Flow characterisation in an exhaust manifold of a single-cylinder internal combustion engine (ICE)

N A Aziz¹, M T A Rahman¹, N A M Amin¹, M S Bin Mohamad¹, A Mohamad¹, M Izham² and M A M Saad¹

¹Faculty of Mechanical Engineering Technology, Universiti Malaysia Perlis (UniMAP), Kampus Alam Pauh Putra, 02600 Arau, Perlis, Malaysia.
²Institute of Engineering Mathematic, Faculty of Applied Science and Humanities, Universiti Malaysia Perlis (UniMAP), Kampus Alam Pauh Putra, 02600 Arau, Perlis, Malaysia.

Email: nasrulamri.mohdamin@unimap.edu.my

Abstract. This paper presents an investigation of flow characteristic inside the exhaust manifold that were designed with different bending angle (BA), bending radius (BR) and pipe diameter (Dp). Five exhaust manifold models were developed and analysed by the computational fluid dynamic (CFD) method. Accordingly, the pressure distribution, velocity streamline and backpressure values were observed. The simulation results showed a different flow pattern for all five models, indicating the manifold design affect the flow characteristic inside the exhaust system. The results demonstrated that the pressure distribution inside the exhaust manifold is influencing its velocity streamline pattern, that directly effecting the outlet velocity of the exhaust gas. From this work, a small bending angle with a short straight pipe has led to a smoother exhaust flow and even exhaust velocity across the model. The results obtained from the simulation can be used as a guide to improve the understanding of the flow behaviour in the manifolds and might be used to improve the manifold design.

1. Introduction

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. The general purpose of an exhaust system for an ICE is to transfer hot gases to a location where they will not harm any occupants of the vehicle or drain the performance of the engine. The exhaust gases can exceed a temperature of 700-1000 °C [1]. Exhaust system provided by the manufacturers are often known as stock exhaust system, which are often limited to the particular exhaust gas flow through the system. This is because exhaust gas velocity is influenced by engine speed that is measure in rotation per minute (rpm). Nonetheless, an engine equipped by stock exhaust system failed to produce its best performance compared to customized exhaust system [2]. The engine with stock exhaust system design failed to perform at its best performance due to the increase in backpressure which takes more energy from the engine and effecting the percentage of power output used to move the vehicle.

Fundamentally, the performance of engine is influenced by the shape of the exhaust system where length, diameter and the bending angle of the pipes are the controlling parameters [3]. The shape of the exhaust manifold and the collector geometry is crucial for tuning of the torque curve in a multiple
cylinder ICE [4]. Previous studies have shown that pipe diameter and valve timing for the exhaust system play a prominent role in overall engine performance [5]. Besides, the sharp elbows and long exhaust pipe was found to increase the exhaust backpressure [3], that is directly influencing the performance of the engine. For instance, for an exhaust backpressure of 2.5 psi (17.2 kPa), the power output was found to decreased by 30 hp, estimated from 430 to 400 hp [4]. The power output in the vehicle is affected by the excessive backpressure in the muffler which forces the piston to use some of the energy from the combustion to push the exhaust gases out of the cylinder to the exhaust system [6].

The backpressure is known as the greater static pressure exerted by exhaust muffler due to restriction in its design. Great backpressure can be seen in exhaust muffler which have the capabilities to eliminate great deal of noise from engine [7]. Excessive exhaust pressure in a system will also cause failure in the system such as failure in engine breathing system such as engine intake manifold and catalyst system failure in which its function is to reduce pollutant emission. Therefore, it is important to have the right amount backpressure limit according to the engine size. The right amount of backpressure in exhaust system is capable to induce scavenging effect in the engine [2]. For the exhaust system to have minimum backpressure, it is crucial to design the exhaust manifold with a suitable bending angle in the pipe, as the sharp bending angle was found to reduce the speed of exhaust gas flow and resulted the backpressure to be higher when compared to the exhaust with a smoother bend [8]. Also, a smooth bending radius is suggested for a better flowing exhaust gases, so that the exhaust gases can be released to atmosphere before exhaust valve open again [8].

Besides, the design of exhaust manifold was also found to affect the characteristic of exhaust gases inside the exhaust system. The exhaust gases that travel in an exhaust system travels in the form of pulses and sound. The formation of exhaust pulses in the area due to the piston movement at power stroke to push the exhaust gases at exhaust valve open (EVO). The travel of exhaust gas begins at the exhaust valve after EVO. The high-pressure air escapes from the combustion chamber into the exhaust system by entering in exhaust manifold. Exhaust manifold receives the exhaust gas in the form of exhaust pulse due to its pressure differences between the gas in combustion chamber and atmospheric pressure. The exhaust gasses losses its velocity as the pressure equalised between the combustion chamber and the atmosphere [6].

The exhaust gases then form exhaust pulse with medium pressure that will help to lower the pressure in the combustion chamber. This is because the momentum in the high medium exhaust pulse induces a low-pressure area within the exhaust manifold that helps to execute the gases from combustion chamber by a process known as exhaust scavenging [1]. Besides, there is sound wave propagating at speed of sound in the system. They are faster and propagates at different direction compared to the exhaust pulses when travelling through the system in the form of low-pressure wave. The best design for exhaust manifold which receives these waves should be such that, the geometry of the manifold must be fabricated to allow this low-pressure wave to reach the exhaust valve before it opens [9]. The pressure wave begins at a piston position at bottom dead centre where the negative wave forms in system due to openings of exhaust valve [10,11]. This wave executes the gases from the combustion cylinder to the exhaust system by entering the exhaust manifold. Rarefaction happens during cam overlap. This action begins when the piston is at top dead centre (TDC) resulting both inlet and exhaust valve to open partially. During the cam overlap, a compression wave or a rarefaction happens which enable another negative pressure scenario. This scenario contributes to the engine scavenging [6]. From the previously published studies, hence in can be concluded that the exhaust design is directly influencing the performance of vehicles in various aspect. In other words, the right design of the exhaust system is a key to further improving the vehicle performance.

Accordingly, this work was conducted to find a solution to improve gas dynamics in an internal combustion engine. This research was conducted in conjunction with the participation of UniMAP Automotive Racing Team (UniART) in Shell Eco-Marathon 2019. This work 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. To this purpose, this paper presents a computational fluid dynamic analysis for an exhaust manifold that was designed with different design parameters. The effect of different bending angles, bending radius and pipe diameters towards the flow characteristic and its backpressure are observe and analysed.

2. Exhaust manifold modelling
In the previously published work, Aziz et al. [12] have found that the bending angle gave a major influence to the pressure loss, when compared to the effect of different bending radius and pipe diameter. Henceforth, this work analysed five optimised models designed with different bending angles of 30°, 60°, 90°, 120°, and 150°, respectively. The models are obtained from the numerical analysis presented in the previously published work [12]. The specification for each model is shown in Table 2. For instance, Model 1 was designed with the length of the straight pipe \( l_p \)=100 mm, bending angle \( BA \)=30°, bending radius \( BR \)=40 mm, and pipe diameter \( D_p \)=34 mm. Prior to the design parameter selection for each model, a numerical analysis has been conducted [12] and the design with the lowest pressure loss was selected as optimised model as shown in table 1.

Table 1. Selected parameters for analysis of exhaust manifold

| Model | Length of straight pipe \((l_p)\) | Bending angle \((BA)\) | Bending radius \((BR)\) | Diameter \((D_p)\) |
|-------|---------------------------------|----------------------|----------------------|-----------------|
| 1     | 100 mm                          | 30°                  | 40 mm                | 34 mm           |
| 2     | 100 mm                          | 60°                  | 100 mm               | 44 mm           |
| 3     | 100 mm                          | 90°                  | 80 mm                | 28 mm           |
| 4     | 100 mm                          | 120°                 | 80 mm                | 28 mm           |
| 5     | 100 mm                          | 150°                 | 20 mm                | 38 mm           |

Accordingly, these five models were modelled and simulated by utilising the commercially available CAD and CFD software. Figure 1(a) shows the 3D model of exhaust manifold that was constructed with rib function in CATIA. This function helps the user to transform 2D drawings into 3D drawings with similar diameter throughout the model. The 3D model is imported to ANSYS Fluent. Prior to the simulation setup, the meshing was done with the end product is shown in figure 1(b).

Figure 1. (a) 3D model (b) Mesh model for exhaust manifold
The exhaust manifold models are then transferred to setup section within ANSYS Fluent. At this section, the manifold models were setup with boundary conditions as shown at Table 2 at inlet and outlet of the exhaust manifold models.

### Table 2. Boundary condition

| 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  |

3. Results and Discussion

The effect of designing the exhaust manifold with different parameters (BA, BR and DP) can be seen in figure 2. As shown, all five models can be easily distinguished, where Model 5 are found to have a sharper bent when compared the other models. Consequently, all these models are simulated with similar boundary conditions and settings, to see how the design parameters influencing the flow inside the exhaust manifold. The flow visualisation of the pressure distribution and velocity streamline are recorded and shown in Figures 2 and 3.

![Figure 2. Visualisation of pressure distribution in exhaust manifold model.](image)

In figure 2, the inlet and outlet are situated at the bottom and top side of the picture, respectively. For Model 1, the pressure at exhaust manifold inlet begins at 101722 Pa and the pressure decreases to 101444 Pa at exhaust manifold outlet. The highest pressure is shown at the first pipe bend, with the pressure contour recorded in red, representing the pressure to be as high as 102000 Pa. Model 1 also experiences a backpressure of 278 Pa, which occurs at straight pipe after the first bend. Nevertheless, the amount of backpressure for Model 1 is acceptable, as the backpressure limit is set to 40 kPa for an engine producing maximum power of 7.4kW [11-12]. For Model 2, the pressure at exhaust manifold inlet begins at 101250 Pa and the pressure increases unevenly to 101500 Pa at exhaust manifold outlet.
The exhaust backpressure across the manifold occurs at the second bend after exhaust manifold inlet to the outlet of exhaust manifold which is in the range of 0.2 kPa to 1.5 kPa.

While the pressure contour for Model 3 showed that pressure decreases before increasing at straight pipe after first bend and second bend from the inlet. For Model 3, the backpressure at straight pipe after first bend and at the second bend from the inlet is 0.25 kPa respectively. Meanwhile, the pressure contour result for Model 4 was seen to decrease evenly across the exhaust manifold. The backpressure across the straight pipe between the first and second bend from the inlet is 0.2 kPa. For Model 5, the pressure contour result showed that pressure decreases evenly from the inlet, but then the pressure increased sharply after the second bend from inlet its outlet. The backpressure after the second bend from the inlet to its outlet is 1.6 kPa. This backpressure value is the highest among the results obtained from all 5 simulated models. The pressure distribution in exhaust manifold effects the velocity of exhaust gases which is shown in figure 3.

From figure 3, it showed various velocity streamline contours that are represented by the velocity value from 0 – 40 ms\(^{-1}\). For Model 1, the decreases of pressure were found to affect the velocity of exhaust gases in Figure 3. It showed that the change of velocity streamline colour from yellow to red at inlet to outlet of exhaust manifold respectively. The final velocity obtained from the change of velocity streamline is magnitude 36 ms\(^{-1}\). In contradict to the pressure contour pattern, the velocity at the first bend is found to be the lowest in Model 1. Meanwhile, for Model 2, the velocity streamline is seen in various colours, ranging from red, yellow, green and blue region that represents 40 ms\(^{-1}\), 31 ms\(^{-1}\), 22 ms\(^{-1}\) and 4 ms\(^{-1}\) at the outlet of exhaust manifold respectively. This is due to uneven increase of pressure at straight pipe after second bend from inlet and outlet results. Nevertheless, the uneven pressure at exhaust outlet is due to the backpressure in the exhaust manifold.

For Model 3, the increases of pressure have resulted the velocity to decrease, showed by the change from yellow to green region in Figure 3. Nonetheless, the exhaust velocity improves at exhaust outlet, travelling with a maximum exhaust velocity of 36 ms\(^{-1}\) which indicating that the increase of pressure at straight pipe after first bend and at second bend do not influence the exhaust velocity at the outlet of Model 3. While for Model 4, the
velocity streamline is seen to be even across the exhaust manifold, with high exhaust velocity of 36 ms\(^{-1}\) at its outlet. The backpressure at Model 4 was only seen at the straight pipe between first bend and second bend from the inlet. Nevertheless, the backpressure was found to not influencing the exhaust velocity at the outlet because the pressure and velocity across Model 4 is shown to decrease and increases respectively.

For Model 5, the velocity was seen to decrease sharply after the third bend. This is because the bending radius and the geometry of Model 5 causes to much restriction for the exhaust gases to flow smoothly. Besides, high backpressure of 1.6 kPa was also an indicator that have influence the velocity streamline pattern in the exhaust manifold. The occurrence of backpressure is due to restriction at the diameter despite having a bending radius that result a smooth flow of exhaust gases. The average backpressure values found in this work is 0.2 kPa with the highest backpressure is 1.6 kPa for Model 5. Nevertheless, in accordance to the backpressure limit set by Umesh, Pravin and Rajagopal [13] and Puneetha, Manjunath, and Shashidhar [14], this backpressure is acceptable.

The backpressure is known as the greater static pressure exerted by exhaust muffler due to restriction in its design. Great backpressure can be seen in exhaust muffler which have the capabilities to eliminate great deal of noise from engine [2]. Excessive exhaust pressure in a system that can cause a system failure, such as failure in engine breathing system such as engine intake manifold and catalyst system failure in which its function is to reduce pollutant emission. Therefore, it is important to have the right amount backpressure limit according to the engine size as shown at Table 1 because right amount of backpressure in exhaust system is capable to induce scavenging effect in the engine [15].

From this analysis, Model 4 that was designed with 120° is selected as the most suitable model because the flow behaviour of velocity and pressure in the exhaust manifold was shown to increase and decrease evenly, agreeing the good characteristic of exhaust manifold [16]. Moreover, the backpressure value was also found to be in the acceptable range. In contrary, Model 5 was found to be unsuitable to be used in designing the exhaust manifold. In accordance to the different pressure distribution and velocity streamline pattern obtained from the analysis, it can be concluded that the design parameters found to directly influencing the overall flow pattern inside the exhaust.

4 Conclusion

In the present work, the effect of different design parameters to the flow characteristics in an exhaust manifold have been investigated. Five exhaust manifold models have been developed and analysed. Accordingly, Model 4 that was designed with Model 1 was designed with the length of the straight pipe (\(L_s\)=100 mm, bending angle (BA)=120°, bending radius (BR)=80 mm, and pipe diameter (Dp)=24 mm was found to be the best model in this work. Model 4 complies with the suggested flow characteristic suggested, that the pressure decreases from exhaust inlet to outlet evenly, that resulting an increase of exhaust velocity across the model. Moreover, Model 4 has sufficiently large bending radius with short straight pipe resulting smoother exhaust flow. Besides, the range of backpressure values was also found to be in the suggested range that does not harm the performance of exhaust system.

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