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Analysis of Modified Exhaust Tip Geometry on Flow Behavior and Backpressure in Car Exhaust Systems for Electricity Harvesting

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Abstract. The efficiency of vehicle exhaust systems is critical for reducing backpressure and emissions, enhancing performance and sustainability of harvesting energy. This study investigates the effect of an additional body modification at the exhaust tip on pressure and velocity distributions using Computational Fluid Dynamics (CFD) simulations in SolidWorks. Simulations were conducted at inlet velocities of 10, 15, and 20 m/s. Results show that the modified design does not increase backpressure, with the maximum observed change being a minor reduction of 0.137% at 20 m/s. These findings confirm that the additional body can be safely integrated without adversely affecting engine performance, while also improving downstream flow uniformity. This supports its viability for use in energy harvesting systems and highlights its relevance for sustainable exhaust system development.

Keywords: Back Pressure, Energy Harvesting, Exhaust Backpressure, Exhaust system, Solidwork Flow Simulation,

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1. Introduction

The exhaust system is a crucial component for the engine's regular and effective operation, influencing both engine performance and exhaust emissions, while being perceived as a basic portion that facilitates the expulsion of burned gasses from the engine [1]. The system typically consists of two main components: the exhaust header, which connects to the exhaust manifold, regulating the pressure of the exhaust gases, and the muffler, which helps reduce the noise generated by the gases as they exit the vehicle [2]. Despite these essential roles, exhaust systems contribute significantly to urban air pollution, especially in major cities across Indonesia, where emissions from motor vehicles are a key factor in deteriorating air quality [3].

Exhaust manifold design is a complex structure depending on several parameters such as back pressure, exhaust speed and mechanical efficiency. One of the crucial element is back pressure in the exhaust manifold which play a crucial role in manage the engine effiency [1][4]. In recent studies, higher back pressure can lead to lower efficiency such as Increased emissions due to incomplete combustion and reduced volumetric efficiency, which is crucial for engine power output [4][5] [6][7][8].

While the primary purpose of a vehicle's engine is to convert fuel energy into mechanical energy to move the vehicle, it is important to note that not all energy produced in the combustion process is used efficiently. Approximately 35% of the initial energy in an internal combustion engine is dissipated via the exhaust system. This considerable energy loss, coupled with heat dispersion, underscores the necessity for recovery systems to enhance efficiency and mitigate environmental effect [9][10]. The substantial amount of energy lost suggests there is room for improvement, particularly in optimizing the use of exhaust gas flow. This optimization could serve a dual purpose: reducing emissions and harnessing waste energy from the exhaust gases to improve overall system efficiency.

From this perspective, the development of sustainable engineering designs to recover energy losses from the exhaust manifold is essential. By integrating renewable energy harvesting mechanisms into conventional systems, it is possible to enhance the preservation and utilization of sustainable energy resources. This paper addresses this need by proposing a design concept aimed at harvesting electrical energy from exhaust gases within the exhaust manifold, contributing to the broader goal of advancing renewable energy technologies.

Recent studies have explored various methods to harness energy from exhaust gases. One notable approach involves the use of an exhaust energy harvester, which can capture energy from the exhaust flow and convert it into electricity. Research indicates that the addition of a turbocharger modified with a high-speed generator can significantly enhance the amount of energy harvested from exhaust gases. This method results in increased pressure within the exhaust manifold and a rise in exhaust gas temperature [11]. Another study harvest energy loss used the heat in the exhaust manifold to electic energy as viable energy source [12][13][14]. A piezoelectric flexible device, leveraging vortex-induced vibration, was studied for its ability to harvest kinetic energy from exhaust gas flow and produce electrical energy via piezoelectric transduction [15]. Similarly, the use of a wind turbine alternator mounted on the exhaust body has also been explored, with results showing improved voltage and current output at higher vehicle speeds. Such modifications aim to capture the energy otherwise wasted as exhaust gases are expelled from the vehicle [16].

However, these studies have identified several limitations in their respective methodologies. For instance, despite higher exhaust heat at increased engine speeds and throttle openings, full-throttle performance is limited by real-world factors, suggesting further optimization is necessary [14]. In systems utilizing an Electric Turbo Compounding (ETC) mechanism, the proximity of the ETC unit to the exhaust manifold results in excessive back pressure, which can cause overheating and potentially damage the engine [11]. To mitigate this issue, it has been suggested that the ETC unit should be relocated away from the exhaust manifold to reduce the risk of back pressure buildup. Similarly, research on wind turbine alternators has pointed to inefficiencies in exhaust gas flow due to improper alignment of the gas entry path. When the exhaust gases do not directly reach the turbine, the energy extraction becomes suboptimal [16]. Modifying the exhaust system to direct the gas flow more efficiently toward the turbine could enhance performance and energy recovery.

Building on these existing studies, this research tries to fill the gap by exploring further improvements in exhaust system design, focusing on the potential benefits of an additional body structure attached to the exhaust system as shown in Figure 1. This study will examine the effects of such modifications on exhaust gas flow, with particular attention to key parameters such as pressure, velocity, and back pressure. Understanding these parameters is crucial, as they directly influence the efficiency of the exhaust system and the overall performance of the engine. For example, back pressure, which occurs when the exhaust gases encounter resistance during expulsion, can significantly reduce engine efficiency. High back pressure forces the engine to expend more energy to expel the gases, thereby lowering performance and fuel efficiency [17][18][19][20].

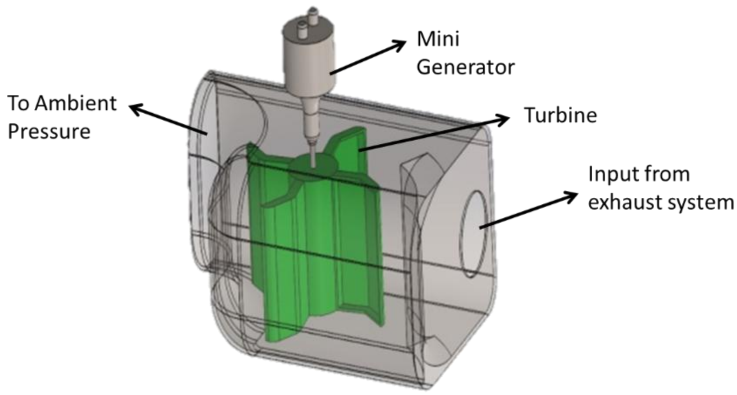

Figure 1. Additional body structure design

Despite advancements in exhaust energy recovery technologies, there remains a lack of detailed data on exhaust gas flow characteristics—particularly pressure distribution and backpressure—in vehicle exhaust systems [21]. These parameters play a critical role in engine performance and emission outcomes, especially given the complex interactions between exhaust flow and system components. The influence of backpressure on turbocharger behavior and engine output remains insufficiently addressed in the literature, marking a gap in current research [18].

To address this, the present study investigates how integrating an additional structural body at the exhaust tip affects flow behavior. Using Computational Fluid Dynamics (CFD) simulations in SolidWorks, this research evaluates changes in pressure, backpressure, and velocity at varying inlet conditions. The aim is to optimize exhaust system design in a way that minimizes backpressure while enabling energy harvesting—contributing to improved engine efficiency and more sustainable vehicle technologies.

2. **Methods**

This study employed a simulation-based approach using Computational Fluid Dynamics (CFD) to analyze a three-dimensional model of a vehicle exhaust system. CFD was chosen for its ability to efficiently predict pressure, velocity, and backpressure characteristics in complex internal flows [22][23]. Although experimental methods are also available [24], CFD provides a faster and flexible alternative for preliminary design analysis. The simulations were conducted in SolidWorks Flow Simulation, modeling two configurations: (1) a baseline setup without the additional body structure, and (2) a modified configuration with the body structure integrated at the exhaust tip. As illustrated in Figure 2, the system consists of the exhaust manifold, catalytic converter, muffler, and optional additional body.

Data were collected in both graphical and tabular forms. Parameters analyzed include pressure distribution, velocity magnitude, and backpressure levels across various inlet flow velocities. The simulation setup and mesh settings are described in the subsequent section.

1. Design Phase: In this initial stage, the exhaust system and additional body structure will be designed. Specific data will be gathered on the vehicle’s exhaust system to create a 3D model, and the body structure will be designed with precise dimensions.
2. Model Creation: The second stage involves creating the 3D models of both the exhaust system and the additional body structure to serve as the research objects.
3. Simulation: The third stage consists of running simulations on the 3D models, both with and without the additional body structure.
4. Boundary condition and mesh setting : The study will compare the exhaust system with and without the additional body structure across three parameters: pressure, temperature, and velocity. The simulation conditions include a pressure of 20,000 Pa, temperature of 300°C, and inlet velocities

of 10, 15, and 20 m/s, with Stainless Steel 321 as the material [2][25][26][27]. Furthermore, in this study, mesh generation and solver are generated automatically by the software. The mesh level used in this paper is level 3 out of 7.

5. Data Collection: The fourth stage focuses on collecting and storing simulation data. Figure 4 illustrates the data collection process, where the exhaust system is marked with red lines to represent the exhaust gas flow. The data will be collected along the length of the exhaust system, presented descriptively in graphical format.

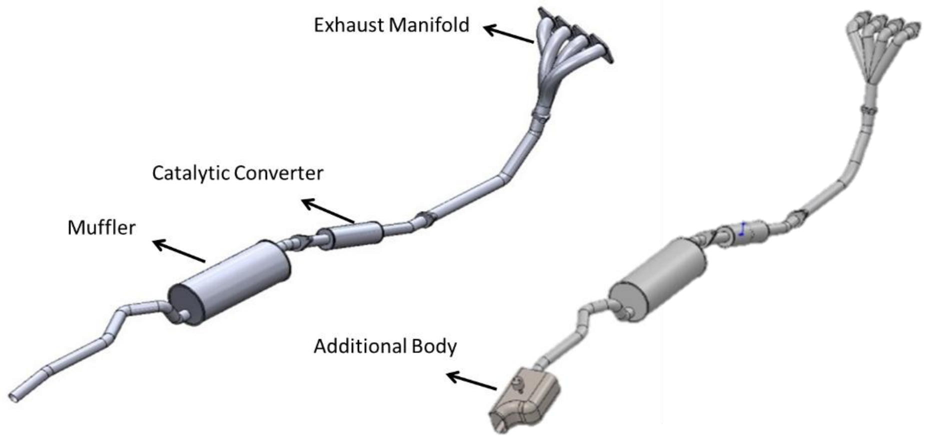

Figure 2. Exhaust system, (a) without additional body, (b) with additional body

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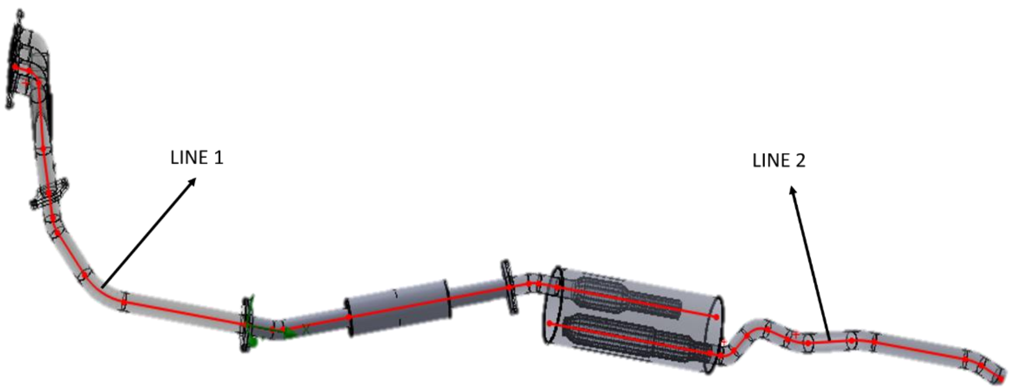


Figure 3. 3D model Exhaust system

Figure 3 shows two reference lines: Line 1, from the exhaust manifold to the muffler, and Line 2, from the muffler to the muffler tip. These lines represent the length of the 3D exhaust system model and serve as data collection points. The lines also indicate the direction of exhaust gas flow.

Furthermore, Figure 4 shows all the fluid parameter and steps in conducting the simulation.

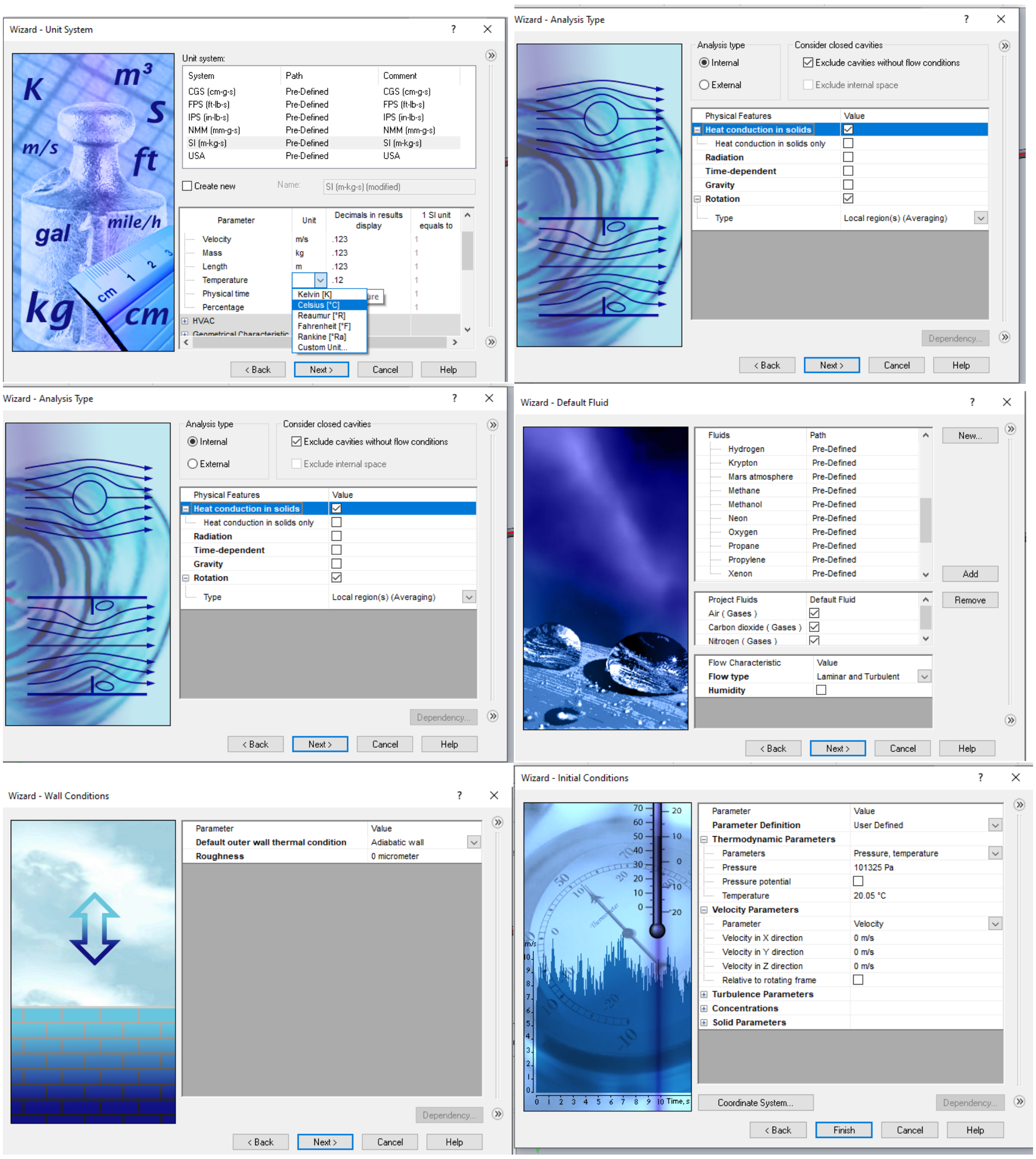


Figure 4. The steps to input fluid properties

Figure 5 illustrates the procedure for setting the initial velocity and temperature for the simulation. As previously stated, this study focuses on varying the inlet velocity to investigate its effect on the exhaust manifold performance, both with and without the addition of an additional body at the exhaust tip.

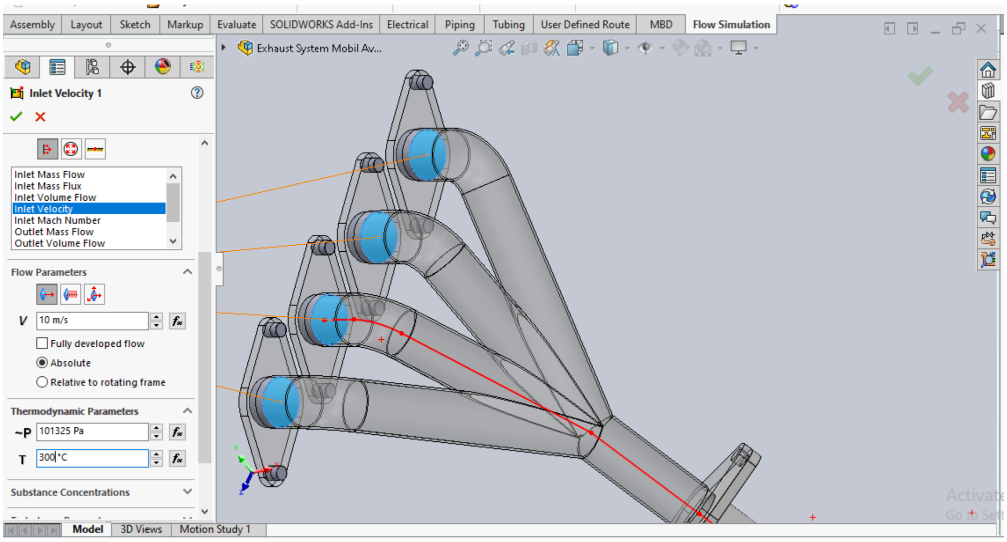
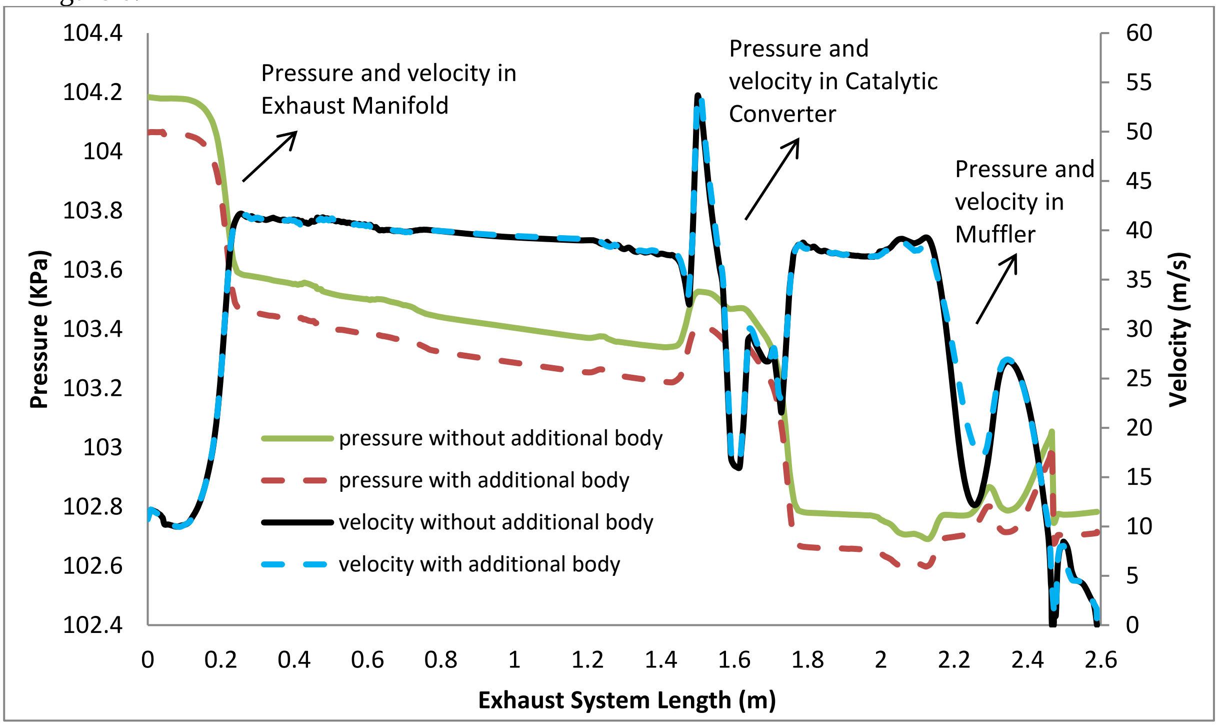


Figure 5. Inlet velocity assigned at Lid

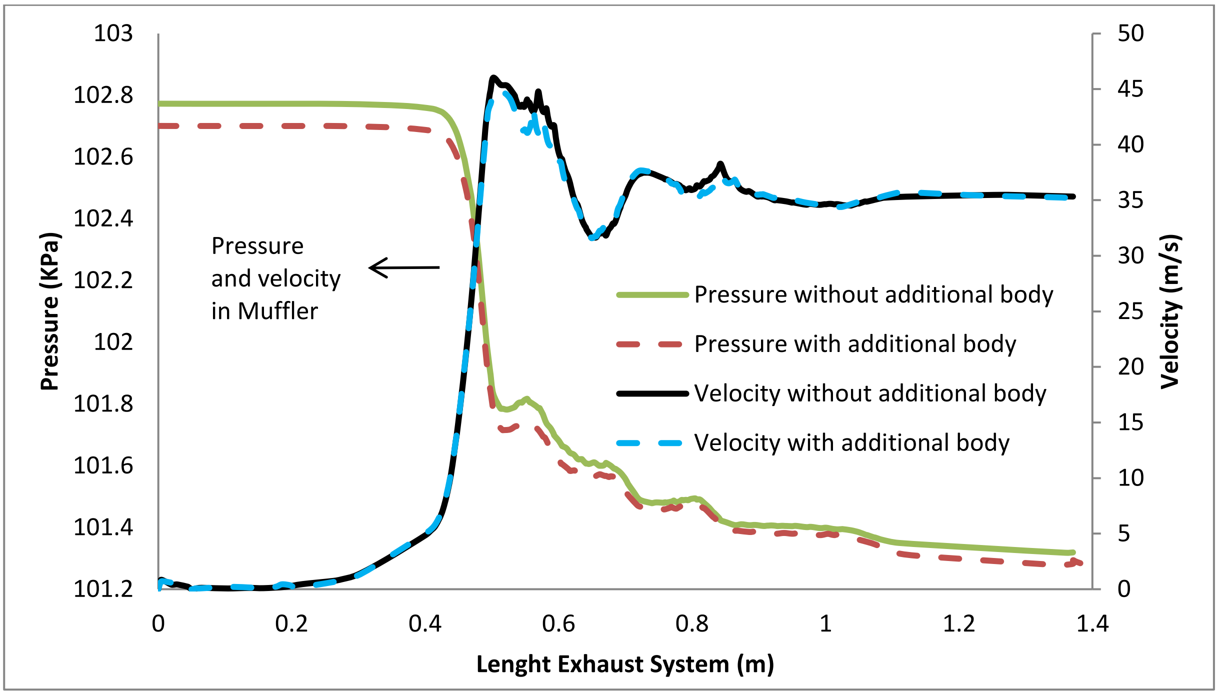
3. Results and Discussion

3.1. Pressure Vs Velocity Simulation at 10 m/s

Simulations were conducted on the exhaust system with and without the addition of an additional body at an inlet velocity of 10 m/s. The parameters under investigation—pressure and velocity—are illustrated in Figure 6.



(a)



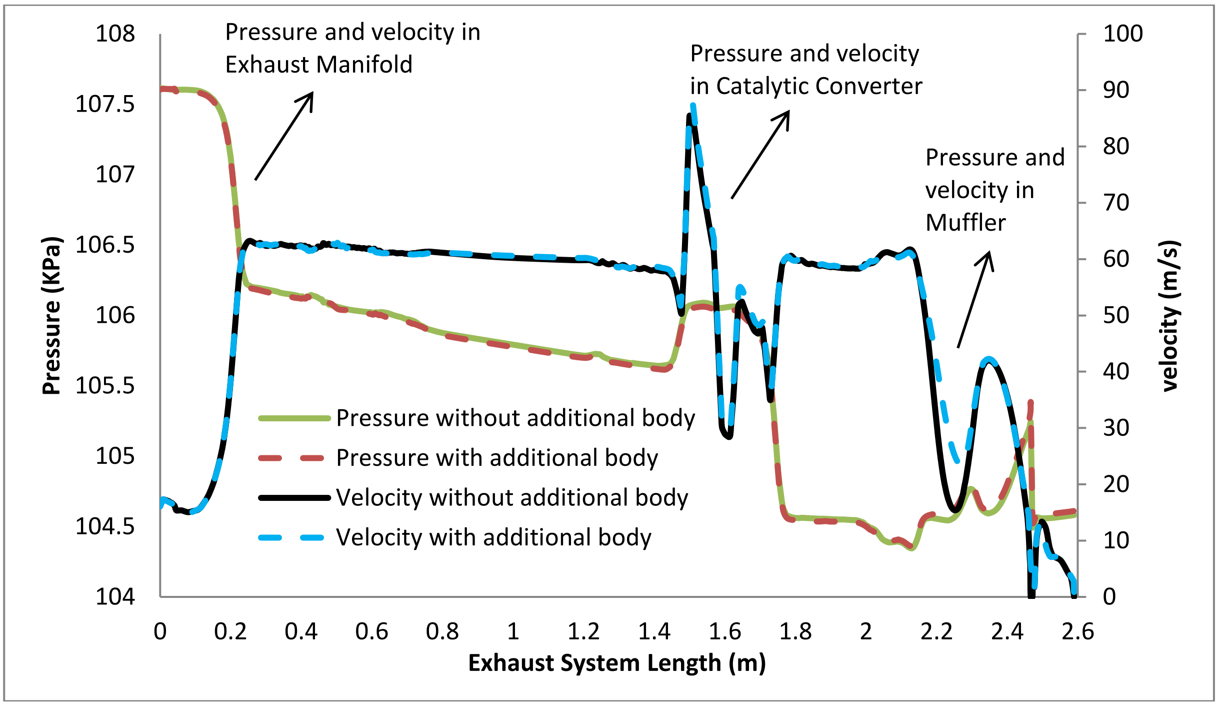
(b)

Figure 6. Pressure vs Velocity at 10 m/s, (a) along line 1, (b) along line 2

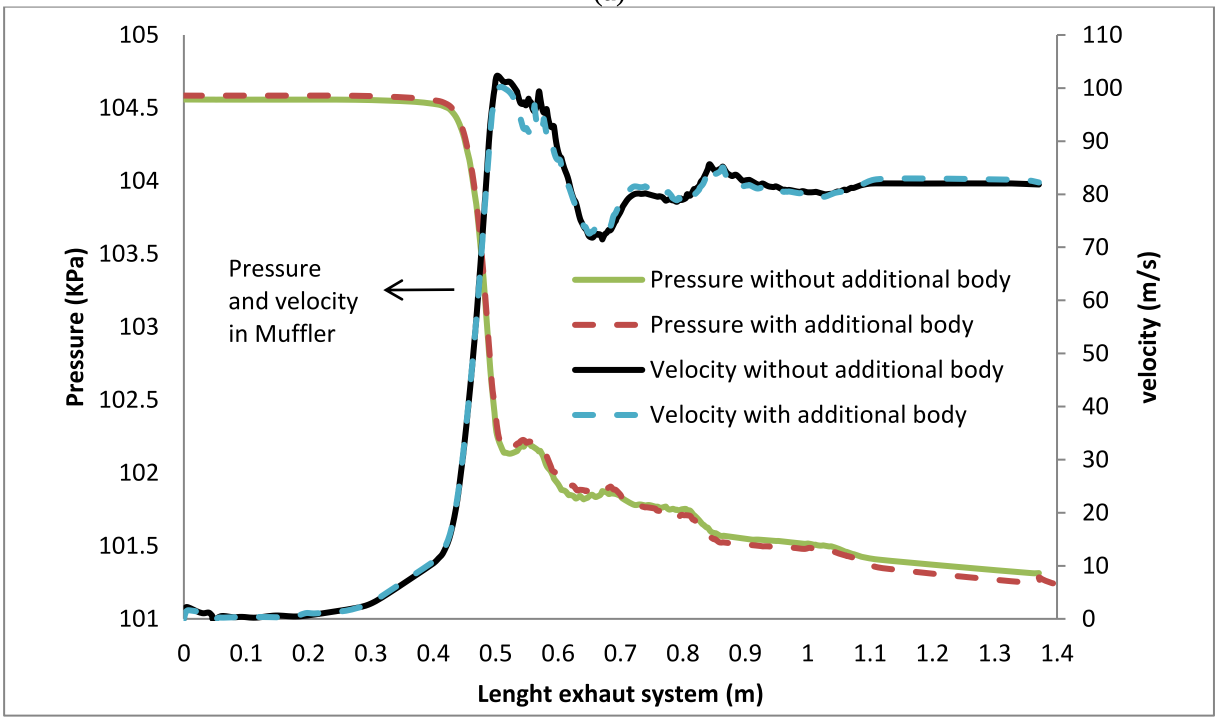
At an inlet velocity of 10 m/s, Figure 6(a) indicates that the baseline configuration exhibits higher static pressure between the exhaust manifold and the muffler. Velocity profiles remain nearly identical between the two configurations. In the downstream region (Figure 6b), pressure also remains higher in the baseline, with minimal velocity differences. Although minor changes in pressure and velocity are observed with the additional body, statistical analysis confirms that these differences are not significant, especially along the exhaust manifold. This supports the conclusion that the additional body does not contribute to increased backpressure. These results are in line with previous findings [17] [18], which demonstrate that design changes can influence exhaust flow behavior. However, consistent pressure stability across configurations indicates that the energy-harvesting body can be safely integrated without affecting engine efficiency [1][4][5][6].

3.2. Pressure Vs Velocity Simulation at 15 m/s

Simulations were conducted for two distinct configurations: one with the additional body installed and a baseline configuration without the additional body. A constant inlet velocity of 15 m/s was employed for both simulations. Pressure and velocity were selected as the key performance indicators for this analysis. The resulting data, illustrating the spatial distribution of these parameters, are presented in Figure 7.



(a)



(b)

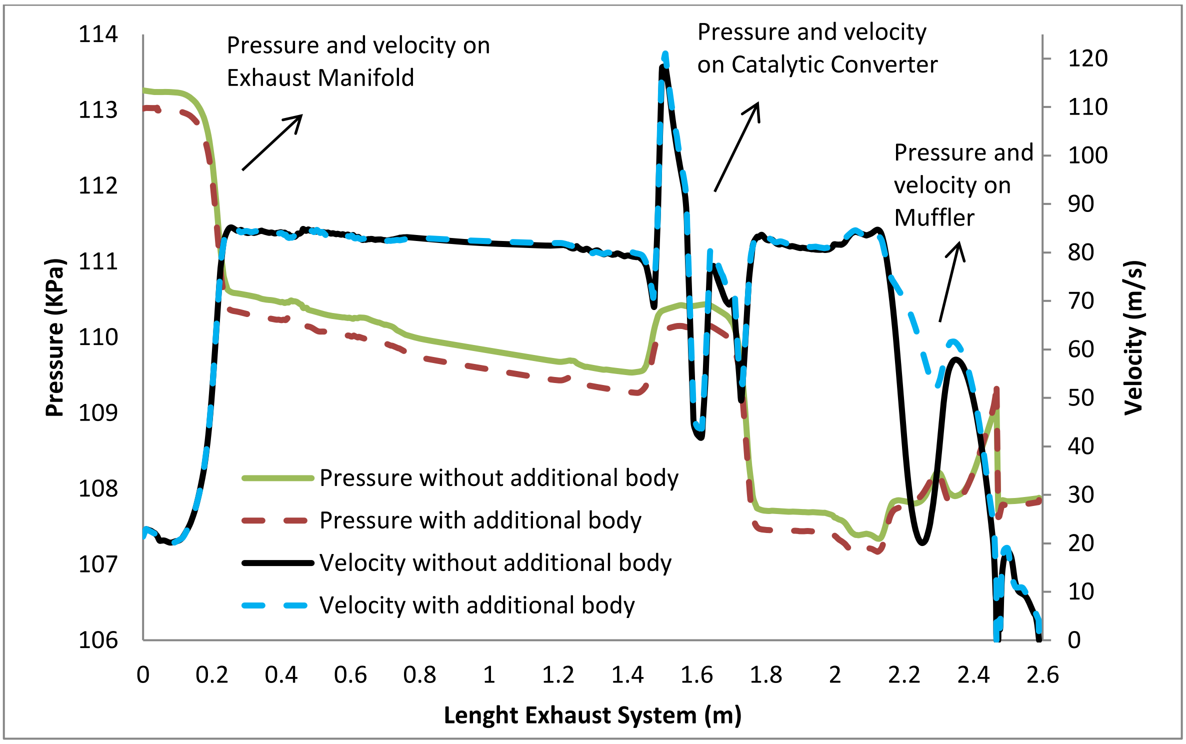
Figure 7. Pressure vs Velocity at 15 m/s, (a) along line 1, (b) along line 2

Figure 7(a) presents the flow characteristics from the exhaust manifold to the muffler inlet. The pressure profiles for both configurations are nearly identical, indicating that the additional body does not significantly influence the pressure drop in this upstream section. However, the modified configuration exhibits a higher axial velocity upstream of the muffler inlet, suggesting improved flow acceleration induced by the geometry. Figure 7(b) shows results from the muffler outlet to the exhaust tip. Pressure profiles remain consistent between the two setups, although a slight increase in tip pressure is observed in the baseline configuration, potentially reflecting minor differences in backpressure. In contrast, the baseline configuration also demonstrates a higher axial velocity downstream of the muffler. This may indicate that the additional body introduces localized turbulence or flow redirection, reducing axial velocity and affecting downstream flow uniformity.

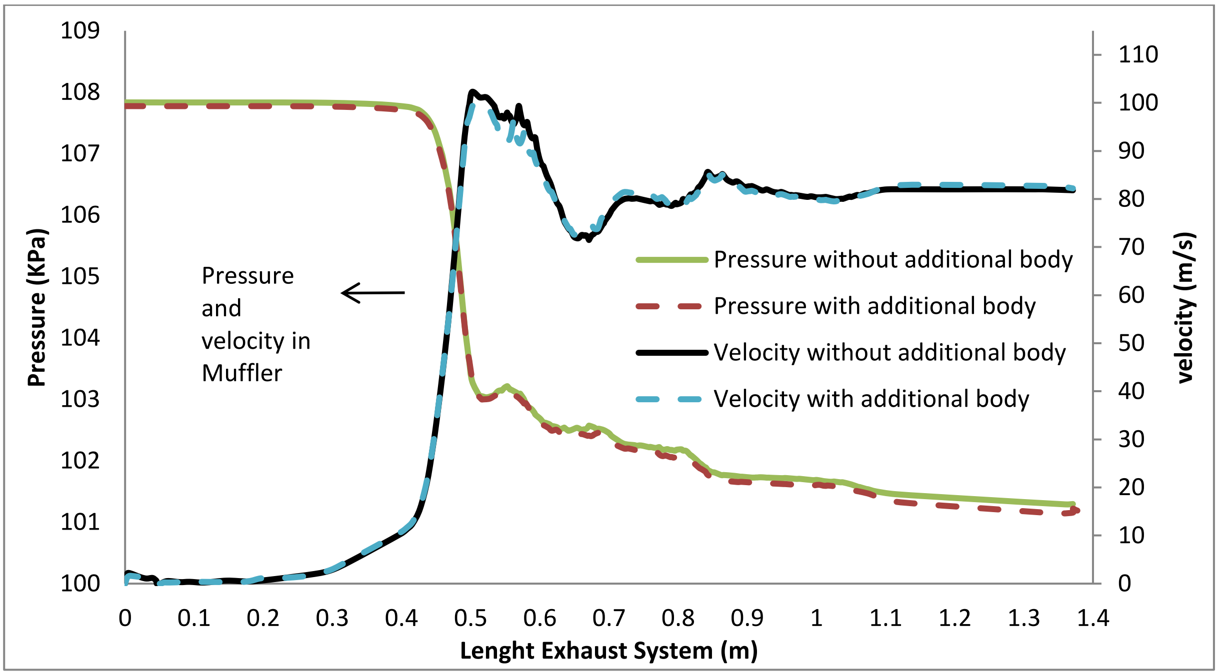
To sum up, at an inlet velocity of 15 m/s, the pressure differences between the baseline and the additional body configuration were found to be insignificant, aligning with observations made by [20] regarding backpressure effects in exhaust systems. However, the increase in flow velocity observed in the additional body configuration suggests the potential for optimizing exhaust flow to improve overall system efficiency.

3.3. Pressure Vs Velocity Simulation at 20 m/s

Two distinct configurations were modeled: a baseline configuration representing the exhaust system without the additional body and a modified configuration incorporating the additional body. A constant inlet velocity of 20 m/s at temperature of 300 °C was imposed at the inlet boundary for both simulations, ensuring consistent inflow conditions. Pressure and velocity fields were selected as the primary parameters for this investigation, providing insights into the flow dynamics within the system. The resulting data, illustrating the spatial distribution of these parameters along the exhaust system centerline, are presented in Figure 8. These figures depict the axial variation of pressure and velocity.



(a)



(b)

Figure 8. Pressure vs Velocity at 15 m/s, (a) along line 1, (b) along line 2

Figure 8(a) shows that in the upstream section (manifold to muffler inlet), the modified configuration consistently exhibited lower static pressure and higher axial velocity than the baseline. This indicates that the additional body promotes smoother flow entry into the muffler while reducing upstream resistance. In the downstream section (Figure 8b), pressure distributions were nearly identical across both configurations, confirming that the additional body has minimal impact on pressure drop across the muffler. However, higher axial velocity was again observed in the modified configuration, suggesting that the additional body may function as a flow straightener, improving flow uniformity and potentially reducing turbulence intensity beyond the muffler.

Therefore, analysis at 20 m/s inlet velocity reveals a consistent trend of pressure reduction in the additional body configuration. This aligns with the findings of [21][17] showed that structural modifications in exhaust systems can reduce static pressure within the exhaust pipe. The observed pressure drop suggests that the additional body aids in optimizing exhaust flow without significantly increasing backpressure.

3.4. Back Pressure analysis

Surface goals refer to the predefined targets or parameters used to analyze fluid flow in this simulation. These surface goals aim to determine the physical pressure values measured or calculated at the muffler tip's surface, both before and after the installation of the additional body. The surface area used to measure back pressure in this study is illustrated in Figure 9. These goals also serve as specific observations or key points for evaluating the performance of the design. Below are the pressure parameter data obtained from the simulation's surface goals.

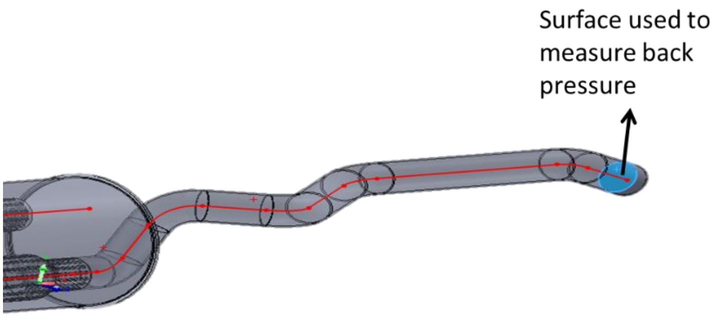


Figure 9. Surface used to measure back pressure

Surface pressure at the muffler tip was measured under three inlet velocity conditions (10, 15, and 20 m/s), as summarized in Table 1. In all cases, the addition of the extra body resulted in a reduction in pressure. Specifically, pressure decreased from 101,325 Pa to 101,287 Pa (0.037%) at 10 m/s, to 101,265 Pa (0.059%) at 15 m/s, and to 101,187 Pa (0.137%) at 20 m/s. These results indicate that the modified geometry does not increase backpressure and can be safely integrated into the exhaust system. Moreover, the increasing magnitude of pressure reduction at higher velocities suggests improved flow characteristics due to the presence of the additional body.

Table 1. Surface pressure at different condition

	Surface Pressure (Pa)		
	10 m/s	15 m/s	20 m/s
Baseline configuration	101325	101325	101325
Adding additional body	101287	101265	101187
Pressure decreasing (%)	0.037503	0.059215	0.136195

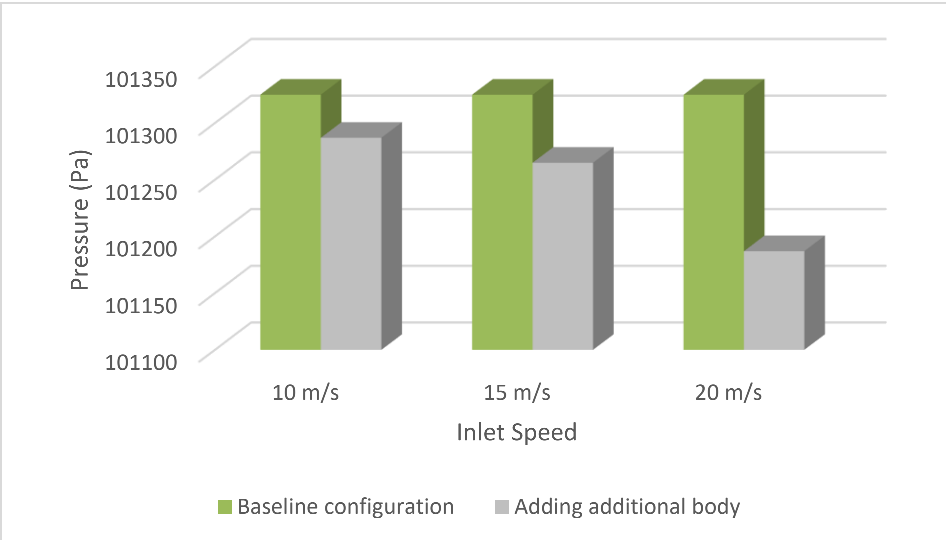


Figure 10. Back pressure on different inlet velocity

The results reveal a proportional relationship between inlet velocity and the degree of pressure reduction associated with the additional body. Specifically, backpressure decreased by 0.037% at 10 m/s, 0.059% at 15 m/s, and reached a maximum reduction of 0.137% at 20 m/s. This trend suggests that the pressure-mitigating effect of the modification becomes more pronounced at higher flow rates. Notably, no increase in pressure was observed under any condition, confirming that the additional body does not contribute to increased backpressure. This finding aligns with previous studies [19], which emphasize the importance of maintaining low backpressure in exhaust system design. As shown in Figure 8, backpressure values remain stable across all inlet velocities, reinforcing that the modification does not disrupt pressure dynamics within the exhaust system. Therefore, the additional body can be integrated as an energy-harvesting component without compromising engine efficiency. This outcome is further supported by earlier research [1][5][6][17], which confirms that minimal backpressure variation is essential to preserving optimal engine performance.

3.5. Discussion

The results of this study provide a comprehensive analysis of the impact of introducing an additional body in the exhaust system on pressure and velocity dynamics under various inlet velocities. The findings highlight several key patterns and implications for system performance.

3.5.1. Pressure and Velocity Dynamics at Different Inlet Velocities

Across all simulated conditions, the baseline configuration consistently exhibited higher pressure values compared to the configuration with the additional body. This trend was observed from the exhaust manifold to the muffler inlet and downstream from the muffler outlet to the tip. For example, at an inlet velocity of 10 m/s, the additional body induced reductions in both pressure and velocity, suggesting a potential mitigation of backpressure within the exhaust system. At higher velocities of 15 m/s and 20 m/s, the reduction in pressure became more pronounced, with the maximum decrease observed at 20 m/s, where static pressure dropped by 0.137%. Although previous studies have shown that pressure drop increases with flow velocity, the present results demonstrate that the addition of a harvesting body at the exhaust tip causes only minor and statistically insignificant pressure variations along the manifold. Thus, the integration of the additional body is not expected to impact the overall pressure distribution or exhaust system performance [28].

3.5.2. Velocity Distributions and Flow Characteristics

The velocity profiles varied depending on the flow location. Upstream of the muffler inlet, the configuration with the additional body displayed higher velocities compared to the baseline configuration. This can be attributed to the body's influence on directing flow, which may reduce turbulence and enhance velocity uniformity. Conversely, downstream of the muffler outlet, reduction in velocity was observed in the presence of the additional body and this reduction likely stems from increased turbulence or flow disruptions caused by the additional body. Interestingly, at an inlet velocity of 20 m/s, the additional body appeared to act as a flow straightener, promoting a more uniform axial velocity profile. Given that elevated exhaust gas velocities can exacerbate turbulence and subsequently increase backpressure as a result of flow resistance [4][28], the observed data—which indicate the absence of increasing velocity along the exhaust manifold—suggest that the integration of the additional body at the exhaust tip does not contribute to elevated backpressure. These findings imply that such a modification may offer practical benefits for optimizing exhaust flow dynamics and reducing energy losses in similar exhaust system configurations.

3.5.3. Backpressure Analysis and System Implications

The backpressure analysis revealed minimal changes in surface pressure due to the additional body, with reductions of less than 0.14% across all conditions. These minor reductions demonstrate that the additional body does not significantly impact the overall system's backpressure, a critical parameter in exhaust system performance. The observed trend of increased pressure reductions at higher velocities underscores the additional body's capability to mitigate pressure while maintaining efficient gas flow. This finding is particularly relevant for energy harvesting applications, as it suggests that the additional body can be integrated into exhaust systems without causing adverse effects on backpressure or performance efficiency [1][4][5][6].

3.5.4. Practical Implications and Future Directions

The introduction of the additional body holds promise for enhancing exhaust system performance by optimizing pressure and velocity profiles. Its potential to act as a flow straightener and energy harvester highlights a valuable application in automotive and industrial systems. Future research could further explore the influence of the additional body on other performance metrics, such as turbulence intensity, energy recovery efficiency, and long-term durability under varying operating conditions. Additionally, experimental validation of the simulation results would provide a robust foundation for practical implementation.

4. Conclusion

This study concludes that the integration of an additional body at the exhaust tip does not negatively impact engine performance, as evidenced by the absence of increased pressure along the exhaust manifold. Across all simulated inlet velocities, the additional body did not lead to higher backpressure, with the maximum observed pressure change being a slight reduction of 0.137% at 20 m/s. This finding confirms that the design can be safely applied without compromising engine efficiency, making it a viable solution for integrating energy harvesting mechanisms into exhaust systems. By maintaining stable pressure and enhancing downstream flow uniformity, the modified design supports both performance optimization and sustainable energy recovery. These outcomes contribute to the development of cleaner and more efficient vehicle technologies, and encourage further exploration into exhaust-based energy harvesting solutions. Due to computational resource limitations during simulation setup—specifically using mesh refinement level 3—the current findings represent preliminary insights; future work will employ finer meshes expected to yield even more precise characterizations. Overall outcomes contribute toward cleaner vehicle technologies development while encouraging continued exploration into optimizing fluid dynamics within automotive exhausts.

Acknowledgements

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