Design and Analysis of an Operative Inlet

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Abstract. This paper describes the effect of intake manifold with the application of intake runner as the operative inlet used in racing car that participate in Formula Student (FSAE) competition. The design analysis of the runner is carried out to give uniform distribution of the air flow getting into engine. Air flow behavior plays an important role in order to provide better air fuel mixture inside the intake manifold before it is drawn to the combustion chamber. The results from this study indicate that longer runner gives low percentage of pressure loss but cause the air velocity to drop. Changing the outlet diameter of runner gives higher velocity at the smaller diameter and highest angle resulted higher air mass flow rate inside the runner. The new design of runner is built of 60mm length, 55mm outlet diameter and 55° angle and the results show 0.05% improvement occur in air flow distribution at the end of each runner outlet.

Keywords—Intake manifold runner geometry, Air flow behaviour, Pressure loss, Air velocity, Mass flow rate

1. Introduction

Formula SAE is an event organized by Society of Automotive Engineers International (SAE) to enhanced student in designing automobile racing car. The concept of Formula SAE is fully designed and build vehicle independently by a team of student from worldwide universities. The finished product of the racing cars are evaluated based on the potential as production car. The car is tested on the two main event which is static and dynamic event including technical inspection, cost report, presentation, engineering characteristic design, time attack performance and high-performance endurance challenge.

The engine and vehicle design in Formula SAE competition need to comply with a strict regulation provided by the organizer. Regarding the engine intake line an air restrictor of circular cross-section must not greater than 20 mm and should be fitted between the throttle valve and the engine inlet [1]. The function of restrictor is to limit the engine air flow rate as it is strongly affect the volumetric efficiency and the maximum power of the engine. All parts of the engine air and fuel control systems (including the throttle or carburetor, and the complete air intake system, including the air cleaner and any air boxes) must lie within the surface defined by the top of the roll bar and the outside edge of the four tires [1].

Excellent engine performance requires the simultaneous combination of good airflow in intake manifold and good combustion characteristic. To maximize the mass of air inducted into the cylinder during the suction stroke, the intake manifold design, which plays an important role, has to be optimized. The air has to be distributed equally in all four cylinders for multi-cylinder engine. Intake runner is a series of tubes or channel in the manifold distribute the air/fuel mixture from the plenum chamber to the individual cylinder. The geometry of the intake runner plays an important role as the high pressure of air can be produced for the air/fuel mixture distributes into the cylinder.
UniMAP Automotive Racing Team (UniART) has participating FSAE-ASEAN since 2016. The formula car was developed using Suzuki GSX-R 600 2005 engine model. All the participant team need to follow the rule and regulation provided by the FSAE-ASEAN for passing all the inspection before they can run their car on track. The main rule for air intake system is that all gasoline internal combustion engines must have a restrictor on intake manifold. Due to this application of this restrictor, the performance of engine has decreased 10% to 30% of its original performance. Besides, an insufficient air flow in intake manifold entering engine cylinder. The air flow has the biggest effect in internal combustion engine. Incorrect air fuel mixture can cause inconsistence combustion in cylinder. Due to this problem, the engine was unable to achieve its idle RPM. The RPM for idle speed on previous UniART racing car is 4000 RPM. The standard idle RPM for this engine is about 1000 RPM. The engine needs to breathe in more air to keep the engine run. This is why the idle RPM is high due to the engine needs more pumping air into the combustion chamber.

Numerous research in optimising the performance of UniART racing car have been carried out [2-7]. With the same aim, this paper provided a study on the geometry of the intake runner to stabilize the air flow in the intake manifold into the combustion chamber. Thus, with the better air distribution at each outlet of intake manifold, it could help in improving the volumetric efficiency of the engine.

2. Computational fluid dynamic (CFD) analysis inside the intake manifold runner

Air flow analysis inside the intake manifold runner was performed using CFD software – Ansys CFX. The objective of this study is to investigate the air flow behavior and the effects on the flow inside the runner with different geometry to the engine performance. The geometry parameters studied are the length, diameter and bending angle of the intake runner, presented in the following subsections.

Three results characteristic are discussed, which are; percentage of pressure loss, air velocity and mass flow rate. Each geometry is tested under the steady state condition. The parameters used in the simulation are tabulated in Table 1.

| Parameters                  | Conditions                        |
|-----------------------------|-----------------------------------|
| Inlet Pressure              | 101325 Pa                         |
| Outlet Pressure             | 0 Pa                              |
| Intake Runner Wall          | No slip wall and smooth wall roughness |
| Air Velocity                | 15 m/s                            |
| Air Temperature             | 300 K                             |

2.1 Analysis on the intake runner length

Runner length has big effect over torque curve in RPM range. Longer runner length would give higher torque at lower engine RPM while shorter length tend to give peak torque at high engine RPM [8]. The runner are tested for the length of 20 mm, 40 mm, 60 mm, 80 mm, and 100 mm (figure 1). The diameter of the inlet and outlet of the runner is fixed at 55 mm to suit the outlet of the intake manifold and the inlet of the engine cylinder. The runner length is selected based on less value in pressure loss, higher air velocity flow into engine and highest mass flow rate into the combustion chamber. The results of the runner length effect on the pressure loss, air velocity and mass flow rate are presented in figures 2(i), (ii) and (iii) respectively. The pressure loss is the pressure different between inlet and outlet of the runner. The lowest amount of pressure loss is to be found. The air velocity is the speed of air flow through the runner. Highest air velocity is to be select in the runner design process. The mass flow rate is the amount of air entering the runner. The more mass air flow get into the cylinder, the better engine performance of the engine. The intake runner must be kept as short as possible to minimize fuel delivery lag [8].
Figure 1. Intake Runner Length

Figure 2(i) Graphical result for pressure loss at different length

Figure 2(ii) Graphical result for air velocity at different length
From figure 2(i), it can be seen that the highest pressure loss occurs at 20 mm runner length. The reason why the value is higher is because air flow stream does not have enough time to build back the pressure flow in the runner. The 60 mm length of runner have resulted 40.1% of pressure loss. All these value shows only a slightly difference since the tested runner length is perform on small increment of the dimension. Meanwhile, figure 2(ii) shows that air velocity are the highest (261.4 m/s) at 20 mm runner length. This is because the air flow travel small distance in short runner length. Thus, it can be concluded that he runner needs to be kept as short as possible so high air flow speed can enter the engine [9]. For the analysis of the effect of runner length towards the mass flow rate, it can be seen that the speed is lowest at 100 mm runner length. This high amount of mass flow occurs is because of the surface area in the pipe is larger than other tested pipe. The lowest mass flow rate shows at length 20 mm which the surface area is smaller inside the runner pipe.

2.2 Analysis on the runner diameter

A second approach in increasing the volumetric efficiency of the engine is to vary the diameter of intake runner. Basically, larger cross sectional of the air passage will cause low air velocity flow through it. This is because more flow resistance occurs during suction stroke. By changing the cross sectional area at the outlet of the runner, it creates nozzle either converging or diverging depending on the change made [10]. The 60 mm length is selected to be fixed. The diameter varies in range of 40 mm to 50 mm as shown in figure 3. The dimension cannot be more than the size of the inlet of the engine since it cannot be fit with the inlet.
Generally, larger diameter of air passage will cause low air velocity flow through it. This is because more flow resistance occurs during suction stroke. By changing the cross sectional area at the outlet of the runner, it creates nozzle either converging or diverging depending on the change made [11]. The results of the analysis are shown in Figure 4(i), (ii) and (iii).

**Figure 4(i)** Graphical result for pressure loss at different diameter

**Figure 4(ii)** Graphical result for air velocity at different diameter

**Figure 4(iii)** Graphical result for mass flow rate at different diameter
In figure 4(i), it can be seen that the changes in diameter is obviously have caused the pressure loss in the system. Theoretically, the high pressure loss should occur at diameter of 45 mm but since the analysis result only varies at the end of the outlet and no sudden changes of the diameter occur that’s why the highest pressure loss shows at 55 mm diameter.

Meanwhile, as depicted in figure 4(ii), air velocity is the highest and lowest at 45 mm and 55 mmm respectively. The change in cross sectional area at the outlet of the runner created a nozzle either converging or diverging depending on the change made. This will affect either increasing or decreasing in air speed at the entrance into engine cylinder. Decreasing the diameter value would theoretically cause the air velocity to reach a point where it is no longer affected by the restrictor, but by the runner diameter itself.

Figure 4(iii) showed the trends of mass flow rate with the different diameter. From the graph, the data indicated that the smallest (investigated value) diameter results lowest mass flow rate, and vice versa. The amount of mass flow rate is high because there is no obstacle in the air flow. The surface are also play roles since the larger surface area gives advantage for mass flow rate in the flow. The lowest mass flow occur at diameter 45mm because the less surface area traveled by the air.

2.3 Analysis on the intake runner bending angle

Air flow behavior plays an important role to the system as it to provide better air fuel mixture getting into combustion chamber [9]. High angle of intake manifold results better engine performance in terms of high brake torque, brake power, brake mean effective pressure, and volumetric efficiency [12]. Bends and junctions for example will create turbulent air flow characteristics which will choke the flow in the pipe [9]. Pressure differences also will be created on either side of the pipe in bends geometry, because as the air goes through the bend it is subject to a centrifugal effect where the air is pushed to the outer radius resulting in higher pressure and velocity on one side and lower on the other. The test angle are varies from 40° to 60°. The diameter is fixed at 55 mm and length to be at 60 mm.

![Figure 5. Intake Runner Bending Angle](image)

Air flow behavior gives an important role as it to provide better air fuel mixture getting into combustion chamber. Five angles are selected for the analysis to find which angle is suitable to provide better engine performance. In this study, the intake runner are tested at five different angle, namely 35°,40°,45°,50° and 55° (figure 5). The bending angle are selected based on the allowable position of the intake manifold assemble on chassis following the rule stated in FSAE 2017 [1]. The analysis are all conducted on the fixed length and inlet pressure of 60 mm long pipe and 101325 Pa (ambient pressure at sea level) respectively. The results are plotted and presented in the following figures.
Figure 6(i) Graphical result for pressure loss at different bending angle

![Graphical result for pressure loss at different bending angle](image)

Figure 6(ii) Graphical result for air velocity at different bending angle

![Graphical result for air velocity at different bending angle](image)

Figure 6(iii) Graphical result for mass flow rate at different bending angle

![Graphical result for mass flow rate at different bending angle](image)

From figure 6(i), it can be seen that the pressure loss is the highest at 35° angle. The pattern of the pressure loss are inclined with the increment of bending angle until it reaches 40.2443 % of pressure loss at 50° angle, then it dropped to the 40.2391% of loss at 55°. The highest pressure loss occurs at 150° angle. This high value is because the air flow collides with the inner wall of the bending angle. This is due to narrow corner of the runner that causes the collision to happen. The lowest pressure loss occurs at 35° angle. The air travel shorter distance since the length is change with the change of the angle.

As for the effect of bending angle on the air velocity, figure 6(ii) depicted a different trend compared to the line of pressure loss percentage. Highest velocity occurs at 55° angle. The air flow travel inside the pipe with no resistance causes the velocity to shot up. There is less collision occurs between the air flow
and the wall. The lowest velocity occurs at 35° angle. The narrow corner of the angle will provide the high collision between air flow and runner and reduced the air flow velocity [13]. Meanwhile, figure 6(iii) showed that the mass flow rate is the highest at 50° and the lowest at 35°. The mass flow rate is greatly related with the surface area. Theoretically, the highest angle tend to gives more surface area inside the runner pipe while decreasing in bending angle reduces the mass flow rate. Highest angle of runner inclination produce the highest turbulence kinetic energy [13].

3. Selected Runner Design on Current Intake Manifold Analytical Result

Based on the finding in analysis on the runner geometry, runner with the 60mm length, 55mm outlet diameter and 55° angle is selected to be applied on the current intake manifold. Table 2 shows the analytical result on the current intake manifold without installation of the runner. The current intake manifold is analyzed for comparison of the result. Meanwhile, Table 3 shows the analytical result of current intake manifold with application of selected data to study on the effect of the runner on the intake manifold. Both tables 2 and 3 show the comparison of analytical result between intake manifold without application of runner and intake manifold with installation of intake runner. The graphical results of the comparisons are depicted in figures 7(i), (ii) and (iii).

| Outlet pressure (Pa) | Velocity (m/s) | Mass flow (kg/s) | Pressure Loss % |
|----------------------|----------------|------------------|-----------------|
| outlet 1 59068.3     | 41.5           | 0.0022           | 41.70           |
| outlet 2 59047.2     | 52.9           | 0.0029           | 41.72           |
| outlet 3 59090.7     | 57.1           | 0.0035           | 41.68           |
| outlet 4 59062.1     | 40.2           | 0.0024           | 41.71           |

Table 3. Analytical result of current intake manifold with application of selected data to study on the effect of the runner on the intake manifold

| Outlet pressure (Pa) | Velocity (m/s) | Mass flow (kg/s) | Pressure Loss % |
|----------------------|----------------|------------------|-----------------|
| outlet 1 59030.4     | 33.1           | 0.00229          | 41.74           |
| outlet 2 59036.0     | 39.6           | 0.00265          | 41.74           |
| outlet 3 59038.6     | 38.2           | 0.00239          | 41.73           |
| outlet 4 59033.0     | 40.7           | 0.00286          | 41.74           |

Figure 7(i) Graphical result of comparison of percentage of pressure loss between selected runner and without runner
From Figure 7(i), it can be seen that the percentage of pressure loss is high for the intake manifold with runner. But there’s only a small difference between installed runner and without runner. This high in value may be cause by additional distance that the air needs to travel before exit the intake manifold. Although there is high pressure loss compared to without runner, is shows the uniform flow of air at the outlet of each runner. This uniform distribution of air is good which it can supply stable amount of air before entering the combustion chamber. The performance of the engine can be increase due to this effect. At outlet 1, percentage of pressure loss of intake manifold with runner is 0.04% higher than current condition of intake manifold. The highest difference shows at outlet 3 which is 0.05% more of pressure loss for intake manifolds with runner than without runner.

![Graphical result of comparison of air velocity between selected runner and without runner](image1)

**Figure 7(ii)** Graphical result of comparison of air velocity between selected runner and without runner

![Graphical result of comparison of air mass flow rate between selected runner and without runner](image2)

**Figure 7(iii)** Graphical result of comparison of air mass flow rate between selected runner and without runner

Figure 7(ii) shows the graphical result obtains from analysis of the air velocity on the current intake. The air velocity for application of runner is reduce compared to no runner attach on the manifold. As from previous study, the longer distance by the air flow will cause low in its speed. The bending angle also affects the reduction in speed of the air. The air need to be high in speed so more air can enter the combustion chamber. But there’s only a small difference between the result and this difference will cause only in small percentage of the engine performance. Highest velocity difference for velocity occurs at outlet 3 with 33% more on current condition of intake manifold. Only 1.2% velocity difference between both intake manifold occurs at outlet 4.
The graphical result of the air mass flow rate shows in Figure 7(iii) explain that the application of runner on intake manifold cause the mass flow rate to be decrease compared to no runner attached. This occurs because of the sudden change in flow at the runner. To obtain high air mass flow rate, the flow need to move as smooth as possible before getting out from the manifold. Since the limitation on the rule of FSAE 2017, the intake runner must be applied for positioning the intake manifold on the chassis. From the result, highest difference of mass flow rate occurs at outlet 3 which intake manifold with runner gives about 38% less than current intake manifold.

4. Conclusion

Based on result obtained, the application of intake runner on intake manifold give some effect in improving the distribution of air flow getting into the engine. Better air distribution in the intake manifold can help to improve the volumetric efficiency of an engine. The runner design need to meet requirement for increasing engine performance which is minimizing the pressure loss, increasing air velocity and improve amount of air mass flow rate flow into the engine. 60 mm runner length is selected as first consideration in runner design since it balance all requirement needed. Higher air velocity is better since the air can be forced into the engine before valve is closed for better compression of air fuel mixture but the diameter cannot be change due to limitation on fitting the runner with the engine. Bending angle of the runner helps for positioning the intake manifold on the chassis. The highest angle inclination is better for the air to flow into the engine. Lower angle can increase the resistance for the air flow in intake runner. Due to limitation of space, highest angle is given by the 55° angle for the runner. Combining these three design consideration, new runner design is produced and analyzed along with the current intake manifold. The comparison of result between intake manifold with runner and without runner has proven that the runner provided uniform flow of the air distribution at the outlet of each runner. The improved design with even air distribution for better engine performance are ready to be tested on real running engine.

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