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SIMULATION ANALYSIS OF SPARK IGNITION ENGINE INTAKE MANIFOLD FOR BETTER PERFORMANCE

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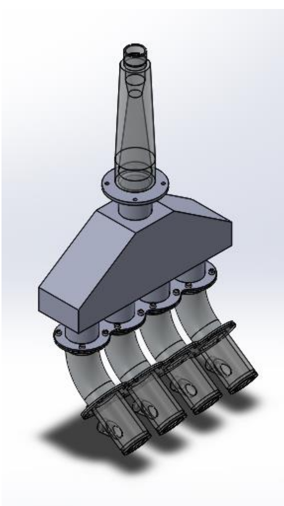
Graphical abstract



Abstract

Intake manifold system is one of the important component in the engine system which functions to evenly distribute the air flows into every cylinder of the engine. With the restricted air intake rule regulation, the intake air system for a car must be properly designed in order to minimize the performance losses caused by the restrictor. The paper presents the study on the effects of intake design parameter towards the performance of the engine and then improves the performance of previous intake manifold system. This study starts with the development of Honda CBR 600RR engine model and intake manifold system model using GT-Power engine simulation software to be used for the simulation purposes. After developing the reference engine model, the parametric study was carried out to study the effect of the intake manifold parameter design on the engine performance. The optimization process was then performed to achieve the target of improvement which has already been set prior to performing the optimization. The final results show an increase up to 4.83% and 4.45% of torque and air flow rate respectively at the desired operating range of engine speed.

Keywords: Intake manifold, Restricted air, Formula SAE, Optimization, GT-Power

1.0 INTRODUCTION

Intake study is one of the most important and vital aspect to the development of automotive nowadays. A good designed of intake system can improve engine power, increase torque and volumetric efficiency, while reducing harmful emissions and fuel consumption rate [1, 2]. Some researchers have studied on the modelling of intake flow characteristic [3-6]. Besides, the effect of geometrical parameters towards intake flow is also the key to understand the relation between intake design and engine performance [7, 8].

One of the intake components that essentially effect air intake pressure and engine performance is intake manifold. Thus, there are various studies conducted on intake manifold design which incorporate methods such as variable plenum length and active manifold with different runner length for different engine speed (rpm) [9-12]. Studies done in this paper is centered on the development and design of each component and an essential part of the intake manifold system in accordance with the requirements and restrictions in the Formula SAE competition. Intake manifold system is one of the main components in the engine system where the engine delivering power capability that can be obtained by an engine intake manifold located on the system itself [13-15]. However, this system consists of many sub-components that need to be joined to produce a component that will be able to assist in producing the engine system that is able to operate normally as it is to be achieved. With the introduction of the regulations and laws which contain restrictions for air intake system, air intake system that has been designed to use the engine no longer suitable for use and should be modified in accordance with the restrictions mentioned in the regulation.

However, studies on the intake manifold of this system always has a lot of room for improvement in the system and this study is intended to create a knowledge database to build the intake manifold system for the next generation of Formula SAE (FSAE) for our car [16, 17]. Basis of this study, which involves the theory underlying physics that governs the system of intake manifold air is "good practice" in the industry, a discussion on changes in the design of the various components of the system and how they affect the performance, and to establish procedures to fabricate and use the tools available to improve the quality of the final design of the air intake manifold system.

Besides the discussion on the theory of the intake manifold system, this report segments are discussing in parts, which is the various components of the air intake system, and how to design them specifically for a particular engine and type of performance needed, and the considerations for the peculiarity of the engine which every established FSAE team is using. Another component of the entire design process is the physical testing of the completed air intake manifold system on a dynamometer with a running engine, but will not be covered due to limitations in resources. Otherwise, this paper seeks to be a basic collection of information which indirectly complementing those that have been extensively studied, documented and are readily available which are required to design and analyze an air intake manifold system for a naturally aspirated Formula SAE racing car engine [18].

In automobile racing, several rule committees are appointed to oversee and regulate the event or class such as Formula SAE competition develop its own rules to provide a safe environment, and to provide more fairness level on playing this sport. With Formula SAE competition, many of the rules are intended to challenge the designers to provide a solution based on predefined rules and also from test or analysis, to a particularly challenging issue. One rule that is often imposed as a big concern on designing air intake manifold system is a restriction on the air intake diameter which the rules only allowed air past a single circular restrictor with a limited size only 20 mm of diameter and its body must be rigid.

The purpose of this is to limit the amount of power the engine can produce, to reduce the speed of the vehicle, and bring the power to more comparable levels across the class for more equal competition. With the restricted air intake rule that has been referred, it becomes the design engineer's job to maximize the performance, while strictly adhering to these rules.

The main problems and constraints in developing an intake manifold system for Formula SAE competition are as follows:

i. FSAE competition regulation restricted only air can flow through a 20mm diameter restrictor before entering the engine.
ii. The intake manifold component system position must not exceed the admissible component envelope.

From the literature review and after taking into consideration the major effect of every sub component in the intake manifold system to the performance of the engine, the main focus of optimization mainly consists of properly designing the following mentioned parameters:

i. Runner length.
ii. Runner opening diameter.
iii. Plenum volume.

2.0 METHODOLOGY

2.1 Research Methodology

For this research, the simulation was performed using GT-Power to visualize how different geometries affect parameters such as volumetric efficiency of the engine and achieved certain peak torque at high range of engine speed. The simulations analysis is performed at engine full load condition. The simulations were done to study the effect of the parameter variations by optimizing the design and geometry of every sub components in the intake manifold system on the performance of engine.

The explanation of this research is as below:

a. Develop engine model for this research using GT-Power 1D engine simulation software. The engine model used in the current Formula SAE car is 2008 Honda CBR 600RR. The purpose of conducting this simulation is to improve the performance of the engine through optimizing the intake air system to be used for the future Formula SAE competition. To develop the present engine model to be a reference for this simulation, all related and detailed engine specifications required to make a Honda CBR 600 engine model need to be collected.
b. Construct a 3D modelling of the present intake manifold system using SolidWorks.
c. Create a component modelling using GEM 3D of the present intake manifold system from the SolidWorks 3D model to be discretized after which the 1D GT-Suite mapping for the current intake system to be used in GT-Power engine simulation software shall be created.
d. Assemble the developed engine model and both intake and exhaust system to form a

complete 1D engine mapping for the simulation purposes.

e. Run the simulation on the complete system of engine to obtain the performance result of the engine.
f. Perform a parametric study on the intake manifold system.
g. Analyze the results from the parametric study and perform the optimization towards the parameter of intake manifold system by using the method named Design of Experiment (DOE) setup.
h. Review the results after implementing the optimization values of parameter on the present intake manifold system.

2.2 Engine Model Development

Developing an engine model for any kind of vehicle from scratch whether a motorcycle engine or a car engine model requires a long period of time. In this research, constructing a 1-D engine model of Honda CBR 600RR that used for our Formula SAE car are one of the challenging part in this research. To develop an engine model, the user has to gather all of the detailed specifications of the vehicle to be set as an input to construct the engine model.

After that, the engine model has to go through a correlation process in order to validate the performance of the engine model build perform similar with the actual Honda CBR 600 RR engine.

2.3 Intake Manifold Modeling

The intake manifold system has been constructed first using SolidWorks to construct a 3D modelling of the present intake manifold. After that, to convert the 3D modelling into 1D modelling, the 3D model must undergo component modelling to discretize the detail shape of the intake system on GEM 3D.

The model is then discretized to produce a 1D model in GT-Power engine simulation software. The 1D intake manifold model is assembled with the developed engine model to perform a simulation.

2.4 Parametric Study of Intake Manifold System

Parametric study is performed on the reference intake manifold system for the main purpose to investigate and identify the relationship of the effect of changing the design parameter of intake system towards the performance of the engine and to ensure this research are producing relevant data compared with previous research from the literature review findings. The parametric study was carried out for the purpose of determining a suitable range of the design parameters and also acts as a guidance when performing the optimization at a later stage. Table 1 shows the design parameter values to be analyzed.

Table 1 Design Parameter values for parametric study

Design Parameter	Present Values	Selected Values
Plenum Volume	2.3 Liters	1 Liters
		3 Liters
		4 Liters
		5 Liters
Runner Length	247.6 mm	100 mm
		150 mm
		200 mm
		300 mm
Runner Opening Diameter	44 mm	30 mm
		40 mm
		50 mm
		60 m

2.5 Optimization of Intake Manifold system

To find the best values of all these three design parameters that give the most significant improvement of performance, the optimization of these values is being performed using Design of Experiment (DOE) method. Prior to that, the users must create a parameter in the case setup menu to declare the design parameter in the intake manifold system on the engine model.

For this research, there are targets that need to be achieved which can be set in this optimization setup, i.e. to improve the peak torque and air flow rate at mid and high range of engine speed (rpm).

3.0 RESULTS AND DISCUSSIONS

3.1 Validation of Engine Model Results

The validation process of the engine model used in this research is very important to give the engine model that has been built in this research to acquire almost similar performance behavior compared to the actual condition of the real engine. Figure 1 shows correlation results of Honda CBR 600 RR engine model. The graph indicates that the engine model has been successfully correlated and being validated with the highest percentage difference and not exceeding 15% of difference.

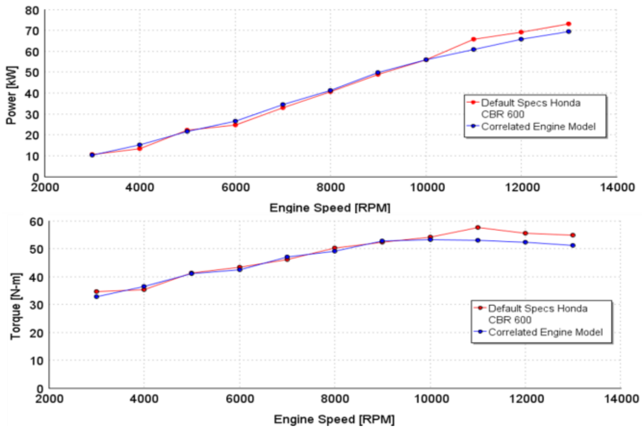


Figure 1 Brake Power and Torque vs. Engine Speed Correlation Results of Honda CBR 600 RR Engine Model

Only one point of engine speed is near the 15% difference which is still acceptable where the rest of percentage differences are still under 10% differences. Thus, the engine model is successfully validated in this research and the engine model can be used in further simulation works.

3.2 Parametric study on Intake Manifold system

Parametric study was performed in this research to identify and analyze the behavior of changing design parameters against the performance of the engine so that they are clearly related.

3.2.1 Plenum Volume

With reference to Figure 2, in the mid to high range of engine speed which is at 3,000 to 8,000 rpm, the plenum volume of 5 L has the highest value of both power and torque with 3.5% and 3.0% maximum percentage difference compared to the reference model respectively and it is followed by 4 L plenum volume. This is due to the effect of pulsation from the restrictor where the bigger the plenum volume, the better the damping of restrictor pulsation as well as to reduce the flow loss inside the manifold. However, if the plenum volume is too big, it can also reduce the throttle response. In Figure 3, the air flow rate and volumetric efficiency values indicate similar results with 5 L plenum volume showed the best performance at most part of the engine speed variation up to 8,000 rpm.

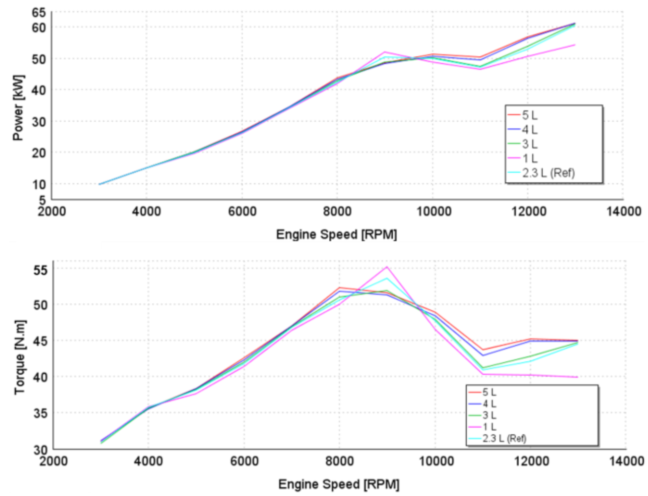


Figure 2 Brake Power and Torque vs. Engine Speed. Comparison Effect of varies Plenum Volume

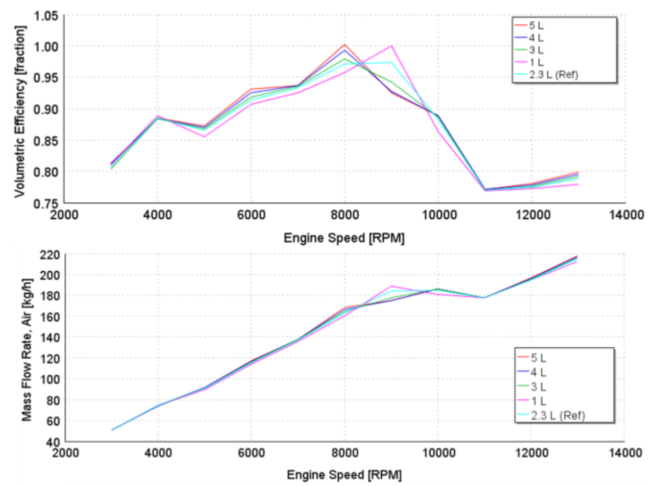


Figure 3 Volumetric efficiency and Air flow rate vs. Engine Speed. Comparison Effect of varies Plenum Volume

It can be seen that 5 L of plenum volume indicates the highest air flow rate compared with other plenum volumes. This is probably because of the even static pressure on the plenum that allows the air distribution to every runner to be properly distributed because of its bigger size of plenum volume. Only nearing to 9,000 rpm range, the 5 L plenum showed moderate mass flow rate compared to 1 L plenum which performed better. This is similar to the findings by Ceviz and Akın where the higher the plenum length or volume, results in better engine performance at low engine speed whereas shorter plenum length performed better at higher engine speed [9].

3.2.2 Runner Length

For the 300 mm of runner length which is the longest, it shows best power increment from mid to high rpm values followed by the second longest runner length as can be seen in Figure 4. At engine speed of 9,000 rpm and above, the highest values of power are achieved by the shorter runner lengths.

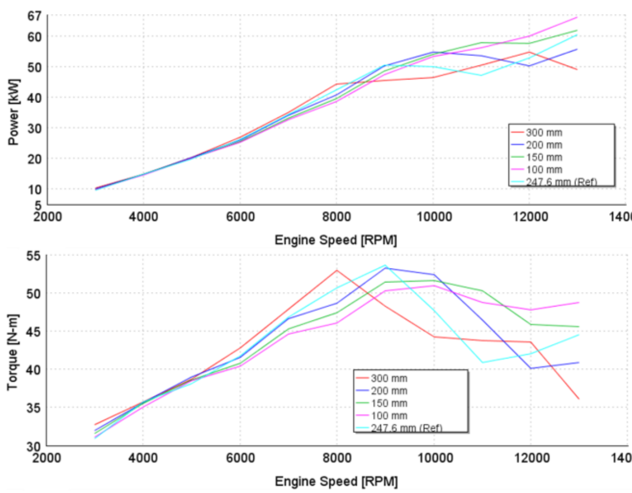


Figure 4 Brake Power and Torque vs. Engine Speed. Comparison Effect of varies Runner Length

For the torque curve, the longer runner length starts to reach its peak torque early at the high range of engine speed followed by the shorter runner length that reaches their peak torque values at much higher engine speed. But for the longer runner length, the torque values drop significantly right after it reaches the peak torque value resulting in the lower value of torque at the higher engine speed range. However, it is not a big concern since it already passed the 8,000 rpm engine speed range. Figure 5 depicts similar pattern of performance ranking for the air flow rate graph and volumetric efficiency graph. The 300mm runner length produced maximum improvement of up to 5.1% and 5.4% for volumetric efficiency and air flow rate respectively when compared to the reference model.

The similarity of the results shown in Figure 4 and Figure 5 is due to the strong relationship of power with air flow rate and also torque with the volumetric efficiency that shows the same effect to the performance of the engine. Thus, to conclude the relationships of the runner length parameter to the engine performance, the longer runner length is best operating for the early mid to high-range of engine speed but indicates poor performance if it was to operate on engine speed of more than 8,000 rpm. This runner length effects towards engine performance can be explained by the air pulsation in the runner before it enters the intake valve. This is why some researchers and even car manufacturers opted for variable intake runner length than conventional fixed runner to optimize engine performance at both low and high rpm engine speed [19, 20].

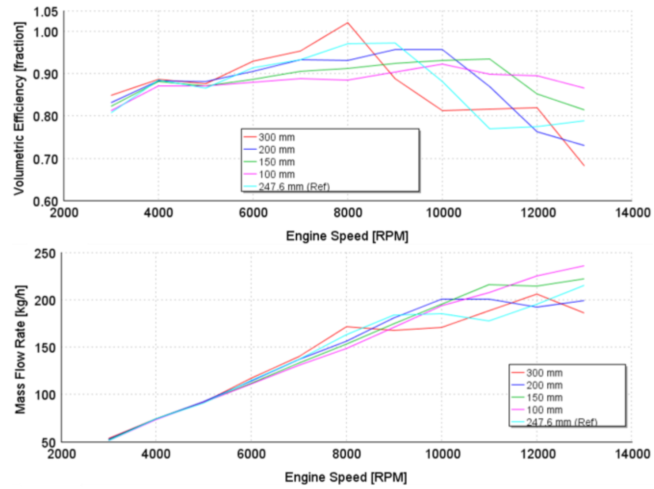


Figure 5 Volumetric efficiency and Air flow rate vs. Engine Speed. Comparison Effect of varies Runner Length

3.2.3 Runner Opening Diameter

For the power curve, through the increasing of engine speed, the 60 mm runner diameter produces the highest peak power compared to others as shown in Figure 6. The smaller diameter of runner produces lesser power at 8,000 to 11,000 rpm engine speed. Mid runner diameter of 40mm shows best overall performance from mid to high engine speed which is at 3,000 to 8,000 rpm.

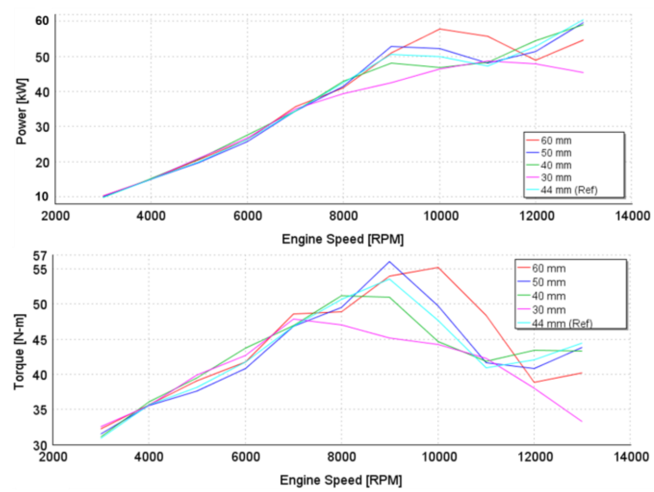


Figure 6 Brake Power and Torque vs. Engine Speed. Comparison Effect of varies runner opening diameter

The torque curve shows similar result with high runner opening diameters produced highest peak torque, while 40mm runner diameter produced best overall performance with constant and stable torque increment with the increasing of engine speed up to 8,000 rpm. This is due to the restriction by small diameter runner caused the amount of air entering the cylinder becomes insufficient especially when operating at the higher engine speed which need a more leaner combustion in the cylinder and thus to provide more power to the engine. However if the diameter is too big, it can cause air pressure drop in the runner which will affect the engine performance [1]. In Figure 7, the runner of 40 mm of diameter achieves best air flow rate in the engine speed range of 3,000 to 8,000 rpm.

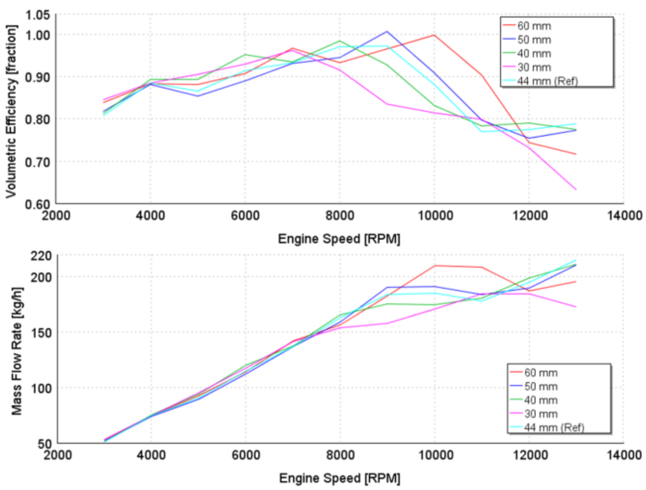


Figure 7 Volumetric efficiency and Air flow rate vs. Engine Speed. Comparison Effect of varies runner opening diameter

The smaller diameter of runner indicates lesser air flow rate when starts to operate at very high engine speed of 10,000 rpm resulting in insufficient air flows into the cylinder. While for the volumetric efficiency, larger diameter of runner indicates a higher volumetric efficiency when operating at 10,000 rpm engine speed whereas the smaller runner diameter indicates higher values of volumetric efficiency when operating at mid to early high range of engine speed due to the factor of runner volume that affect the performance of the engine. Optimal size of runner diameter may depends on the targeted operating engine speed, with mid-size runner diameter suggesting best overall performance for both mid and high engine speed.

3.2.4 Optimization Results of Intake Manifold

After running the optimization process using the DOE method according to the proposed setup in order to achieve the desired target, the values for each of these three design parameters were obtained through the optimization results performed earlier. In Figure 8, it shows the graph that is plotted to provide a comparison between the previous Formula SAE reference model performance data and the performance results after the implementation of optimization values.

Figure 8 shows a clear improvement of the peak torque at the high engine speed range which starts at 8,000 rpm until 10,000 rpm with the most significant improvement achieved at 9,000 rpm for a torque of 56.16 Nm compared to previous value of 53.56 Nm with a percentage improvement of 4.83%. Optimized intake manifold also showed positive percentage difference throughout the mid to high engine speed range which is at 3,000 to 8,000 rpm with average percentage improvement of 0.68% compared to the reference model. In Figure 9, it also indicates a significant improvement of the air flow rate which depicts highest increment at 9,000 rpm, i.e., from 183.9 kg/h to 192.1 kg/h with a percentage difference of 4.45% achieved from the optimization results. At 3,000 to 8,000 rpm engine speed range, the new manifold shows improved overall performance with average percentage difference of 0.44%. High air flow rate measurement indicates a good overall intake design since it generates best engine performance.

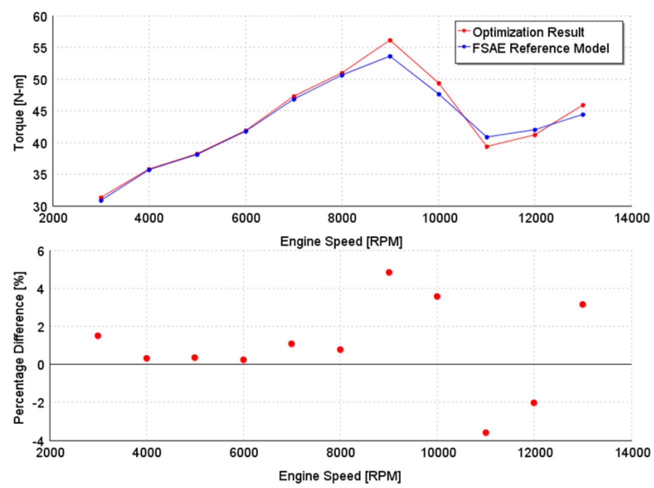


Figure 8 Torque (N.m) vs. Engine Speed (RPM). Optimization Results of Formula SAE Engine Model

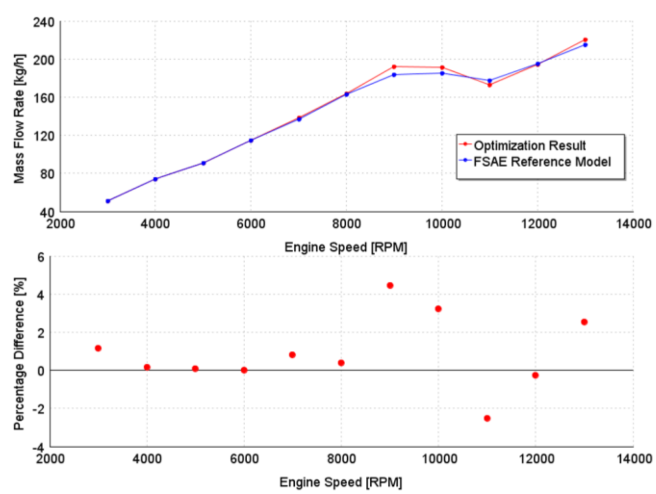


Figure 9 Air flow rate (kg/h) vs. Engine Speed (RPM). Optimization Results of Formula SAE Engine Model

4.0 CONCLUSIONS

In conclusion, the relationship between each design parameter towards the performance of the engine is clearly identified through the parametric study. The targets for the optimization also were successfully achieved. The improvement of torque at mid to high range of engine speed is significant with the highest increment of about 4.83% at 9,000 rpm whereas for the air flow rate, the most significant improvement also occurred at 9,000 rpm with 4.45% increment. To conclude, the overall performance of the engine for the improvement at the mid and high range of engine speed has been successfully achieved through the implementation of the optimization approach.

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