparisons between diesel internal combustion engines (ICEs) and turboshaft engines favoured ICEs for lowering CO2 emissions and fuel consumption, particularly for long-range and medium-to-high loads [13], [14], [21].

Building on this, the study implements electric turbo compounding (ETC), akin to mechanical turbo compounding, with a focus on producing electrical energy. The system integrates a clutch and high-rotation generator, allowing energy storage or direct use for vehicle operation. This technology has shown energy savings of 3% to 10%, making it particularly suited for small and medium-sized engines [4]. Our research aims to contribute to this field by further exploring the advantages and addressing potential drawbacks of ETC, emphasising its practicality and efficiency for widespread implementation.

The application of turbo compounding in heavy-duty engines has gained notable success and attention for its potential benefits [12]. Previous studies have extensively explored different configurations, including integrated, series, and parallel setups. A numerical comparison revealed that the parallel configuration demonstrated the best fuel performance, achieving notable success [6]. Notably, research employing the integrated configuration successfully extracted excess power from the turbine with a generator integrated into the turbocharger shaft, resulting in significant fuel savings of 10% and 6% [2], [14], [20]. However, conflicting results were found in a numerical comparison of series and parallel configurations, where the series architecture outperformed the parallel design [8], [23]. It can be possibly influenced by adjustment methods, engine types, and turbine characteristics. Generally, smaller power turbines are required in the parallel case. Additional literature supports the positive impact of the series configuration, reporting fuel savings ranging from 1.9% to 2.76% [5], [10]. As this field continues to evolve, our research aims to contribute by further exploring the advantages and drawbacks of different turbo compounding configurations, focusing on practical implementation, and optimising fuel efficiency for varying engine types and conditions.

The organic Rankine cycle (ORC), thermoelectric generator, and turbo compounding are utilised in exhaust energy recovery systems. Among these, the ORC stands out for its application in vehicles, offering increased thermal efficiency without causing exhaust gas backpressure.

Over the past 30 years, researchers have explored the Rankine cycle's potential for internal combustion engines (ICE), revealing a 15% efficiency improvement in 4-cylinder engines. While the Rankine cycle is commonly used in stationary engines, the thermoelectric system shares similarities but avoids causing pressure back on the flue gas utilization. It operates based on the Peltier-Seebeck effect, converting thermal energy into electrical energy [17].

Materials such as silicon germanium, lead telluride, bismuth telluride, and new oxide materials like NaxCO2O4 are commonly used in these systems, chosen for their thermal properties. Additionally, the integration of a turbine generator into the turbocharger system results in two types of turbo compounding: electric and mechanical. Mechanical turbo compounding converts exhaust gas energy into mechanical energy, directly linked to the crankshaft through a gear mechanism. On the other hand, electric turbo compounding converts the energy into electrical energy using a generator connected to the turbine [7].

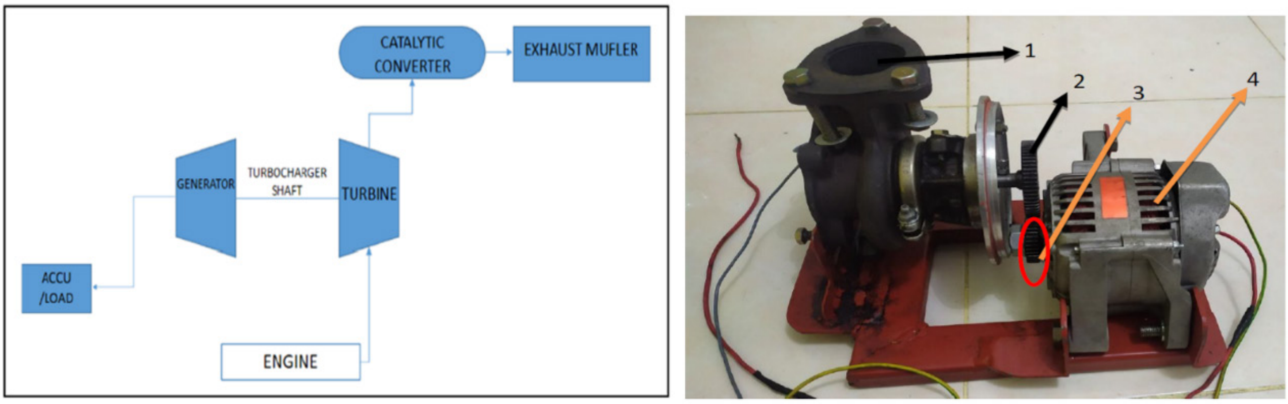
The significance of these systems lies in their potential to enhance thermal efficiency in ICE, particularly in 4-cylinder engines. The upcoming research aims to further explore and compare the efficiency and practicality of electric and mechanical turbo compounding systems, contributing to the ongoing advancements in exhaust energy recovery for improved vehicle performance and fuel efficiency.

2. Research Methodology

This study was conducted at Padang State University's Automotive Engineering Department's Motor Fuel Laboratories. The research aimed to investigate the impact of Electric Turbo Compounding (ETC) on an internal combustion engine's exhaust gas flow, pressure, and temperature.

The engine used for the study has the following characteristics: it is a 1NR-VE 1,329 cc 4-cylinder engine with a power output of 98 PS at 6000 rpm and a torque of 12.4 Kgm at 4200 rpm. The ETC mechanism, explicitly designed for this study, involves a modified turbocharger paired with an electric generator, as depicted in Fig. 1.

The experimental setup involved modifying the exhaust system to integrate the ETC mechanism and conducting simulations and tests to measure its effects on various exhaust gas parameters. The study collected data at six distinct points along the exhaust gas duct to ensure a comprehensive analysis of the changes induced by the ETC mechanism.



(a) (b)

Figure 1. Electric turbo compounding, (a) Schematic of ETC installation on engine, (b) ETC mechanism with 1. Exhaust gas inlet after exhaust manifold, 2. output shaft turbocharger mounted gear, 3. input gear generator, and 4. electric generator

The ETC mechanism designed in this study works by channeling the vehicle exhaust gas from the exhaust manifold to the ETC inlet, and inside the ETC mechanism is a fan that will rotate if passed by the exhaust gas flow. Pressured exhaust gas will rotate the fan contained in the ETC mechanism, and the rotation of the turbo charger will be channeled to the electric generator via the gear mechanism. The gear used has a 1: 2 ratios, which means that one rotation of the turbo charger gear results in two rotations of the electric generator.

The generated electricity will be proportional to the engine rotation, the higher the engine rotation, the greater the generated electric current. In this study, 2D simulation was used to see the effect of ETC installation so that the application's effect on back pressure and temperature increase can be easily determined. The research data is presented descriptively in the form of tables and graphs. The data is then analyzed, and the results are used to compare pressure, velocity, and exhaust gas flow temperature between systems that use ETC mechanisms and those that do not. The outcomes will be related to how it affects engine performance.

3. Results and Discussion

This section presents the findings from the simulations and tests conducted to understand the impact of the electric turbo compounding (ETC) mechanism on exhaust gas flow, pressure, and temperature. The goal is to evaluate how the ETC mechanism influences these parameters and subsequently affects overall engine performance.

3.1. Characteristics of Engines Using ETC

Testing was performed three times in the engine simulation using the ETC mechanism, with the parameters observed being pressure, temperature, and velocity. Based on the previous simulation, this research was carried out by making modifications to the exhaust system. As shown in the Fig. 2, the difference in pipes between points 2 and 3 was cut and then paired with the ETC mechanism. The research data was collected at six different points along the exhaust gas duct, as shown in Fig. 2. It is expected that the addition of the ETC mechanism to the exhaust system will result in a change in the exhaust gas flow value. Description of point selection is as follows:

- Point 1, was chosen before the connection to the exhaust manifold to observe how the exhaust gas fluid is before entering the exhaust pipe.
- Point 2, after connecting the exhaust manifold to the exhaust pipe, choose this position to determine the state of the exhaust gas after entering the exhaust pipe.
- Point 3, is visible in Fig. 2, this position was chosen because the pipe between points 2 and 3 will be severed and paired with the ETC mechanism, thus, this position was chosen as a comparison with the situation afterwards.
- Point 4, between the silencer connection and the sewer filter.
- Point 5, before the exhaust gas enters the gas line filter exhaust.
- Point 6, at the end of the first pipe filter.

Point 6 was chosen as the last reference because, after the exhaust gas passes point 6, it will be retained and moved through several filter plates before finally flowing to the exhaust duct. Placing a new point after point 6 would result in less precise data. The flow movement of exhaust gas in the filter can be seen in Fig. 3, where the red arrow indicates the direction of the exhaust gas fluid after exiting point 6. With the turbine in the mechanism, the exhaust gas flow is temporarily contained, which can raise the exhaust gas temperature and pressure. Research was conducted to analyze the input parameters and the simulation results are depicted in Fig. 4.

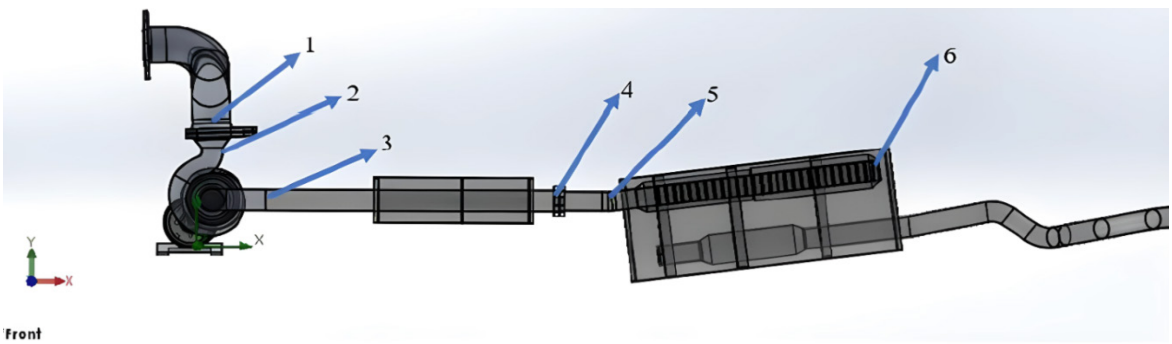


Figure 2. Extermination system with ETC mechanism and data collection points

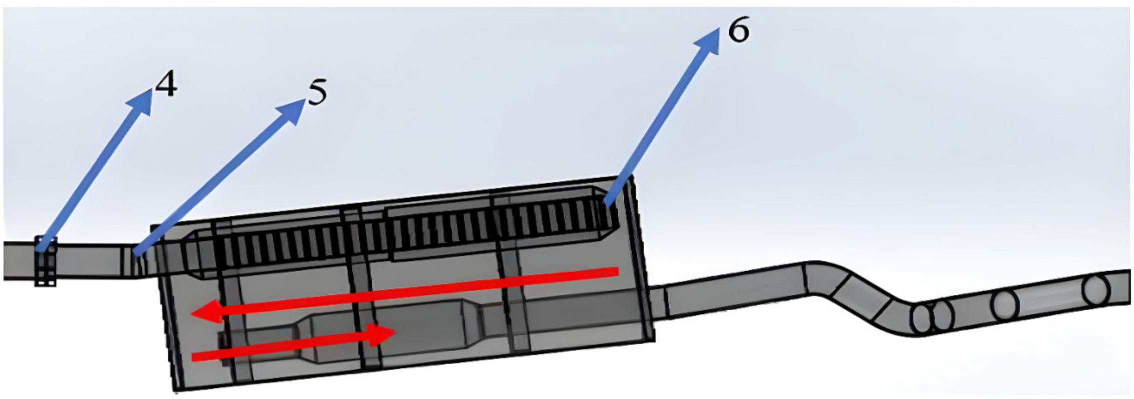


Figure 3. Exhaust gas flow after entering the filter

3.2. Simulation Results with Inlet Mass Flow

This research reveals a new understanding of the effect of the ETC mechanism on the characteristics of exhaust gas flow in the engine, as well as its impact on overall engine performance. The findings showed that the use of the ETC mechanism caused significant changes in the pressure, temperature, and speed of the exhaust gas flow. In particular, the pressure increases overall, while the exhaust gas temperature tends to decrease and the flow velocity increases. However, the increased pressure that occurs due to containment of the exhaust gas flow in the ETC turbine can inhibit complete combustion and reduce the power generated. In addition, the increase in temperature caused by the use of the ETC mechanism can result in overheating of components, interfere with work, increase the risk of detonation, and reduce machine efficiency, and service life.

Unlike previous studies that only focused on emission aspects [11], [20]. This study highlights the influence of the ETC mechanism comprehensively, from exhaust gas flow characteristics to overall engine performance. Thus, this research makes a valuable contribution in deepening the understanding of the specific effects of the ETC mechanism on gas exhaust systems and engine performance. This makes this study different and relevant compared to other similar studies, as it focuses on this important aspect of machine technology.

Fig. 4 shows the results of simulations performed on engines that do not use the ETC mechanism with an inlet mass flow. According to Fig. 4 (a), the pressure in the system decreases from point one to point six. The exhaust manifold is the most stressed component. Based on the results shown in Fig. 4(b), the exhaust gas temperature values drop relative to the temperature in the exhaust manifold.

When the exhaust gas exits the exhaust pipe, the temperature is already approaching the ambient temperature because the environment, which is significantly lower than the system temperature, influences the temperature decline. As can be seen in Fig. 4(c), the exhaust gas flow velocity starts off low in the exhaust manifold and increases as it gets closer to the exhaust pipe. According to Bernoulli's law, the increase in speed is caused by changes in cross-sectional size. The pressure in the exhaust system is very high, around 210000 Pa, compared to the pressure input of 200000 Pa, with the highest pressure at point 1 caused by exhaust gas buildup because it is retained by the turbine, as shown in Figure 5(a). While the temperature in the intake manifold and the ETC mechanism is quite high compared to the temperature in the silencer, the increase in temperature is due to the retained exhaust gas in the ETC mechanism. The increase in pressure triggers an increase in temperature, but the temperature increase is not significant, as shown in Figure 5(b). When exhaust gas exits the turbine and is pushed, it accelerates, improving the acceleration value in the ETC system. However, prior to the exhaust gas exiting the turbine, there is temporary detention at points 1 and 2, which results in low pressure at those locations, as illustrated in Fig. 5(c).

The difference in pressure between systems that use the ETC mechanism and systems that do not use the ETC mechanism can be seen in Figures 4 and 5. The system that uses the ETC mechanism has a higher pressure than the system that does not use the ETC mechanism, which is due to the containment of exhaust gas flow that is held in the ETC turbine. This increase in pressure can affect engine performance. As explained by state that there is back pressure then this can inhibit the rest of the combustion out of the combustion chamber [8]. This causes the total fuel entering the combustion chamber to decrease, resulting in a reduction in power generated. The combustion chamber is reduced, allowing the engine's power to be reduced in the end. Systems with the ETC mechanism have a higher temperature than systems without the ETC mechanism [9].

In comparison to systems that do not employ the ETC mechanism. Increased temperature can influence the engine, causing overheating, which can disrupt the work of several components. Overheating can disrupt the work of some components and cause rapid wear on others. Detonation can also be caused by an increase in temperature. Temperature can cause engine detonation. As a result, incomplete combustion occurs, and engine power is reduced. Incomplete combustion can occur because of detonation. At point 5, the exhaust gas flow velocity of the system utilising the ETC mechanism decreases and rises further, whereas the system not utilising ETC has a significantly lower exhaust gas flow velocity. The rotation of the ETC turbine, which gives the exhaust gas that has gone through the turbine an extra push, affects the difference in speed.

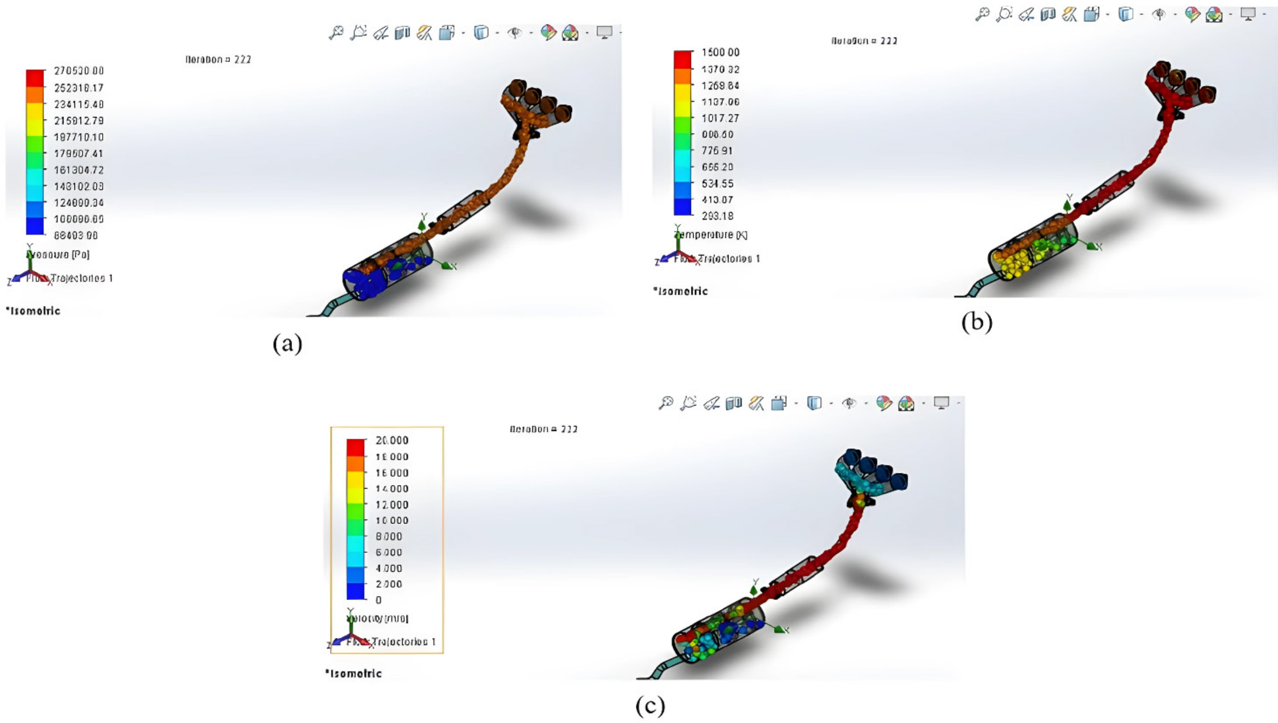


Figure 4. Combustion gas properties without ETC, (a) pressure characteristics, (b) temperature properties, (c) velocity properties

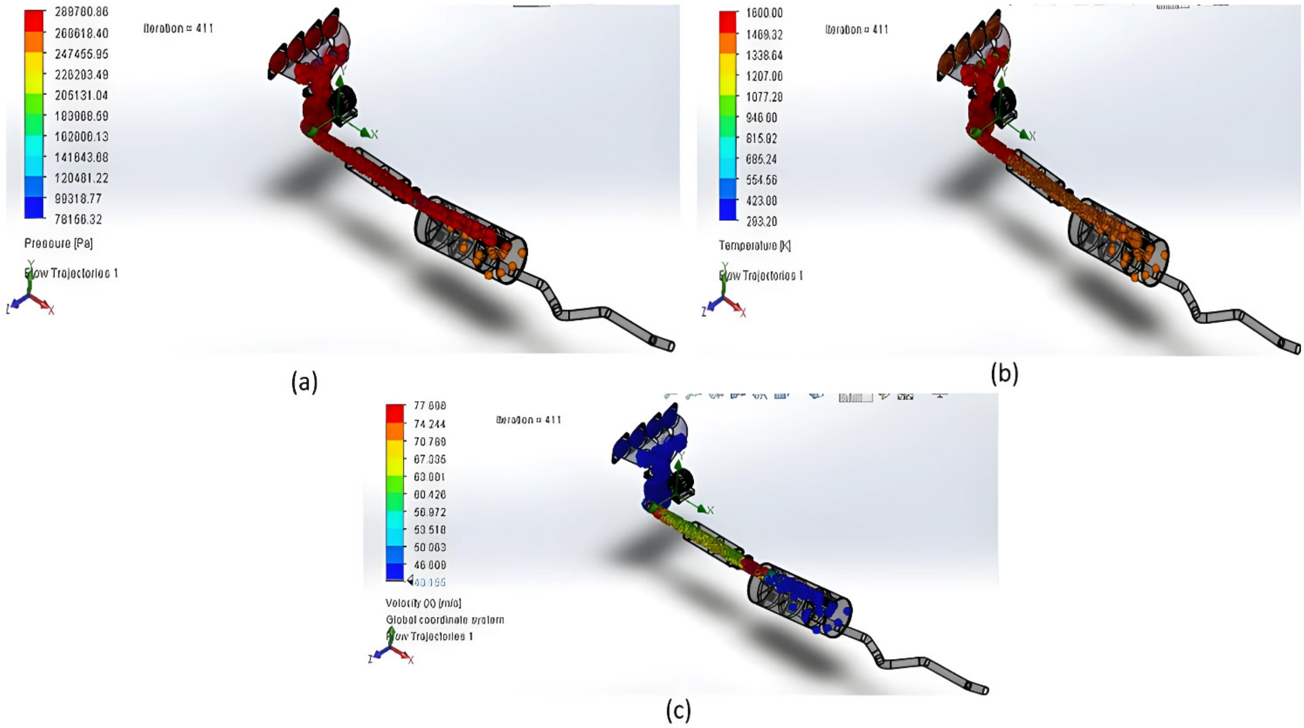


Figure 5. Combustion gas properties with ETC (a) pressure, (b) temperature, and (c) velocity

3.3. Characteristics of Engines Using ETC

Table 1. Generation currents from the application of ETC

Engine Speed (RPM)	Current (A) measurement			Average	Back pressure (bar)			Average	Normal back pressure (Bar)
	1	2	3		1	2	3		
850	1,25	1,18	1,29	1,24	1,2	1,2	1,23	1,21	1,1
1200	1,35	1,35	1,4	1,37	1,23	1,23	1,23	1,23	1,2
1800	1,45	1,4	1,41	1,42	1,3	1,3	1,3	1,30	1,23
2000	1,48	1,47	1,46	1,47	1,4	1,4	1,4	1,40	1,3

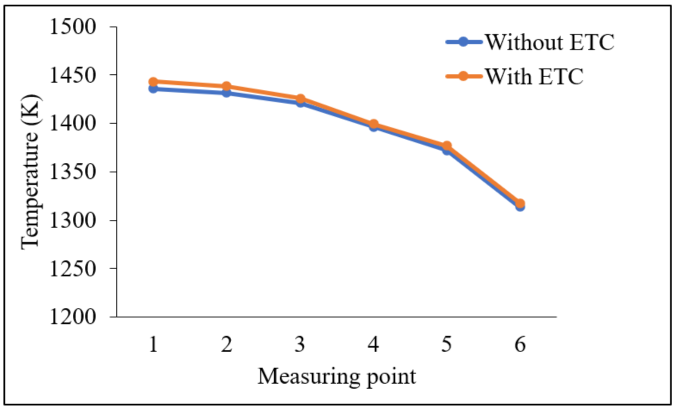


Figure 6. Temperature generation in exhaust manifold

As illustrated in Table 1. The results of electric current measurements taken by installing the ETC mechanism on the engine stand are 1.4 - 1.6 Ampere at 1200-2000 rpm. The electric current generated will increase in tandem with the increase in rotation. Additionally, it is verified that the exhaust manifold pressure, as indicated by Figure 5(a), temperature 5(b), and velocity 5(c), would rise. According to the results of the back pressure measurement, the back pressure increases by 9% at engine speed 850 rpm but decreases by 7% at engine speed 2000 rpm. Of course, an increase in back pressure raises engine temperature. Figure 6 depicts the graph of temperature increase in this study. The figure clearly shows that the temperature rise is not significant. As a result, the increase in engine temperature will have no effect on vehicle fuel consumption. The findings of this study are consistent with those of study [23]. According to many tests, the turbo-compound approach yielded fuel savings ranging from around 2-6%. [5], [8], [10]. Notably, fuel savings of 10% were attained with the engine running at full load. Heavy-duty diesel engines are best suited for the turbo-compound technology due to its brief igniting phase [22].

The efficiency distinctions between engines containing and not containing ETC are more pronounced [8], where the initial BSFC percentage variation is compared to the total BSFC of the ETC-equipped test engine under the same operating conditions. Fuel consumption decreases at each level of ICE rotation speed when induction conditions exceed about 60% of the entire load. When applied to gasoline engines, the values displayed are consistent with those discovered by other researchers [2], [14]. Even when the latter is accomplished using a low-pressure turbine parallel to or after the turbo generator (TC). Only at test engine rotation rates below 2000 rpm and full load does a minor improvement become visible due to the electrical power consumed to reach the required piston pressure. Nonetheless, a higher backpressure increase is obtained compared to not using the ETC, offering a definite benefit regarding power output. Under aspirated circumstances, only a tiny increase in BSFC occurs below around 60% of the full load [12].

According to the findings of this study, the energy produced by the generator can be used to support the electrical load of the vehicle, thereby lowering the alternator resistance torque. It should be noted that, while the generator unit allows for a partial return of exhaust energy, it also causes increased back pressure with increased SFC. A more engaging simulation study is made possible by the powertrain model and the reciprocal interplay of the ICE and ETC models.

4. Conclusion

The primary benefit of this study is demonstrating ETC's ability to generate a substantial amount of electrical current without significantly impacting the exhaust manifold's pressure and temperature. This makes it a promising technology for integration into existing vehicle systems. However, the study also highlights potential shortcomings, such as the risk of increased back pressure leading to incomplete combustion and reduced engine power. Additionally, the increased temperature caused by the ETC mechanism could lead to overheating and faster wear of engine components.

Future research should address the identified shortcomings, such as developing strategies to mitigate back pressure and temperature increases. Studies could explore optimising ETC mechanisms to balance energy recovery with minimal impact on engine performance. Further investigation into the long-term effects of ETC integration on engine durability and maintenance requirements is also essential. Additionally, expanding research to include different types of engines and varying operational conditions would provide a more comprehensive understanding of ETC's potential and limitations.

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