Design and Analysis of Exhaust Manifold for a Single-cylinder Internal Combustion Engine (ICE)

NA Aziz¹, MTA Rahman¹*, NAM Amin¹, MSA Majid¹, A Rojan¹, NFM Nasir² and YMN Rahman²

¹Faculty of Mechanical Engineering Technology, Universiti Malaysia Perlis (UniMAP), Kampus Alam Pauh Putra, 02600 Arau, Perlis, Malaysia
²Faculty of Electronic Engineering Technology, Universiti Malaysia Perlis (UniMAP), Kampus Alam Pauh Putra, 02600 Arau, Perlis, Malaysia

E-mail: tasrif@unimap.edu.my

Abstract. An efficient exhaust system is vital to maximising the performance of an internal combustion engine (ICE), hence improving overall vehicle performance. To have an efficient exhaust system, the amount of exhaust backpressure is to be minimised. To decrease the backpressure effects in the exhaust system, the exhaust has to be redesigned according to the certain bending radius, length of straight pipe and bending angle and pipe diameter. This paper presents design and analysis of the exhaust system used in Shell Eco-Marathon 2019 competition. In this project, the exhaust manifold was redesigned according to the specification of the chassis, the exhaust outlet in the engine and the rules and regulations of the competition. Computational Fluid Dynamic (CFD) analysis was employed to identify the optimum exhaust system design with minimum pressure loss. Among the tested models, the exhaust manifold with 100 mm length, 30° bending angle, 34 mm diameter, and 40 mm bending radius was the optimised design that resulted in the lowest pressure loss of 12.24 kPa. This study shows that a small bending angle with a short straight pipe has led to a smoother exhaust flow and even exhaust velocity across the model.

1. Introduction
Exhaust system is one of the mandatory systems equipped in all internal combustion engine (ICE) system [1]. An exhaust system in a vehicle is used to discharge hot exhaust gas produced in the combustion chamber during the combustion process to the atmosphere [1]. The design and performance of the exhaust system are directly influencing the performance of the vehicle [2]–[5]. For instance, larger holes in a manifold will produce loud exhaust noise, contributing to environmental pollution [2]. Most importantly, an efficient exhaust system increases fuel efficiency in a vehicle [3],[4]. An efficient exhaust system capable of increasing fuel efficiency is an exhaust system that promotes engine scavenging, increasing effective combustion rate [3],[4].

To have an efficient exhaust system, the pressure in the exhaust system must decrease across the system to promote even exhaust velocity at the outlet [5]. Shehkar et al., [6] have suggested a smooth bending radius and fast-flowing exhaust gases be designed to induce low-pressure area; so that the exhaust gases can be released to atmosphere before exhaust valve open again. Nursal et al., [7] have stated that the flow in the exhaust backpressure is contributed by exhaust manifold that has sharp excessive elbows and long exhaust pipe with a small diameter. The exhaust manifold is one of the components in an exhaust system that connects the exhaust port to the engine cylinder head. The exhaust
manifold funnels the hot exhaust gases to the exhaust pipe. A leak in the exhaust manifold or its gasket can allow exhaust gases to escape, which poses a health hazard to the car’s occupants and can result in erroneous readings by the oxygen sensor, triggering a check engine light [8],[9].

The exhaust manifold is typically welded together with a different dimension of steel tubes and some manufacturers prefer to change the dimension of tubes by welding smaller dimension to bigger dimension tubes to form a diverge or converge shape to increase the gas flow in the exhaust manifold [10]. A research found that convergent-divergent tube known as the Laval nozzle enables fast gas flow in the tube [11]. The design restriction in this exhaust system component is typically limited to its length and diameter. According to the research that used computational tools to calculate and simulate gas flow, exhaust manifold with bigger diameter was found to increase engine efficiency. Nonetheless, the diameter depends on the number of cylinders in the engine as the total emission of exhaust particles depends on the engine cylinder [12],[13].

This research was conducted in conjunction with the participation of UniMAP Automotive Racing Team (UniART) in Shell Eco-Marathon 2019. Together with the previously published works [14]-[16], this research aims to increase the engine performance of the vehicle used in the competition. In this work, the exhaust manifold for 115cc single-cylinder internal combustion engine was redesigned by varying the bending angle, bending radius and pipe diameter, aiming to reduce the backpressure and increase the overall performance of the internal combustion engine. The muffler was replaced with a long cylindrical tube to meet the vehicle’s length requirement to channel the exhaust out of the vehicle as it was found that applying muffler to an exhaust pressure will promote excessive backpressure in the exhaust system [17]. In this paper, the influences of exhaust manifold design to the total pressure loss in the exhaust system are analysed The internal pressure throughout the exhaust manifold is obtained by numerical and CFD analysis using the internal flow equation ANSYS Fluent software.

2. Methodology
Figure 1 shows the skeleton or model path that was used to model the exhaust manifold. This path is constructed and used by adjusting the exhaust manifold geometry according to the chosen parameters, as shown in Figure 2. The exhaust manifold is actually the combination of bend pipes and straight pipes, as shown in Figure 1. In this project, the length of the exhaust pipe was fixed at 100mm. The model was then designed by varying the bending angle, bending radius and pipe diameter that were predetermined by mathematical modelling approach. As the pressure required for each model was not consistent for every engine condition, wide range data parameters are listed for this analysis. The pressure differences for each model are computed and the range of each parameter (Figure 2) is determined.

![Figure 1](image_url)
30° bending angle and 40mm bending radius

Figure 2. Design parameters for exhaust modelling; (a) exhaust length, (b) pipe diameter, (c) bending angle and (d) bending radius

Pressure drop for each model is calculated by using the internal flow equation; Equations (1), (2), (3) and (4). Equations (1) and (2) are used to obtain the frictional factor, \( f \). The frictional factor is then used in Equation (3) to obtain the pressure drop (kPa) in the geometry. The pressure loss here represents the total pressure loss between the inlet and outlet of the straight exhaust pipe. The pressure differences in the bend pipe are calculated by using Equation (4). The bend loss coefficient used to solve the equation is obtained and the data from pressure loss in a bend pipe and straight pipe is added and arranged to be documented.

\[
Re = \frac{\nu_{avg} D}{\mu} \quad (1)
\]

where, \( \rho \) is the density of the fluid. \( D \) is the pipe diameter that the fluid is flowing, and \( \mu \) is the dynamic viscosity of the fluid.

\[
\frac{1}{\sqrt{f}} = -2.0 \log \left( \frac{\varepsilon}{3.7D} + \frac{2.51}{Re\sqrt{f}} \right) \quad (2)
\]

where the pipe, \( f \) is the frictional factor. \( D \) is pipe diameter. \( Re \) is the Reynolds number, and \( \varepsilon \) is the roughness of the materials.

\[
P_L = f \frac{L \rho V^2}{D} \quad (3)
\]

\[
P_L = f \frac{L \rho V^2}{D} \quad (3)
\]
where \( f \) is the frictional factor, \( L \) is the length of the pipe, \( D \) is the diameter of pipe, \( V \) is the average velocity, and \( \rho \) is the density.

\[
\Delta P = \frac{1}{2} f \rho U^2 \left( \frac{\pi R_b}{D} \cdot \frac{\theta}{180} + \frac{1}{2} k_b \rho U^2 \right)
\]  

(4)

where \( f \) is the Moody friction factor in a straight pipe, \( \rho \) is the density; \( U \) is the mean flow velocity; \( R_b^\circ \) is the bend radius; \( D \) is the tube diameter; \( \theta \) is the bend angle; and \( k_b \) is the bend loss coefficient [18]-[20].

The pressure loss data in bend pipe and straight pipe are then filtered to obtain the best exhaust manifold models for respective bending angles that provide the least pressure loss. The filtered data is used to plot the graph according to two groups of results. The first group is pressure loss in comparison to diameter. The second group is pressure loss in comparison to the bending radius. The 20 best model data is filtered again to choose only a single best model with the least pressure loss to undergo CAD modelling and ANSYS analysis.

From the calculation, 5 bending angles with the least pressure loss are 30°, 60°, 90°, 120° and 150°. In conjunction with that, the bending radius was found to be within the range of 20 mm to 200 mm, and the manifold diameter are 28 mm, 34 mm, 38 mm, 40 mm, 42 mm and 44 mm. These data are then used for exhaust modelling by using CATIA. The 3D model of the exhaust manifold is constructed with rib function in CATIA that allows the user to transform 2D drawings into 3D drawings with similar diameter throughout the model. Figure 3 shows the complete model of the exhaust manifold, including the flange that is used to secure the exhaust manifold to the exhaust outlet in the engine bay.

![Figure 3. CAD representation of full exhaust design](image)

3. Results and Discussion

The total of 43 exhaust manifold models with varied bending angle, bending radius and pipe diameter are modelled at a similar 100 mm exhaust length has been studied. All developed models are analysed by using ANSYS Fluent to obtain the pressure loss (kPa). The boundary condition used to set up the simulation is shown in Table 1.
Table 1. Boundary condition for CFD simulation

| Exhaust analysis boundary condition |       |
|-------------------------------------|-------|
| Supersonic or initial gauge pressure| 101325 Pa |
| Temperature at inlet                | 500 K |
| Outlet Gauge Pressure               | 101325 Pa |
| Temperature at outlet               | 300 K |

The results are shown in Figures 4 and 5. The results were depicted in two graphs, representing the graph of pressure loss versus pipe diameter (Figure 4) and the graph of pressure loss versus bending radius (Figure 5). The pressure loss graph versus bending radius was constructed to investigate the relationship between the pressure loss to diameter in the exhaust manifold with constant bending radius and exhaust manifold length.

Figure 4. Pressure loss at 100 mm exhaust pipe length in comparison to pipe diameter
Figure 5. Pressure loss at 100 mm exhaust pipe length in comparison to bending radius

From the pressure distribution in Figure 4, it showed that exhaust manifold with 30° bending angle, 40 mm bending radius, and 34 mm pipe diameter have resulted in the lowest pressure loss with the value of 12.24 kPa. The highest pressure loss is 27.22 kPa is resulted from the exhaust manifold with 150° bending angle, 40 mm bending radius, and 44 mm pipe diameter. Meanwhile, Figure 5 showed that the bending radius that resulted in the lowest and highest pressure loss is 40 mm. These results indicated that neither the smallest or biggest pipe diameter and bending radius lead to the lowest pressure loss. Meanwhile, having a sufficient pipe diameter and a suitable bending radius to match the bending angle is suggested. From these results, it can be concluded that the bending angle has a more significant influence on the pressure loss of the exhaust manifold. From the analysis, five designs that have resulted in the lowest pressure loss for each bending angle are selected as the optimum designs. The results are tabulated in Table 2.

Table 2. The best model for 100 mm exhaust manifold

| Bending angle | Bending radius | Diameter | Pressure Loss |
|---------------|---------------|----------|--------------|
| 30°           | 40 mm         | 34 mm    | 12.24 kPa    |
| 60°           | 100 mm        | 44 mm    | 18.31 kPa    |
| 90°           | 80 mm         | 28 mm    | 24.11 kPa    |
| 120°          | 80 mm         | 28 mm    | 21.09 kPa    |
| 150°          | 20 mm         | 38 mm    | 24.88 kPa    |
From Table 2, it can be concluded that for each bending angle, different bending radius and pipe diameter are required for the optimum design. The results showed that the best bending angle for exhaust manifold design is 30° with the least pressure loss of 12.24 kPa, while the pressure loss was shown to increase for 103.2% if the exhaust is designed with 150° bending angle. Henceforth, these data indicated that a small bending angle has led to a lower pressure loss than the bigger bending radius. Nevertheless, the bending radius and pipe diameters' values could not be fitted to any data trends, since the values were found to be dependent on other parameters for the exhaust design to be optimum (low pressure loss).

4. Conclusion
The results showed that the value of bending angle is directly affected the total of pressure loss in the exhaust system with 30° and 150° bending angle have resulted the lowest and highest pressure loss, respectively. In conjunction with that, the exhaust manifold was tested with various bending radius and pipe diameter to have the most compatible values for each design. In this study, the exhaust manifold with 30° bending angle, 40 mm bending radius, and 34 mm pipe diameter was found as the best optimum design. In a nutshell, it can be concluded that the parameters are dependent on each other, that different bending angles are found to be most compatible with different bending radius and pipe diameters. In short, the design consideration that can be considered to design an exhaust manifold with better exhaust flow is a small length of straight pipe, small bending angle, and sufficiently large pipe diameter and design geometries of an exhaust manifold that must not constrict the exhaust gas flow.

References
[1] Cengel Y A and Boles M A 2015 Thermodynamics: An Engineering Approach 8th Edition.
[2] Mohiuddin A K M, Ideres M R and Hashim S M 2005 J. Appl. Sci. 5 1292-1298.
[3] Wang T, Zhang Y, Zhang J, Shu G, and Peng Z, 2013 Appl. Therm. Eng. 53 414-419.
[4] Chai J, Yang Y, Wang S, and Lai K K 2016 Technol. Forecast. Soc. Change. 112 188-197.
[5] Baijai K, Chandrakar A, Agrawal A, and Shekhar S 2017 IOSR J. Mech. Civ. Eng. 14 23-29.
[6] Shekhar R, Dhugga P S, and Malik K 2016 Int. J. Aerosp. Mech. Eng. 3 1-3.
[7] Nursal R S, Hashim A H, Nordin N I, Abdul Hamid M A, and Danuri M R 2017 ARPN J. Eng. Appl. Sci. 12 1819-6608.
[8] JGalindo J, Luján J M, Serrano J R, Dolz V, and Guilain S 2004 Exp. Therm. Fluid Sci. 28 863-875.
[9] Luján J M, Climent H, Arnau F J, and Miguel-Garcia J 2018 Appl. Therm. Eng. 137 184-192.
[10] Sunny Manohar D and Krishnaraj J 2018 IOP Conf. Ser.: Mater. Sci. Eng. 455 012132.
[11] Pansari K and Jilani S A K 2013 Int. J. Adv. Eng. Technol. 6 1313-1318.
[12] Kesgin U 2005 Energy Convers. Manag. 46 2258-2287.
[13] Bedoya I D, Saxena S, Cadavid F J, Dibble R W, and Wissink M 2012 Energy Convers. Manag. 53 154-162.
[14] Norizan A, Rahman M T A, Amin N A M, Basha M H, Ismail M H N and Hamid A F A 2017 J. Phys.: Conf. Ser. 908 012069.
[15] Azmeer M, Basha M H, Hamid M F, Rahman M T A and Hashim M S M 2017 J. Phys.: Conf. Ser. 908 01205.
[16] Aziz S, Amin N A M, Rahman M T A, Rahman A, Syayuthi A R A, Majid M S A and Suhaimi S 2018 IOP Conf. Ser.: Mater. Sci. Eng. 429 012075.
[17] Mishra P C, Kar S K and Mishra H 2018 J. Clean. Prod. 183 869-879.
[18] Rowe M 1970 J. Fluid Mech. 43 771–783.
[19] Gajula V and Bari S 2017 Proceedings of the ASME 2017 International Mechanical Engineering Congress & Exposition IMECE2017, Tampa, FL, USA IMECE2017 70362.
[20] Chisholm D 1980 Int. J. Multiph. Flow. 6 363–367.
Acknowledgement

The authors acknowledge the technical support from the Automotive Racing Team (UniART) and Faculty of Mechanical Engineering Technology at the Universiti Malaysia Perlis (UniMAP). Authors are also grateful for the financial support provided by Universiti Malaysia Perlis (UniMAP) via RESMATE grant.