Design optimization of exhaust manifold’s length for Spark Ignition (SI) engine through CFD analysis on low-end rpm using Taguchi’s Method

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Abstract. The exhaust system especially the exhaust manifold is an important factor that affects the performance of any SI engine. The most influential boundary condition in the exhaust manifold is backpressure where it is defined as the difference between maximum pressure in the exhaust system and the atmospheric pressure. Higher backpressure was documented to reduce the overall performance of an IC engine and increases its fuel consumption based on previous studies. Even though backpressure could not be removed entirely from the exhaust system, it could be reduced the maximize the engine’s performance. This study aimed to reduce the backpressure in the exhaust manifold of the 115cc SI engine by optimizing its lengths (by taking consideration of the impact of bending angles) through Computational Fluid Dynamic (CFD) analysis and Taguchi’s method. From the results, it was found that the bending angles are more dominant in reducing the backpressure even after the lengths are optimized. It was found that the optimal length configuration reduces the backpressure by 13.56%. Therefore, the outcome of this study shows that the optimal length configuration offers lower backpressure which significantly reduces the harmful impacts on the engine’s performance.
1. Introduction
An exhaust system, especially an exhaust manifold, is essential to any Spark Ignition (SI) engine to discharge combustion product efficiently and limit the sound energy emitted to the environment, [1]. A good exhaust system always maximizes the engine’s performance, reduces fuel consumption, and reduces harmful emissions to the environment, [1], [2]. The critical boundary condition in an exhaust system that affects the engine’s performance is backpressure,[2]. Backpressure is defined as the difference between maximum pressure in the exhaust system and the atmospheric pressure and its existence does produce a resistance to the flow of exhaust gas,[1], [2]. Therefore, higher backpressure does cause the engine’s performance to experience a certain degree of losses as the engine has to do extra work to push the exhaust gas out of the combustion chamber by opposing the backpressure’s resistance, [1].

Exhaust manifold’s geometry does directly affect the backpressure that is produced. The length of the exhaust manifold apparent to be one of the influential parameters that affect the backpressure. Based on previous studies, it was found that a shorter exhaust manifold produces lower backpressure at higher engine speed while a longer exhaust manifold produces lower backpressure at lower engine speed, [3]. Designing a good exhaust manifold with optimal length gives a positive impact on the performance of the SI engine by reducing its backpressure.

This study aims to optimize the exhaust manifold’s length to reduce backpressure and elucidate the relationship between the length of the exhaust manifold and the backpressure produced to maximize the engine’s power in low-end rpm through Computational Fluid Dynamic (CFD) analysis. MODENAS CT115S engine was used as a platform to obtain boundary conditions for CFD analysis. Therefore, the optimized exhaust manifold’s length could improve the performance of the MODENAS CT115S engine by reducing its backpressure and reduce harmful emissions to the environment.

2. Taguchi’s Methodology
Taguchi’s method was used to obtain the design of the experiment (DOE) for this study in order to optimize the length of the exhaust manifold on reducing its backpressure. Taguchi’s analysis method is mainly used to optimize various manipulative parameters on specific experiments based on the obtained data (experiment results),[4]. Orthogonal array (OA) is used in analysis where it will reduce the number of samples required in the DOE where it directly reduces the time consumption to run the experiment, [4]. S/N ratio analysis is conducted together in the process of the analysis to find the optimal factors configuration based on the desired objective. Three different objectives are available when conducting S/N ratio analysis which are “smaller is better”, “nominal is best” and “larger is better”, [1]. “Smaller is better” objective was implemented in this study as smaller backpressure is required to maximize the engine’s performance.

3. Design of Experiment (DOE)
Figure 1 and figure 2 shows the existing exhaust manifold’s design of MODENAS CT115S where the lengths are labelled from L1 to L6. Based on table 1, point 1 and point 5 represent the coordinate of the manifold’s inlet and outlet, respectively. While point 2, point 3 and point 4 represent the coordinate of the bending point in between L1 and L2, between L2 and L3 and between L3 and L4, respectively. In this study, the positions of the exhaust port and muffler were not varied. Hence, point 1 (P1) and point 4 (P5) were fixed as they are attached to the exhaust port and muffler, respectively. When it comes to the practical approach, varying the length of the exhaust manifold by fixing the position (coordinate) of the inlet and outlet does affect the bending angle at each bend as well. Hence, when L1 is varied, P2 has to move, which affects L2 (assuming P3 and P4 is fixed when varying L1). The cycle continues when varying L2, L3. L4 was not selected in the scope of parameters as selecting it causes point 5 to move, which directly affects the
The position of the muffler. Only one point was moved at a time so that the impact of each length to the backpressure could be studied with minor interference with other factors.

**Figure 1.** The existing design of MODENAS CT115S’s exhaust manifold (Top view)

**Figure 2.** The existing design of MODENAS CT115S’s exhaust manifold (Front view)

| Factor’s Name                | Factor’s symbol | Level 1   | Level 2   | Level 3   | Level 4   | Level 5   |
|------------------------------|-----------------|-----------|-----------|-----------|-----------|-----------|
| Length 1 (Free moving P2)    | L1P2            | 73.01225  | 76.855    | 80.90     | 84.945    | 89.19225  |
| Length 2 (Free moving P3)    | L2P3            | 149.2916  | 157.149   | 165.42    | 173.691   | 182.3756  |
| Length 3 (Free moving P4)    | L3P4            | 252.2488  | 265.525   | 279.5     | 293.475   | 308.1488  |
| Length 5                     | L5              | 162.089   | 170.62    | 179.6     | 188.58    | 198.009   |
| Length 6                     | L6              | 156.0024  | 164.213   | 172.8558  | 181.9535  | 191.53    |

L25 orthogonal array (OA) was selected in this study for six (6) design parameters with 5 levels (variation) for each factor. Based on the OA, 25 samples were designed based on the configuration obtained from the Taguchi’s DOE. The selected parameters and their level is shown in Table 1. The responses were defined from four backpressure values obtained at 1000 rpm (B1), 2000 rpm (B2), 3000 rpm (B3) and 4000 rpm (B5). RPM range in between 1000 to 4000 rpm was selected as low-end rpm is focused for this study.

| Factor’s Name | Factor’s symbol | Level 1 | Level 2 | Level 3 | Level 4 | Level 5 |
|---------------|-----------------|---------|---------|---------|---------|---------|
| Length 1      | L1              | 73.01225| 76.855  | 80.90   | 84.945  | 89.19225|
| Length 2      | L2              | 149.2916| 157.149 | 165.42  | 173.691 | 182.3756|
| Length 3      | L3              | 252.2488| 265.525 | 279.5   | 293.475 | 308.1488|
| Length 5      | L5              | 162.089 | 170.62  | 179.6   | 188.58  | 198.009 |
| Length 6      | L6              | 156.0024| 164.213 | 172.8558| 181.9535| 191.53   |

4. CFD Modelling Technique

This study focused on lowering the backpressure in the exhaust manifold by optimizing its length. The 3D model of the samples based on DOE were converted into a mesh file using ANSYS workbench. Tetrahedral mesh element was used with an element size of 0.001m. Inflation was switched on instead of allowing the program to control it and the smoothing option was set to be smooth to improve the quality of the mesh. The analysis set up and the boundary conditions used, [1], [5], [6], are tabulated in Table 2.
Table 2. CFD simulation set up and boundary conditions

| Mesh Set up | Mesh element type | Tetrahedral |
|-------------|------------------|-------------|
|             | Mesh size        | 0.001 m     |

| Model Set up | Flow | Steady State |
|--------------|------|--------------|
|              | Solver | Pressure based |
|              | Energy | On |
|              | Viscous Model | k-epsilon (Realizable) |
|              | Near-Wall Treatment | Standard wall function |

| Boundary Conditions | Inlet | Mass flow rate |
|---------------------|-------|----------------|
|                     | Outlet| Pressure outlet (opened to atmosphere) |

5. Results and Discussion

Figure 3 shows the pressure contour obtained from CFD analysis for the existing exhaust manifold design at 4000 rpm. It took an average of 145 iterations for the solution to converge for all 25 samples from DOE and 1 existing sample. From figure 3, it can be observed that the highest backpressure was produced at the first bending area as that is the first place where the flow of the exhaust gas is redirected and faces an obstruction. Based on the results obtained from CFD analysis, it was found that sample 1 from the DOE contributed for the lowest Signal to Noise (S/N) ratio and means of backpressure.

Table 3. Response Table for S/N Ratio (smaller is better)

| Level | L1P2 | L2P3 | L4P5 | L5  | L6  |
|-------|------|------|------|-----|-----|
| 1     | -30.10 | -29.92 | -30.40 | -29.99 | -30.29 |
| 2     | -30.73 | -30.06 | -30.27 | -30.57 | -30.72 |
| 3     | -30.51 | -30.49 | -30.42 | -30.35 | -30.71 |
| 4     | -30.30 | -30.31 | -30.67 | -30.54 | -30.32 |
| 5     | -30.82 | -31.68 | -30.70 | -31.01 | -30.41 |
| Delta | 0.72 | 1.76 | 0.43 | 1.03 | 0.43 |
| Rank  | 3   | 1   | 4   | 2   | 5   |
Table 3 shows the response table for the S/N ratio. From the tables, it can be observed that L2P3 has the highest rank (1) which shows that it influences the most on the backpressure that is produced. While L6 has the least impact on the backpressure inside the exhaust manifold.

Figure 4 shows the main effects plot for the S/N ratio of each parameter where the parameter values that map to the least S/N ratio on the y-axis are selected as the optimized values based on the “smaller is better” objective. Therefore, two different optimal parameter configurations are obtained from the DOE table (sample 1) and the main effects plot for the S/N ratio (figure above). The comparison of the S/N ratio and the mean backpressure of existing and the optimal configurations are shown in table 4 where CO1L is the optimal configuration based on the main effects plot for S/N ratio and S11L (Sample 1) is the optimal configuration obtained from DOE.

| Sample        | L1P2 | L2P3 | L4P4 | L5   | L6   | S/N ratio | Means of BP |
|---------------|------|------|------|------|------|-----------|-------------|
| Existing      | 80.9 | 165.4| 279.5| 179.6| 191.5| -30.2960  | 27.38       |
| CO1L (Optimal)| 73.01| 149.3| 265.5| 162.1| 156  | -29.177   | 24.1        |
| Percentage of difference | -9.75 | -9.73 | -5.0  | -9.74 | -18.54 | -3.69 | -12.01 |
| S11L (Lowest BP based on DOE) | 73.01 | 149.3| 252.2| 162.1| 156  | -28.9842  | 23.67       |
| Percentage of difference | -9.75 | -9.73 | -9.77 | -9.74 | -18.54 | -4.33 | -13.56 |

From table 4, it can be observed that the configurations from S11L show the lowest S/N ratio and means of backpressure. Therefore, sample 1 from the DOE is chosen as the optimal parameter configuration for the least backpressure where the mean backpressure is reduced by 13.56%. It can also be observed that all optimal lengths from L1P1 to L6 are shorter than the existing ones. This result is contradicting the previous study where it was mentioned that a longer exhaust manifold will reduce the backpressure produced in low-
end rpm, [3]. However, in this study, the interference of bending angle could not be neglected as discussed earlier. The comparison of the bending angles of the selected optimal configurations and existing design is shown in the table below where $\theta_1$ is the angle in between L1 and L2, $\theta_2$ is the angle in between L2 and L3 and finally $\theta_3$ is the angle in between L3 and L4.

| Bending angle ($\theta$) | $\theta_1$ | $\theta_2$ | $\theta_3$ |
|--------------------------|------------|------------|------------|
| Existing                 | 100.09     | 35.9       | 21.37      |
| Optimal                  | 96.6       | 40.44      | 18.22      |

From the table above, the overall bending angle decreases except for $\theta_2$. Based on previous studies, it was found that a smaller bending angle reduces the backpressure that produced,[2]. Therefore, by comparing the results of this study from the previous research, it can be concluded that the impact of bending angle is dominant in reducing the backpressure compared to the length.

6. Conclusion
The outcome from this study is helpful in reducing the emission and fuel consumption by any SI engine in low-end rpm. This was achieved by optimizing the length of the exhaust manifold through backpressure reduction, which will directly improve the engine’s performance. However, the interference of bending angle could not be neglected as the position of the inlet and outlet of the exhaust manifold was fixed. This study shows that the bending angle is more dominant in reducing the backpressure in the exhaust manifold even though the lengths are optimized. A lower bending angle does reduce the backpressure in low-end rpm. The optimal lengths configuration was obtained using Taguchi’s analysis, and it was found that the optimized design does reduce the mean backpressure by 13.56%.

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