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Elucidating Optimal Exhaust Manifold Divergence and Temperature Distribution in Improving Low-End Engine Speed Performance

Girrimuniswar Ramasamy[1,2], Zuradzman Mohamad Razlan[1,2,*], Shahriman Abu Bakar[1,2], Mohammad Afendi Rojan[1,2], Azizul Aziz Ishak[3], Muhammad Faiz Hilmi Rani[4,5], Ng Yee Guan[6], Rishan Murali[1,2], Sukport Sunan[1,2], Muhammad Hussein Akbar Ali[1,2]

[1] Faculty of Mechanical Engineering Technology, Universiti Malaysia Perlis, Kampus Tetap Pauh Putra, 02600, Arau, Perlis, Malaysia
[2] Motorsport Technology Research Unit (MOTECH), Universiti Malaysia Perlis, Kampus Tetap Pauh Putra, 02600, Arau, Perlis, Malaysia
[3] Research and Development Division, Motosikal dan Enjin Nasional Sdn.Bhd (MODENAS), Gurun Industrial Area, 08300, Gurun, Kedah, Malaysia
[4] Automotive Development Centre (ADC), Institute for Vehicle Systems and Engineering (IVeSE), Universiti Teknologi Malaysia (UTM), 81310 Johor Bahru, Johor, Malaysia
[5] Air-Conditoning Engineering Research Group (ACER), Faculty of Mechanical Engineering, Universiti Teknologi Malaysia (UTM), 81310 Johor Bahru, Johor, Malaysia
[6] Department of Environmental and Occupational Health, Faculty of Medicine and Health Sciences, Universiti Putra Malaysia (UPM), 43400 Serdang, Selangor, Malaysia

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ABSTRACT

The exhaust manifold plays a crucial role in optimizing the performance of Spark-Ignition (SI) engines by effectively expelling combustion products. This study focuses on the optimization of the exhaust manifold design and temperature distribution in a 115-cc single-cylinder SI engine. The objective is to investigate the association between the design characteristics of the exhaust manifold, particularly its divergence, and the engine's performance in terms of brake power. Using computer-aided design (CAD), a three-dimensional model of the exhaust manifold with reduced diameter was developed. The optimized design aimed to enhance the engine's overall performance by achieving lower temperatures, particularly at low-end speeds. Subsequently, a 1D engine study was conducted to evaluate the performance of the engine with the optimized exhaust manifold design and validate the improved temperature distribution. The results demonstrate that the optimized exhaust manifold design leads to higher brake power while maintaining lower temperatures, especially at low-end speeds. This highlights the importance of exhaust manifold optimization and temperature distribution in maximizing the efficiency of the selected SI engine. To further enhance the engine's performance, future research should focus on identifying the most appropriate value for the exhaust manifold's divergence. This will contribute to the ongoing development of more efficient and high-performance SI engines. The findings of this study provide valuable insights into the optimization of exhaust manifold design and temperature distribution for improved engine performance in the context of the tested engine.

Keywords:
Exhaust system; Exhaust manifold; Temperature distribution

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[*] *Corresponding author.*
E-mail address: zuradzman@unimap.edu.my

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1. Introduction

The internal combustion (IC) engine converts fuel's chemical energy into mechanical energy as stated by Hillier *et al.,* [1]. In the Spark Ignition (SI) engine category, which uses petrol and spark plugs for combustion as stated by Pulkrabek [2], the intake and exhaust systems are crucial. The exhaust manifold, part of the exhaust system, affects gas exchange, piston work, and air-fuel mixture intake Hillier *et al.,* [1]. According to Gülmez and Özmen [3], backpressure, caused by the contrast between high exhaust pressure and atmospheric pressure, can impede exhaust flow. The high backpressure significantly degrades the performance of the engine as stated by the findings of Ma *et al.,* [4]. Exhaust manifold characteristics impact backpressure, and optimizing it is important for engine performance as mentioned by Sangamesh *et al.,* [5]. Achieving optimum backpressure is essential for sound energy dampening and maximising engine performance, power, torque, and fuel efficiency. Temperature distribution optimization in the exhaust system is crucial for engine performance efficiency without sacrificing fuel efficiency as mentioned in the past study by Garg *et al.,* [6]. Dewangan *et al.,* [7] discovered that subjecting AISI-304 steel to a heat treatment at 800°C for 2 hours results in a significant loss in both tensile strength and toughness. By receiving this specific treatment, the steel's tensile strength and toughness are lowered by 13% and 35%, respectively, but its hardness is enhanced. Changes in an exhaust system's mechanical features can have an impact on its durability and efficacy, especially given the high temperatures at which it operates. When the steel's tensile strength and toughness are diminished, it becomes more vulnerable to damage when subjected to the mechanical stresses encountered in an exhaust system. While increased steel hardness has certain advantages, it also makes the material more brittle and prone to shattering. Therefore, it is critical to carefully evaluate the impact of temperature on AISI-304 steel while constructing exhaust systems. Mat Noh *et al.,* [8] stressed the importance of variations in AISI-304 steel characteristics at high temperatures. This is especially crucial when considering the temperature range that a car's exhaust system generally experiences, which ranges between 300°C and 500°C and can even exceed 1200°C under some situations. High temperatures reduce a material's tensile strength and toughness while increasing its hardness. Steel's ability to be modified influences the exhaust system's longevity and overall performance. This study focuses on the 115cc SI engine and seeks to investigate the relationship between exhaust manifold divergence features and temperature distribution at low-end shaft rotations using one-dimensional modelling. Establishing this relationship can improve engine performance, outperforming the present exhaust system.

The exhaust manifold is critical in guaranteeing the efficient running of an internal combustion engine, as demonstrated by Hamdani *et al.,* [9]. This critical component is responsible for gathering exhaust gases from several cylinders and efficiently combining them into a single pipe. The primary function of the exhaust manifold is to collect exhaust gases produced by the engine's cylinders and guide them to the exhaust pipe, where they are eventually released from the vehicle. The exhaust manifold is critical for properly and safely eliminating exhaust gases from the engine, improving the vehicle's overall performance and pollution control. The current design of standard exhaust manifold divergence does not improve SI engine performance at low-end shaft revolutions. To enhance engine performance, thorough research integrating 1D engine modelling with experimental data is required to find areas for improvement. To effectively analyse the influence of exhaust on engine performance, it is critical to study the relationship between manifold divergence design and exhaust temperature. Establishing an optimised distribution of exhaust temperatures is critical, but the relationship between manifold configuration and intended temperature distribution requires more research utilising 1D engine analysis.

The goal of this research is to assess the current configuration of the exhaust manifold in a standard exhaust system using both 1D engine modelling and practical testing methodologies. 1D engine simulation allows for a full and detailed knowledge of how the exhaust manifold design impacts the temperature of the exhaust gases. The primary goal is to improve the manifold design to obtain an optimal distribution of exhaust temperature, improving the efficiency of a 115-cc engine, particularly at lower speeds.

The research focuses on the 115-cc single-cylinder spark-ignition engine and its different exhaust manifold configurations. The goal is to investigate the impacts of changing the length and diameter of the manifold to discover the most efficient configuration. The effect of these modifications on the engine's brake power and exhaust temperature distribution is assessed using 1D simulation tools. The focus is on engine shaft revolutions ranging between 2500 and 6000 revolutions per minute, with the prospect of expanding the research to additional speed intervals and operational situations in the future.

The configuration of the exhaust manifold has a considerable impact on performance measurements, as demonstrated by Moses *et al.,* [10]. The configuration of the manifold has a considerable impact on the flow of exhaust gases, including characteristics such as curvature and whether it is a sharp, moderate, or progressive curve. Compared to other types, the long-bend manifold is known for its ability to increase exhaust gas flow, resulting in lower backpressure and higher velocity. Furthermore, this design reduces pressure in the inlet duct, which improves the engine's overall performance and efficiency. Moreover, the power loss in manifold geometry is inversely proportional to the number of edges, implying that as the number of edges rises, the power loss reduces. As a result, the configuration of the exhaust manifold is critical in determining the pressure, velocity, and overall efficacy of the exhaust system.

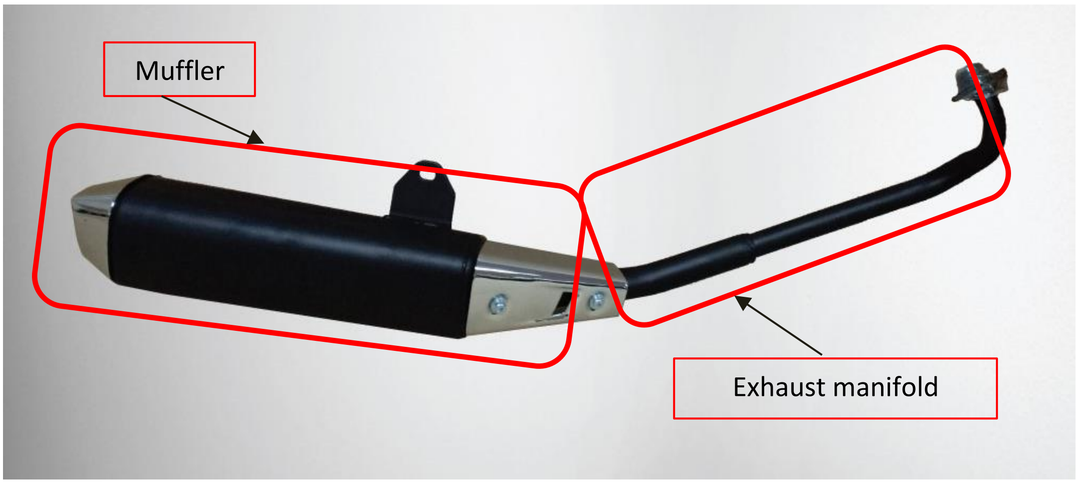

Fig. 1. Exhaust system of MODENAS CT115S Murali *et al.,* [11]

An exhaust manifold's diameter may affect an engine's torque, according to Sawant *et al.,* [12]. Lower rpm torque is improved by smaller diameters, whereas higher revolutions per minute torque is improved by bigger diameters. A smaller exhaust manifold diameter results in better performance at lower revs, and the opposite is also the case. A study by Varun *et al.,* [13] using a 49.5 cc single-cylinder spark ignition engine found that using a range of 22 mm to 34 mm as variables, it was determined that the best output diameter of the exhaust manifold's expansion chamber is 24 mm. Dampened sound energy through a silencer is known as transmission loss. Transmission loss is defined as the difference between sound energy from a system's inlet and outlet based on the study by Fu *et al.,* [14]. Transmission loss is also known as the difference between the power incident on the muffler and the power transmitted through it as stated in a previous study by Zhang *et al.,* [15]. Higher transmission loss means higher sound dampening, but it could only be achieved by introducing sound-dampening mechanisms such as baffles and perforated tubes. These mechanisms are considered as an obstruction to the exhaust flow, which increases the backpressure. This scenario does create a conflict to achieve lower back pressure with higher transmission loss. Therefore, backpressure must be reduced in the exhaust system by maintaining the minimum transmission loss that complies with the legal sound limit. A previous study by Kim [16] says that the design parameters of the exhaust manifold, including diameter, bending angle, and length and diameter combination (divergence), can have a significant impact on the performance of an internal combustion (IC) engine. These factors influence the distribution of exhaust pressure and the interaction of exhaust gas particles with the manifold's wall. A recent study conducted by Mohamad *et al.,* [17] on a 115 cc four-stroke SI engine Honda K20B, operating in 2000 to 5000 revolutions per minute, revealed that modifications to the exhaust manifold's geometry can effectively reduce backpressure when compared to the original design. This optimized design resulted in a 5% increase in engine power efficiency, which translates to more net power being delivered to the crankshaft. Advancing the ignition timing in an engine triggers the combustion process at an earlier stage, resulting in a reduction in the temperature of the exhaust gases. The addition of ethanol to the fuel mixture can further decrease the exhaust temperature. This combination of unleaded gasoline and ethanol not only enhances brake torque by improving the conversion of heat into work but also contributes to lowering the exhaust temperature. The impact of ignition timing on exhaust temperature remains consistent at compression ratios of 8.1 and 10.1. However, retarding the ignition timing can lead to an elevation in exhaust temperature as mentioned by Topgül *et al.,* [18]. The initial step in any analysis involves the creation of a three-dimensional (3D) model, which is subsequently transformed into a one-dimensional (1D) model for analysis purposes. This conversion process also entails the generation of a mesh. In the context of 1D analysis using Ricardo Wave, the exhaust and intake manifolds are segregated into distinct types of ducts, encompassing straight, bending, and expansion ducts. The geometric parameters of each duct can be manually inputted, thereby obviating the necessity to model each duct individually. Nevertheless, as highlighted by Alvarado [19], it is important to acknowledge that while simulations of this nature can offer valuable insights into the impacts of various geometric or environmental alterations, the outcomes may deviate from experimental results due to the assumptions inherent in the theoretical approach.

The primary motivation behind this research is to improve the performance of engines and address the shortcomings found in current exhaust manifold designs. The main objective of the study is to optimize the distribution of temperature within the exhaust manifold, which in turn will enhance power output, torque, and fuel efficiency. The study intends to achieve this goal by researching the link between manifold configuration and exhaust temperature distribution, therefore addressing an existing research gap. This will be performed using a combination of 1D engine simulation and experimental techniques. The study focuses on a 115cc single-cylinder spark-ignition engine and intends to test several manifold configurations to discover the most efficient design. The research also underlines the need of striking a compromise between lowering backpressure and increasing transmission loss, with the primary goal of minimising backpressure while adhering to legal sound limitations. Based on the achievement of improved exhaust manifold design in a Honda K20B engine, the research sets a goal of obtaining a 5% increase in engine power efficiency. Furthermore, additional ways will be investigated, such as the effect of ignition timing and the addition of ethanol on exhaust temperature, to improve engine efficiency.

The complete study of the current literature highlights the research gaps that were discovered:

i. There has been a lack of suitable study to explore the relationship between exhaust manifold divergence and temperature distribution.
ii. The standard exhaust manifold divergence configuration is ineffective for improving performance, particularly at lower shaft rotations.
iii. As a result, it is critical to develop a comprehensive understanding by combining 1D simulation and experimental analytic methodologies.

2. Methodology

2.1 Simulation Method

A 1D simulation evaluates the complete system rather than just the flow inside individual components. To do this, each system component must be described in such a way that the total impact may be represented using library-provided component flow maps. However, the exhaust muffler does not use this method since route flow components cannot adequately reflect it. Because of its complex construction, 3D modelling is required to produce a realistic representation of the muffler during simulation.

2.1.1 1D simulation input for exhaust manifold

The term input data refers to the procedure of transmitting measured data from the exhaust system's muffler and manifold into simulation software to duplicate the experimental setup. The procedure includes designing flow routes for the individual components and entering the data into simulation software. The succeeding simulations are meticulously configured with all the required parameters, such as fluid characteristics, boundary conditions, and initial conditions. This data is then used by the simulation software to generate flow path models and anticipate how the system would react in various scenarios. This technique allows for a thorough evaluation of the system's efficacy, as well as the identification of potential areas for improvement or streamlining. It is critical to understand that the details may differ based on the characteristics of the components and the simulation programme used. To guarantee appropriate connection of each pipe's flow channel, the parameters of the exhaust manifold are first specified, including length, diameter, thickness, bending angle, and radius.

2.1.2 3D modelling of exhaust muffler

The exhaust muffler's complicated design and internal components cannot be effectively represented by a flow route like the exhaust manifold. As a result, importing the muffler and connecting it to the exhaust manifold requires 3D modelling. The dedicated software program, which functions independently of the library, enables 3D modelling. This program allows you to create and manipulate three-dimensional models, which may then be used in a variety of simulations and analyses. The usage of dedicated software for 3D modelling provides flexibility and, in many cases, more advanced features or capabilities than those accessible in a generic library. Nonetheless, the specifics may vary based on the software's specific qualities and the project's requirements. It is crucial to understand that the approaches and tools used will differ based on the programme and type of 3D modelling task. Pipes, a canister, a perforated tube, and a baffle are examples of muffler chamber components that are replicated during modelling. These components are meticulously reconstructed to provide an exact representation of the chosen exhaust mufflers. The exhaust muffler's key measurements, which are required for accurate modelling, are usually available in the project's technical specifications or design papers. It is vital to note that the specifics may differ based on the component properties and the project's individual requirements.

2.1.3 Experimental method

The collaboration with MODENAS granted access to their Research and Development laboratory in Gurun, Kedah, where testing was conducted on a chassis dynamometer to validate the simulation results. The testing specifically involved the selected 115 cc SI engine, with the engine shaft revolutions ranging from 2500 to 6000 revolutions per minute, increasing by 500 revolutions per minute for each test. The engine's idle shaft revolution corresponds to 2500 revolutions per minute. The experiment focused on gathering brake power data across the entire speed range to serve as verification for the simulation throughout the research.

2.1.4 1D simulation results validation of existing design

Before conducting any investigations using simulation, it is necessary to compare the simulation results with the corresponding real experimental results. The simulation model must closely resemble the real system to be considered acceptable. Divergent results would be deemed unacceptable as it is impossible to achieve an exact 100% replication of the real model in simulation, primarily due to internal component friction in the actual engine.

Hence, it becomes a trial-and-error process to recreate the simulation model as closely as possible to the actual model, accounting for any errors that may arise from input inaccuracies in the 1D simulation modelling. The analysis conducted by the 1D simulation software is based on a single cylinder 115cc SI engine, and the shaft revolutions of 2500 to 6000 revolutions per minute are selected to focus on the low-end speed range, as this aligns with the objectives of the study. Deviating from this shaft revolution range would result in inaccurate outcomes regarding the study's objectives.

2.1.5 Design of experiment

Figure 2 and Figure 3 provide visual representations of the selected parameters for the length and diameter of the exhaust manifold. These figures offer a clear depiction of the specific values chosen for these parameters in the study. In this study, "L" refers to a segment in the exhaust manifold where the pipe expands, creating a divergence. This divergence, replacing the length of the larger diameter pipe (42.5 mm), is introduced to assess its influence on the engine's brake power. With 0mm signifying the original design and subsequent levels increasing the length by half of the larger pipe's diameter.

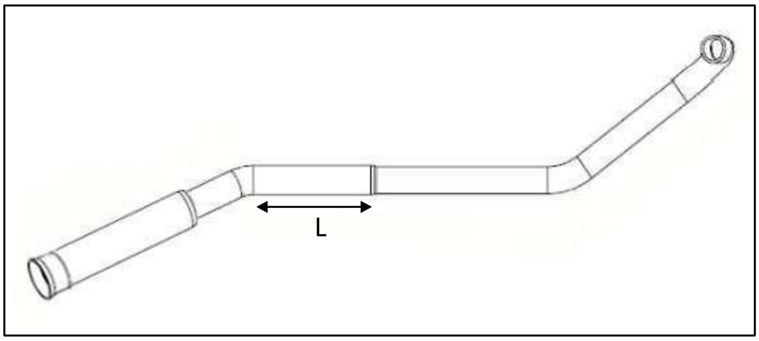

Fig. 2. Length parameter selection of the exhaust manifold

It is crucial to note that extending the length may disrupt the installation location and overall proportions of the exhaust system. In the exhaust manifold design, not all sections of the diameter can be manipulated. The segment that connects to the exhaust port has a predetermined and suitable diameter size of 22.5 mm, prohibiting any form of manipulation. However, a separate pipe that is joined and welded to the end of this segment allows for modification. This pipe needs to have a larger diameter to connect with the initial segment, and the study aimed to investigate the effects of incrementally increasing this diameter size, starting from a default value of 23.5 mm.

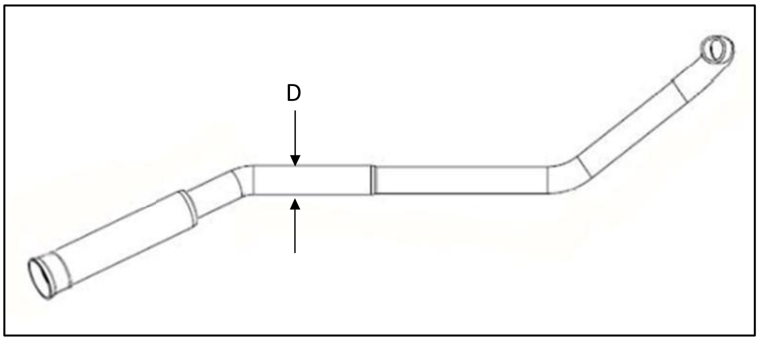

Fig. 3. Diameter parameter selection of the exhaust manifold

Table 1 complements the visual representations provided by Figure 2 and Figure 3. It presents a comprehensive list of the various design combinations of length and diameter that were sampled for the study. The table includes columns for the length and diameter parameters, with each row representing a specific combination. The table provides a comprehensive compilation of the selected values for the length and diameter parameters, making it easy to refer to and evaluate. A total of nine samples were evaluated, with parameters selected at three distinct values for each. A total of nine samples were evaluated, with parameters selected at three distinct values for each. The samples were assessed using a 1D simulation to find the best exhaust manifold design for single-cylinder SI engines with a displacement of 115 cc. Furthermore, the investigation sought to determine how each parameter influenced brake power at low-end shaft revolutions.

Table 1
The samples of length & diameter combination design of the study

Sample	Length (mm)	
	L	D1
1	0.00	23.50
2	0.00	24.50
3	0.00	25.50
4	21.25	23.50
5	21.25	24.50
6	21.25	25.50
7	42.50	23.50
8	42.50	24.50
9	42.50	25.50

Figure 4 shows the flow chart of the research. The research commenced by conducting a comprehensive literature review on the factors that affect temperature distribution and engine performance in exhaust manifold design. Subsequently, a 1D simulation model was utilized to examine the impact of manifold length and diameter on performance, and the results were verified against experimental data obtained from a dyno run on the selected engine. To investigate additional parameters, a design of experiment (DOE) was developed, and analysis was carried out to determine the optimal design parameters. The study concluded that the optimal design, which can be produced using commercially available materials and processes, enhances engine performance in terms of brake power and temperature reduction.

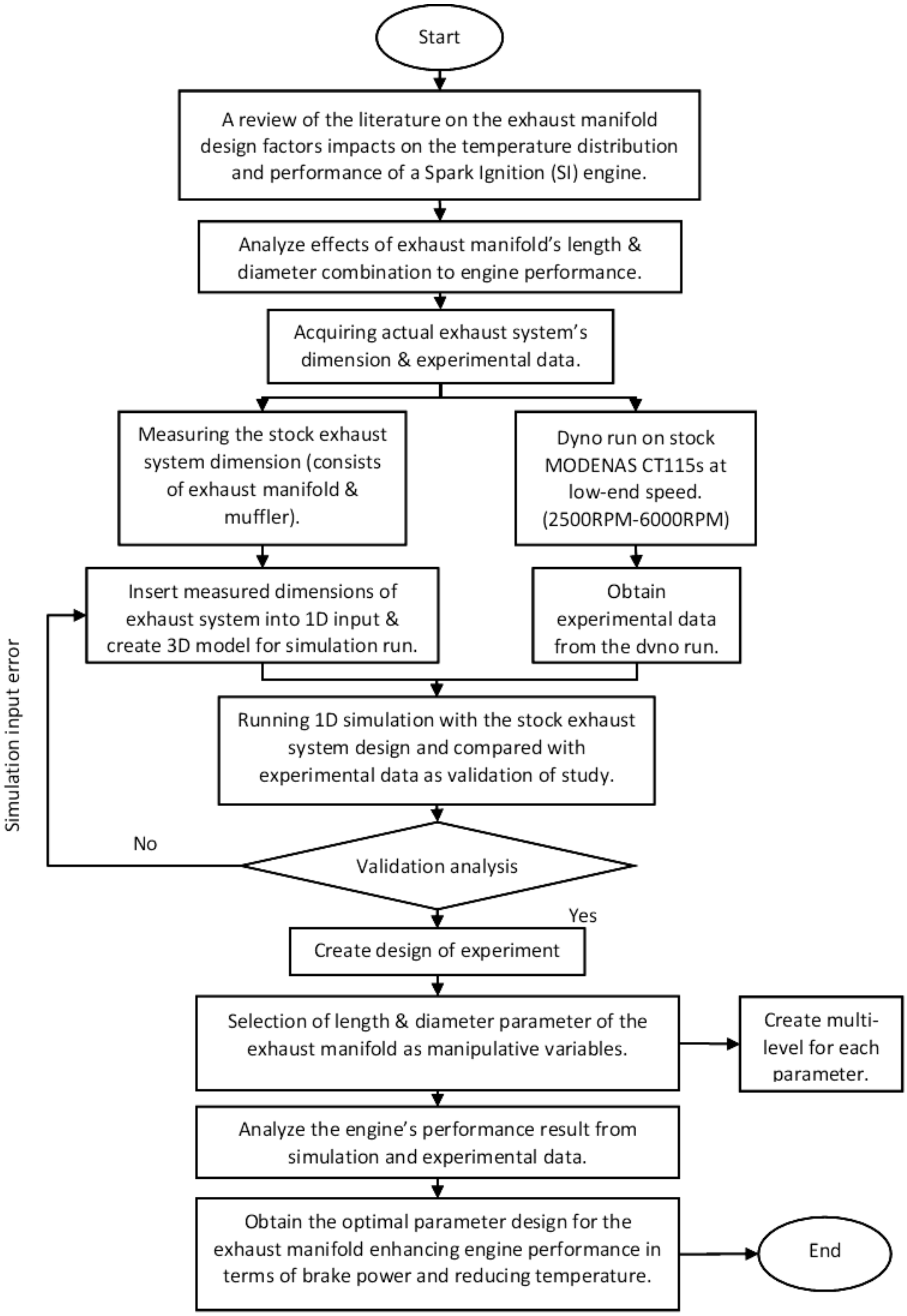

Fig. 4. Flow chart

3. Results

The MODENAS CT115s simulation model's correctness was tested by comparing it to experimental results. Table 2 presents the computed percentage discrepancies resulting from the assessment of braking power at different engine speeds. The validation process demonstrated that the error rate stayed below 10% for all engine speeds, indicating a satisfactory level of accuracy. Murali *et al.,* [20] discovered evidence supporting this validation in their simulation. They did, however, note that the absence of an exhaust muffler resulted in around 30% of the inaccuracies. The results in Table 2 represent the highest level of accuracy achievable in similar research. The research met its primary purpose of investigating the exhaust manifold configuration using 1D engine modelling and experimental analysis.

Table 2
The percentage error of the existing simulation brake power to the experimental result

RPM	Brake Power (kW)		% Error
	Experimental	Simulation	
2500	1.90	2.08	9.68
3000	2.40	2.55	6.40
3500	2.80	2.92	4.34
4000	3.30	3.32	0.76
4500	3.80	3.84	1.03
5000	4.30	4.28	0.47
5500	4.60	4.64	0.89
6000	4.90	4.89	0.26

Based on the validated simulation data of the brake power and the previous analysis, a clear relationship emerges between achieving higher brake power at low-end engine speeds (2500RPM to 6000RPM) and having a high-temperature distribution within the exhaust manifold. In Figure 6, it is observed that when the temperature distribution is higher, the overall average temperature decreases significantly, leading to improved brake power performance.

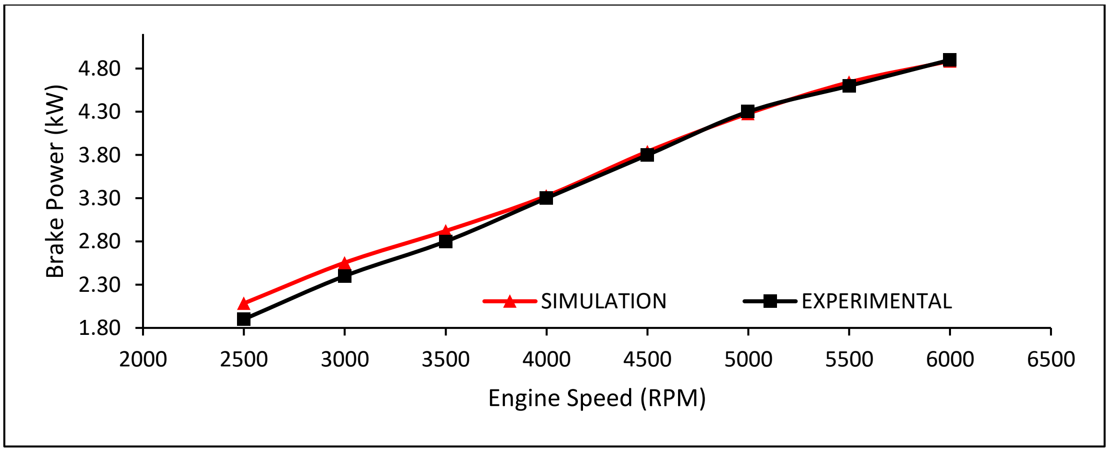

Fig. 5. The existing brake power of experimental and simulation comparison

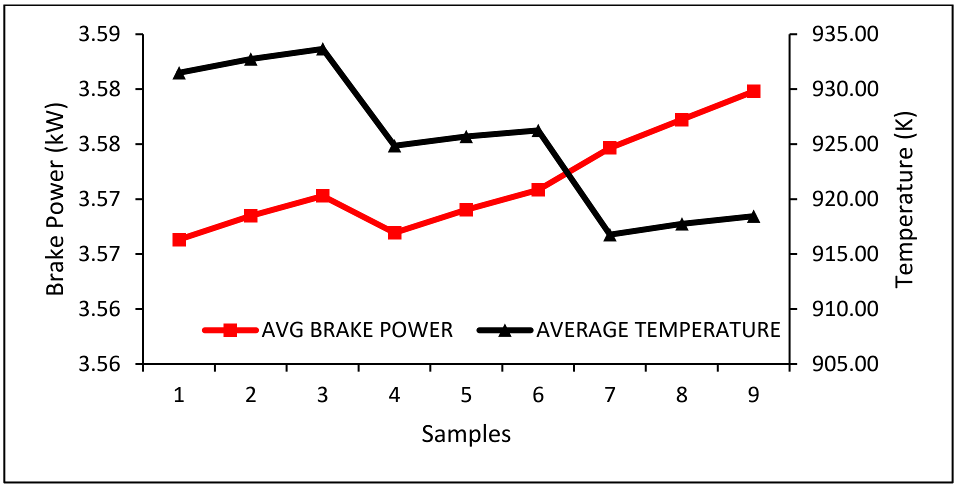

Fig. 6. Average brake power against average temperature in different samples

To enhance the optimization process, regression model analyses were performed using the average brake power and temperature data from all samples. As a result, two optimization equations, Eq. (1) and Eq. (2), were developed, incorporating the parameters L and D. Eq. (1) facilitates the determination of optimal design values for L and D based on the desired average brake power output within the engine shaft revolution range of 2500 to 6000 revolutions per minute. Eq. (2) also allows for the identification of optimal design values for L and D, resulting in the desired temperature output within the engine speed range. These equations are useful tools for designing the most efficient exhaust manifold configuration and constantly monitoring braking power and temperature distribution.

$$\text{Average Brake Power (kW)} = 3.5139 + 0.000209\,L + 0.002169\,D \tag{1}$$

$$\text{Average Temperature (T)} = 911.39 - 0.35271\,L + 0.874\,D \tag{2}$$

The assessment of Sample 9 indicated that its improved manifold divergence configuration resulted in a 0.378% increase in average brake power and a 1.402% decrease in average temperature compared to the existing design. This demonstrates a correspondence between lower temperatures and higher brake power. Sample 9 consistently attained lower temperatures at all engine speeds, increasing brake power. Figure 7 graphically validates these findings, emphasizing the notable design of Sample 9 in terms of brake power and exhaust temperature. These results highlight the significance of optimizing the exhaust manifold's divergence configuration to enhance engine performance.

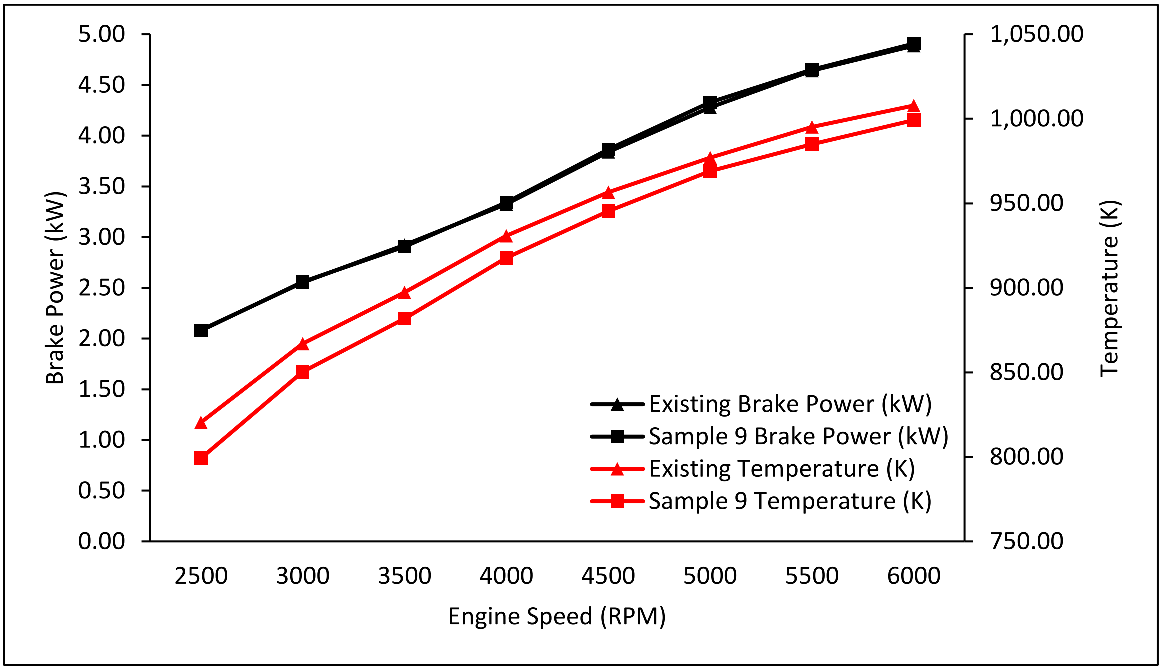

Fig. 7. Comparison of existing and optimised samples in terms of brake power and temperature

Table 3
Percentage error of Eq. (1) compared to the simulated average brake power of every sample

Sample	Parameter		Average Brake Power Simulation (kW)	Average Brake Power Equation (kW)	Error Percentage (%)
	L	D			
Existing	0.00	23.50	3.57	3.56	0.04
1	0.00	23.50	3.57	3.56	0.04
2	0.00	24.50	3.57	3.57	0.04
3	0.00	25.50	3.57	3.57	0.03
4	21.25	23.50	3.57	3.57	0.07
5	21.25	24.50	3.57	3.57	0.07
6	21.25	25.50	3.57	3.57	0.08
7	42.50	23.50	3.57	3.57	0.03
8	42.50	24.50	3.58	3.58	0.04
9	42.50	25.50	3.58	3.58	0.05

Table 4
Percentage error of Eq. (2) compared to simulated average temperature of every sample

Sample	Parameter		Average Temperature Simulation (K)	Average Temperature Equation (K)	Error Percentage (%)
	L	D			
Existing	0.00	23.50	931.50	931.93	0.05
1	0.00	23.50	931.50	931.93	0.05
2	0.00	24.50	932.75	932.80	0.01
3	0.00	25.50	933.66	933.68	0.00
4	21.25	23.50	924.86	924.43	0.05
5	21.25	24.50	925.69	925.31	0.04
6	21.25	25.50	926.26	926.18	0.01
7	42.50	23.50	916.77	916.94	0.02
8	42.50	24.50	917.74	917.81	0.01
9	42.50	25.50	918.44	918.69	0.03

4. Conclusions

This study has made noteworthy progress in the field of spark-ignition engine design, precisely in the improvement of exhaust manifolds. By utilising a combination of experimental and simulation approaches, this research has not only improved the design of the exhaust manifold but has also devised mathematical equations to optimize brake power while considering temperature distribution. The outcomes resulted in the development of an optimal design that notably enhances both brake power and temperature distribution. Moreover, the contributions of this study have provided vital insights to engineers, paving the path for advances in exhaust manifold design. Moving forward, this research provides numerous paths for future research.

4.1 Project Achievements

i. Enhanced Design: The design of the exhaust manifold for a spark-ignition engine significantly improved.
ii. Thorough Investigation: Utilized a combination of experimental and simulation methods to thoroughly examine the effects of various parameters on engine performance.
iii. Optimization Equation Formulation: Developed mathematical equations to effectively optimize brake power with temperature distribution and an error percentage of less than 1%.
iv. Performance Enhancement: Identified the optimal design (Sample 9) that resulted in a substantial increase in brake power (0.378%) and improved temperature distribution (1.402%).
v. Contributions to Advancement: The findings have made a noteworthy contribution to the advancement of exhaust manifold design, providing valuable insights for engineers to optimize both performance and efficiency.

4.2 Recommendations for Future Research

i. Expanded Parameter Variations: Explore a wider range of parameters to better understand their impact on exhaust manifold performance.
ii. Utilization of Advanced Modelling Techniques: Incorporate advanced techniques such as 3D scanning for more accurate modelling.
iii. Comprehensive Heat Transfer Analysis: Conduct a thorough analysis of heat transfer throughout the entire engine system for a more comprehensive understanding.
iv. Experimental Validation: Conduct experiments to validate the findings and ensure their applicability in real-world scenarios.
v. Improved Optimization Analysis: Further refine the combined optimization analysis for exhaust manifold designs.

The proposed directions for future research aim to deepen our understanding of exhaust manifold designs, ultimately contributing significantly to the development of more efficient and high-performing spark-ignition engines.

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