Design Optimization and Flow Analysis of An Air Intake System for SAE Student Formula: A Review

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Abstract — In the research of Formula SAE (FSAE) and racing car engines highlights the important role of air intake system design and performance to finding the volumetric efficiency, torque, and overall power output. As per the rules explains a 20 mm restrictor, which is limits the flow of air into combustion chamber and making the optimization of the intake system. Numerous studies have shown that venturi-type restrictors, when designed with convergent and divergent angles of approximately 12° and 6°, minimize pressure drop while allowing maximum airflow. In addition, the geometry of the intake manifold—including plenum shape (cylindrical, spherical, or elliptical) and runner length—has a direct impact on flow distribution, throttle response, and combustion efficiency. And we add the Advanced computational tools such as ANSYS Fluent, SolidWorks Flow Simulation, along with experimental validation, we have been widely utilize to predict and refine airflow moment. Then the innovations have focused to reducing pumping losses through barrel-type throttle bodies, we use RAM theory for plenum design, and use the variable-length intake manifolds for better sustain across different RPM ranges. with these approaches proves that careful optimization of restrictor geometry, plenum volume, and runner tuning can also improve mass flow rate, minimize pressure losses, and also enhance the performance and efficiency of FSAE race cars.

Keywords: Formula SAE, Air Intake System, Venturi Restrictor, CFD Analysis, Plenum Design, Runner Length, Volumetric Efficiency, Pressure Drop, Throttle Body, Variable Intake Manifold, Engine Performance

I. INTRODUCTION

The SAE Student Formula race car competition challenges the engineering students to design and build the small formula-style cars, with providing a real-world platform and also the innovation and technical skill development. This is one of the most critical component in these vehicles is the air intake system, which is directly affect the engine performance, volumetric efficiency, and fuel economy. According to event rules and regulation, each FSAE vehicle must use a 20 mm intake restrictor placed between the throttle body and intake manifold. It limit the power output of four-stroke engines. During this rule confirm the inovative competition, it also reduces the airflow to the cylinders, which leading to losses of torque, throttle response, and maximum power output. To overcome these effects, the intake system must be carefully designed and optimized. The restrictor geometry particularly the convergent and divergent angles of a venturi-type restrictor has been shown to greatly affect pressure drop and airflow velocity. Similarly, plenum volume and runner length must be tuned to harness the ram and resonance effects, which improve cylinder filling and combustion efficiency at varying engine speeds. The smooth airflow distribution in the intake manifold is necessary to confirm that each cylinder get equal charge, when stop the imbalances that can accept the performance.

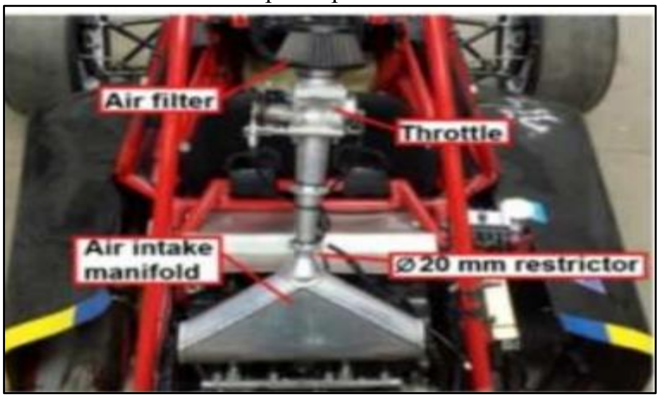

Fig. 1: Manifold with Ø20mm air restrictor

In the Computational Fluid Dynamics (CFD) and simulation tools such as ANSYS Fluent, SolidWorks Flow Simulation are useful to get precise analysis of airflow patterns, pressure distribution, and velocity range. These types of tools reduce the depends on costly physical prototypes and allow critical testing for multiple designs. Experiment shows the accuracy of simulation-based findings. The innovations include the barrel-type throttle bodies to minimize pumping losses and variable length intake manifolds to enhance the across RPM ranges and we have also proved the significant performance gaining.

Thus, the design optimization and flow analysis of the intake system is a crucial part of developing a innovative SAE Student Formula car. By reducing pressure losses, improving airflow distribution, and optimizing restrictor, plenum, and runner parameters, that teams can enhance engine performance, fuel efficiency, and overall efficiency within the restricted of FSAE regulations.

II. DESIGN OF RESTRICTOR

The restrictor is a critical component in the Formula Student intake systems, it is designed with specified competition rules that require all engine have air to pass through in a single 20 mm diameter orifice placed between the throttle and the intake manifold [1]. To accept with their regulation while maximizing engine performance, a converging–throat–diverging venturi design is fixed, as it provides a higher discharge coefficient and lower total pressure loss compared to a sharp-edged orifice [2]. The airflow through the 20 mm throat is limited by choked-flow conditions and both theoretical and experimental studies and report gives a maximum mass flow rate of approximately 0.070 kg/s under atmospheric conditions [3].

The geometry of the restrictor strongly influences its performance. Research shows that an optimal convergent half-angle of about 10.5°–12° and a diffuser half-angle near 6° yield the best balance between efficient flow acceleration and effective pressure recovery without stall [4]. A throat length, around 0.8–1.0 times the throat diameter is recommended to stabilize sonic flow while minimizing frictional losses [5].In Previous studies also indicate that the overall length of a well-performing restrictor between 130–160 mm with one accepted design reporting 145 mm in total, consisting of a 36 mm inlet, 20 mm throat, and 41.5 mm outlet[6]. And smooth profiling at the convergent entrance is improve to reduce separation and losses [7].

After confirm these design, CFD analysis is remaining. A Multiple studies using ANSYS Fluent and CFX performed angle sweeps verifying that the 11° convergent and 6° diffuser geometry to minimized pressure drop when compared to alternative designs [8]. For manufacturing the prototypes can be additively manufactured using sheetmetal or ss sheet, for endurance use CNC-machined aluminum with a polished surface finish (Ra ≤ 1.6 µm) is recommended to achieve the dimensional accuracy and flow smoothness [9]. combination with the intake plenum is equally important, an efficient diffuser exit reduces turbulence and improve the uniform airflow distribution to the cylinder and enhancing the overall engine performance [10].

III. Runner

The runner acts as the channel that guides air from the plenum to the engine cylinders, and its design has a direct impact on airflow velocity, distribution, and engine performance [11,12]. By ensuring that each cylinder receives an equal air charge, the runner helps maintain balanced combustion. Its length and diameter are critical parameters: longer runners are effective at boosting torque at lower RPM, while shorter runners enhance airflow at higher RPM [13-17]. Additionally, the runner takes advantage of the ram and tuning effects, where pressure waves are synchronized with valve timing to push more air into the cylinder, improving volumetric efficiency. Thus the runner is necessary for optimizing cylinder filling, stabilizing airflow, and tailoring torque characteristics across the engine's operating range [18-24]

IV. Plenum

The plenum in an intake system acts as a chamber between the restrictor and the runners, where it stores and stabilizes the incoming air before distributing it to the cylinders. Its primary function is to equalize pressure and maintain a consistent airflow, ensuring that each cylinder receives a uniform charge for balanced combustion [25-27]. The plenum volume plays a key role in performance: a larger volume improves top-end power by allowing more air storage, while a smaller volume enhances throttle response. In addition, the plenum takes advantage of the ram effect, where dynamic pressure generated by the vehicle's motion raises the static pressure inside the intake manifold, increasing the mass of air entering the cylinders. For Formula SAE engines, where airflow is restricted by the 20 mm intake limit, careful plenum design becomes critical for enhancing volumetric efficiency, stabilizing combustion, and improving overall engine responsiveness [28-35].

Fig. 2: PLENUM

V. Venturi

The Venturi is a crucial feature in the restrictor design of a Formula SAE air intake system. It is a smoothly contoured, converging-diverging shape that helps optimize airflow through the mandatory 20 mm diameter restrictor [35-39]. As air enters the converging section, it is accelerated toward the narrowest point (the throat), where its velocity increases and static pressure drops, following Bernoulli's principle. This pressure drop allows more air to flow through the restrictor despite the limited cross-sectional area. After the throat, the diverging section (called the diffuser) gradually slows the airflow, allowing partial pressure recovery while minimizing turbulence and flow separation. Proper Venturi design, with typical converging angles of 10–15° and diverging angles of 5–7°, ensures smooth transitions and high flow efficiency.

Fig. 3: VENTURI

In Formula SAE, where every bit of airflow matters, the Venturi plays a vital role in reducing total pressure loss, improving mass flow rate, and enhancing overall engine performance. Teams often use CFD simulations and flow bench testing to fine-tune the Venturi geometry for optimal results[40-46].

VI. Restrictor

The restrictor in a Formula SAE intake system is a rule-mandated component that limits the airflow into the engine by requiring all intake air to pass through a maximum 20 mm diameter opening (for gasoline engines). Its main purpose is to restrict engine power, ensuring fair competition across all teams. However, because it creates a major airflow bottleneck, its design must be optimized to reduce pressure loss and maintain high air velocity[47-49]. Teams often shape the restrictor as a Venturi to accelerate air through the narrow throat and recover pressure in the diffuser section. A well-designed restrictor helps maintain smooth, laminar flow and minimizes turbulence, which is essential for engine efficiency and throttle response. It is typically analyzed using CFD tools to refine geometry and ensure optimal performance. Despite being a limiting component, the restrictor plays a crucial role in the overall performance of the air intake system[50].

VII. Conclusion

The design optimization and flow analysis of the air intake system for an SAE Student Formula vehicle have demonstrated the critical role of computational fluid dynamics (CFD) and iterative design in enhancing engine performance and overall vehicle efficiency. Through comprehensive CFD simulations and performance evaluations, an optimized air intake design was achieved that meets the target objectives of improved airflow, minimized pressure losses, and effective air-fuel mixing. The final intake geometry shows a significant improvement in volumetric efficiency and throttle response, directly contributing to better combustion and power output. Key design features such as a properly contoured plenum, smooth transitions, and tuned runner lengths have been validated through flow analysis, ensuring compliance with SAE rules while maximizing engine breathing capabilities.

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