Investigation of the influence of the convergent part of the FSAE vehicle restrictor on the airflow using CFD

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Abstract: *The Formula Student competition is the most challenging, complex, and attractive student engineering competition in the world. Students from universities around the world compete to build better vehicles. The competition consists of several different disciplines, which are divided into two groups. The first group consists of static disciplines, where students who are members of the team defend the vehicle project in front of eminent experts from the world of the automotive industry and auto-moto sports. The second group is the group of dynamic disciplines, which is made up of several disciplines related to the analysis of vehicle behavior in real conditions. One of the main challenges facing the team members is designing the vehicle's propulsion system. At competitions in the IC engine class, power units from a certain class of motorcycles are most often used. The main limitation related to the power unit is that all intake air must pass through a 20 mm diameter. One of the solutions to the mentioned problem is the use of a convergent-divergent nozzle with a throat diameter of 20 mm. In this paper, the influence of the convergent part of the nozzle on the airflow through the nozzle itself was examined. Models were created for several restrictors and they were tested by CFD simulation in ANSYS Fluent software.*
Keywords*: CFD, VEHICLE, IC ENGINES, FORMULA STUDENT, INTAKE MANIFOLD*

1. Introduction

Formula Student is an international student engineering competition where students from universities around the world compete to build a small racing vehicle. A big challenge when designing a Formula Student vehicle is the design of the air intake system. In the automotive industry, this system is very complicated and requires a lot of design attention to extracting as much power and torque as possible from the IC engine. Different intake manifold concepts can be applied to Formula Student vehicles. One of the parts that must be included in the intake installation of FSAE vehicles is a restrictor, a type of element to limit the flow of air that can enter the internal combustion engine. In this paper, the influence of one parameter of the convergent part of the convergent-divergent nozzle was examined using the ANSYS Fluent software. The work is divided into six chapters, the first of which is an introduction, and the last is a list of references used in the work. The second chapter discusses the air intake system in general, as well as the restrictions that apply to the Formula Student competition itself. To examine the influence of the convergent part parameter on the convergent part, a CFD simulation was performed, which is shown in the third chapter. The fourth chapter presents the results of the CFD analysis, and the fifth chapter presents the conclusions related to this research. How attractive the topic of Formula Student is in the world, and especially the design of the air intake system, is shown by the large number of papers dealing with this topic [1-10]

2. Air intake system for Formula Student vehicle

2.1. Air intake system

The more air that is sucked into the engine, the more horsepower will be provided. As cold air is much denser than warm air, it is possible to suck more of it into the engine. The intake manifold directs the airflow from the throttle body to the cylinder head intake ports. The choice of the intake manifold and the size of the intake runners affect engine power and engine torque. Larger intake runners and higher plenum locations are more favorable for higher engine revs, generally speaking. When designing the intake system, care must be taken to allow the air and fuel that is sucked into the engine to exit the system with a suitable exhaust system design. Proper design of the exhaust manifold can also allow additional charge to be drawn through the vacuum phenomenon. The configuration of intake manifold runners directly affects engine power and maximum torque. Most intake manifolds are a design compromise. It is necessary to find a balance between engine power output and torque at low rpm according to the intended application and driving conditions. The design of the intake manifold is critical in naturally aspirated engine situations. In the case when the intake installation is equipped with a turbocharger or supercharger, the design of the manifold is less critical [11]. When designing the intake manifold, it is necessary to enable the best possible airflow characteristics.

2.2. Air intake system in Formula Student

According to Formula Student Rules [12] there are two possible configurations of the air intake system. The configuration for naturally aspirated engines is shown in Figure 1, while the Configuration for turbocharged or supercharged engines is shown in Figure 2. It should be noted that in the internal combustion class, the use of engines is limited to 710 cm3 of total volume, so teams are mainly determined to modify engines that are applied to motorcycles.

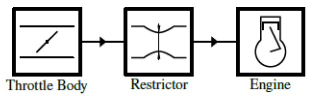

Fig. 1 *Configuration for naturally aspirated engines [12]*

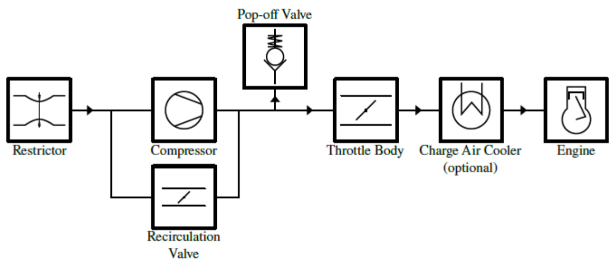

Fig. 2 *Configuration for turbocharged or supercharged engines [12]*

The configuration for turbocharged or supercharged engines enables better air intake into the engine but is a significantly more expensive design solution compared to naturally aspirated engines. Any configuration that the Formula Student teams choose for the air intake system must include a restrictor. The most rigorous restriction according to the aforementioned rulebook is related to the Restrictor. According to the Formula Student rules, the maximum restrictor diameters for gasoline engines are defined as 20 mm, and if E85 fuel is used, then the restrictor diameter is 19 mm. This restrictor must be located in such a way that the diameter can be measured during the competition itself. A restrictor must exist in the system to limit engine power and all air drawn into the engine must pass through it. The modification of the intake system is one of the more complicated undertakings during the construction of the vehicle itself. Designing the intake system is, as already said, a compromise. To ensure the full potential of the engine, it is necessary to pay great attention to the design and exhaust system. A well-designed intake or exhaust system alone will not provide the best performance to obtain greater engine power and torque. Although internal combustion engines installed in motorcycles are used as power units, it is necessary to consider the possibility of redesigning some parts of the engine such as pistons, connecting roads, crankshaft, and the like. When considering the redesign of the crankshaft, it is necessary to perform a dynamic analysis of the forces acting on the piston group. Kinematic analysis precedes dynamic analysis, and an example of kinematic analysis of a piston group is shown in papers [13-17]

3. CFD simulation of Formula Student restrictor

The main goal of the work is to examine the curvature of the convergent part of the restrictor to better understand the influence of this parameter on the flow characteristic of the restrictor itself. The considered geometry is shown in Figure 3. So the inlet and outlet of the restrictor are equal and amount to 40 mm. The length of the convergent part is 25 mm, and the length of the divergent part is 200 mm. The throat of the Restrictor has a circular cross-section with a diameter of 20 mm. The previously mentioned dimensions are fixed (do not change) for each performed CFD simulation in this paper. The parameter R (Figure 3) is defined as the only variable parameter. The goal of this simulation is to examine the effect of changing the parameter R, which represents the radius of the convergent part, on the fluid flow through the restrictor itself. 11 different dimensions of the radius of the convergent part R were tested. The values of the parameter R that were considered were for a certain degree of difference between 45º and 55º inclusive. Eleven 3D models were created with the only difference being the radius R, and the 3D fluid domain model for one of the modeled restrictors is shown in Figure 4.

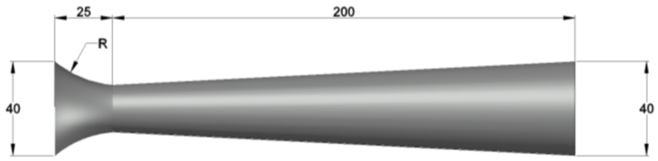

Fig. 3 *Dimension of restrictor*

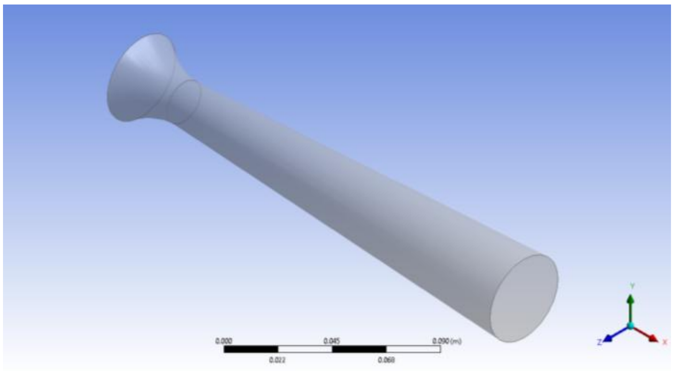

Fig. 4 *3D model of the fluid domain of the restrictor*

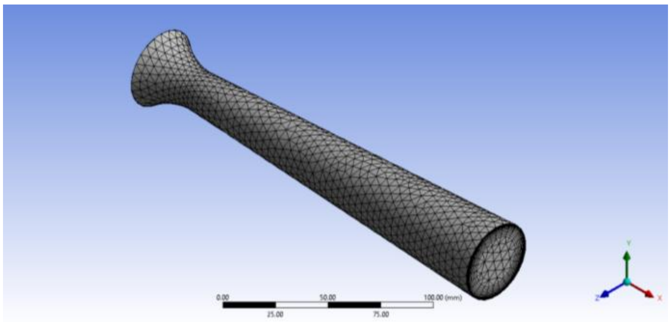

Fig. 5 *Mash of fluid domain restrictor*

After placing the mesh on the 3D model of the fluid domain of the restrictor, it is necessary to define the boundary conditions. In the CFD simulation, the k-ε turbulence model was used. Air was used as the fluid, and a pressure of 101325 Pa was set at the inlet and 91325 Pa at the outlet of the restrictor, which is shown in Figure 6.

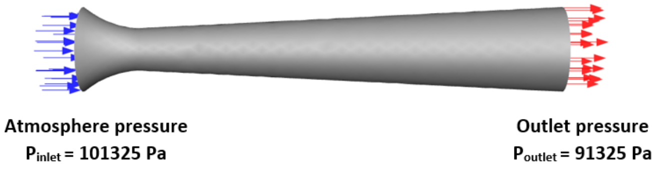

Fig. 6 *Inlet and outlet pressure*

4. Results of CFD simulation of Formula Student restrictor

In this chapter, the results of the CFD simulation of airflow through the restrictor are presented. For each of the 11 restrictors, the average axial velocity and mass flow at the exit were measured using the ANSYS Fluent software. The values of average axial velocity and mass flow at the outlet of the restrictor are shown in table 1. Diagrams of changes in average axial velocity and mass flow at the outlet of the restrictor are also given in Figures 7 and 8.

Table 1: *Average axial velocity and mass flow on the outlet*

The radius of the convergent part R [°]	Mass flow outlet (kg/s)	Average Axial Velocity outlet (m/s)
45	0.11646	76.535
46	0.11662	76.610
47	0.11634	76.423
48	0.11569	76.019
49	0.11475	75.396
50	0.11608	76.253
51	0.11524	75.741
52	0.11576	76.027
53	0.11509	75.616
54	0.11447	75.194
55	0.11480	75.430

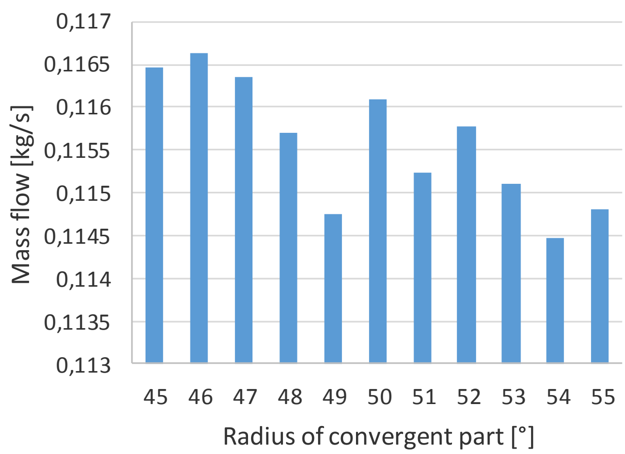

Fig. 7 Chart of mass flow on the outlet

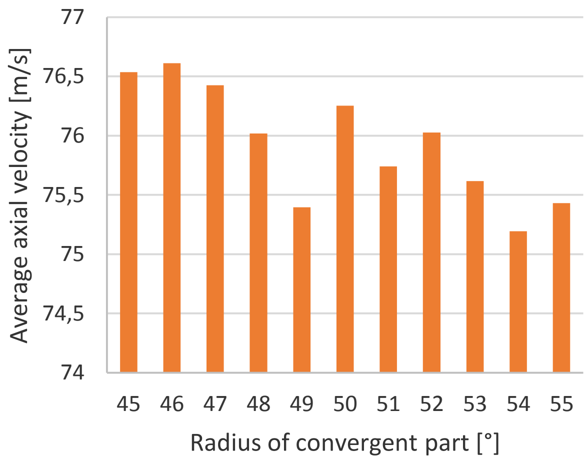

***Fig. 8** Chart of average axial velocity on the outlet*

From the previous diagrams, it can be seen that the radius of the convergent angle affects the flow to a significant extent. A radius of 46º provides the best mass flow and average axial velocity at the exit. Radius 54º has the lowest value of mass flow and average axial velocity on the outlet. If we start from the assumption that the more air sucked into the engine, the greater engine power will be provided, restrictors with a radius of convergent parts 45º, 46º and 47º achieve the best flow characteristics, that is, they have the highest mass flow rate at the exit. As these three radii stand out as the best in terms of mass flow rate maximization at the outlet, Figures 9, 10, and 11 show their pressure contours, and Figures 12, 13, and 14 show velocity streamlines for these three restrictors. Figures 15 to 17 show the contour of turbulence kinetic energy.

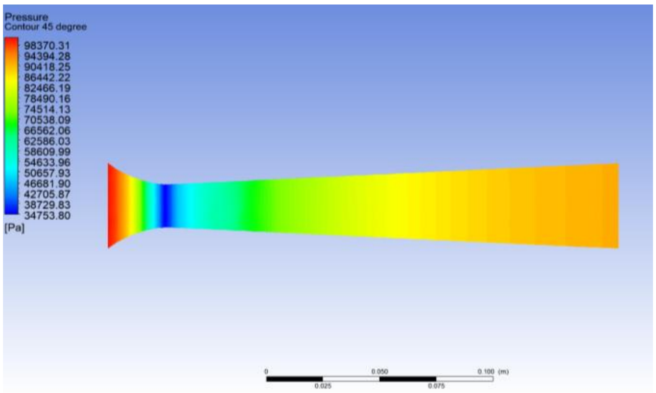

Fig. 9 *Pressure contour for the radius of convergent part 45°*

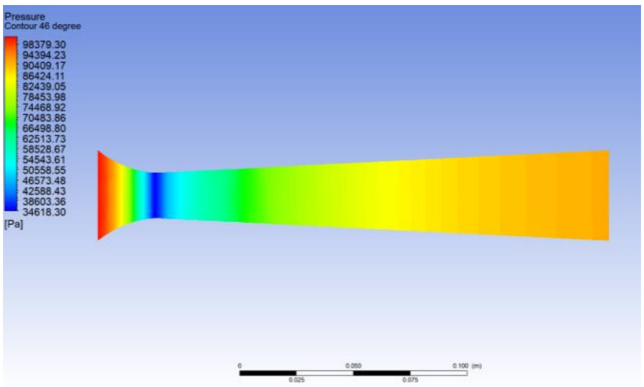

Fig. 10 *Pressure contour for the radius of convergent part 46°*

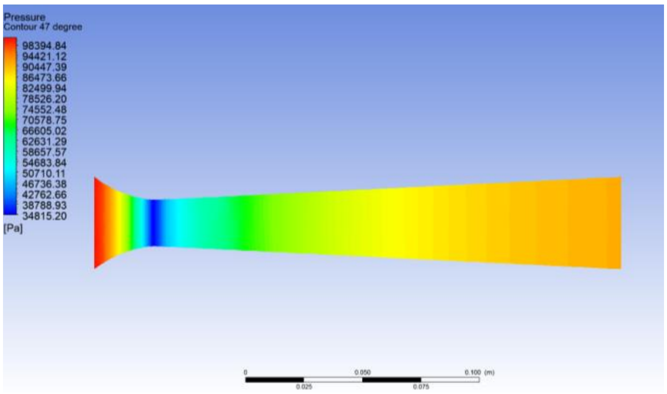

***Fig. 11** Pressure contour for the radius of convergent part 47°*

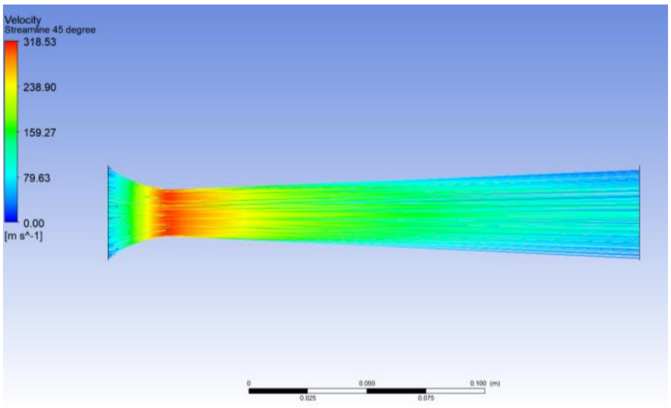

***Fig. 12** Velocity streamlines for the radius of convergent part 45°*

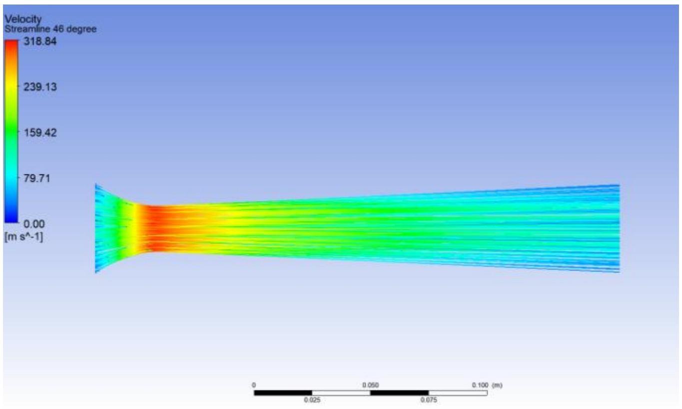

***Fig. 13** Velocity streamlines for the radius of convergent part 46°*

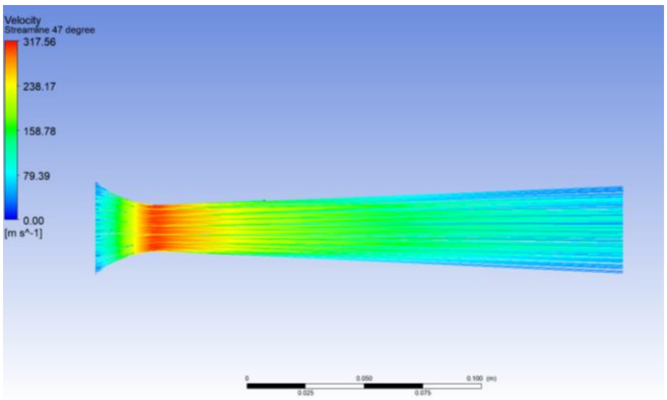

***Fig. 14** Velocity streamlines for the radius of convergent part 47°*

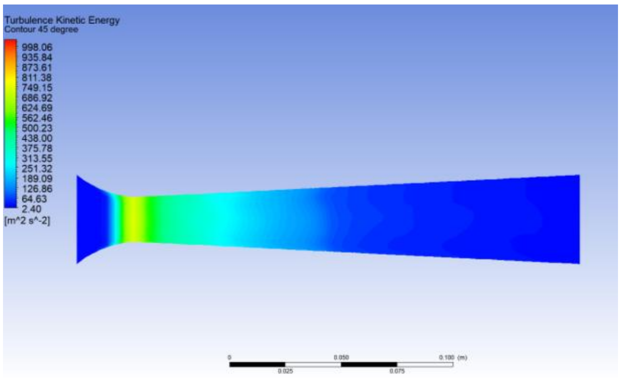

Fig. 15 *Turbulence kinetic energy for the radius of convergent part 45°*

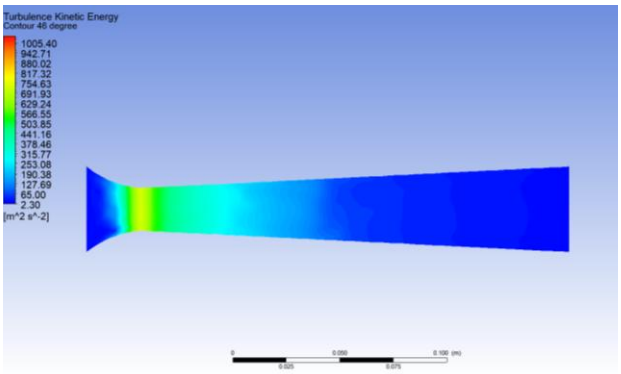

Fig. 16 *Turbulence kinetic energy for the radius of convergent part 46°*

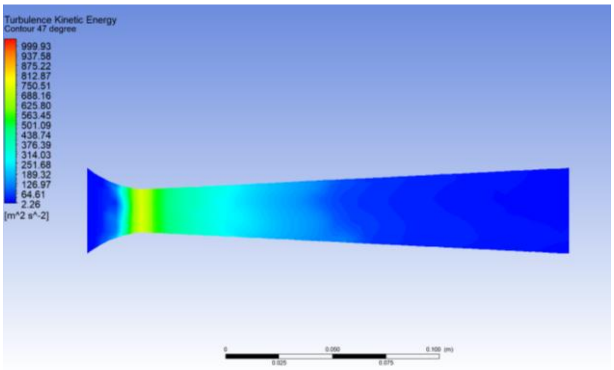

Fig. 17 *Turbulence kinetic energy for the radius of convergent part 47°*

5. Conclusion

Designing an intake system is a very complex job. Proper design of the air intake system directly affects engine power. According to the rules of the Formula Student competition, a restrictor is a mandatory element whether it is a naturally aspirated engine or a turbocharged or supercharger engine. Restrictor design is of great importance for the configuration of naturally aspirated engines. In this case, the restrictor is a bottleneck and its proper design will enable a better flow characteristic of the air intake system. When configured with a turbocharger and supercharger restrictor, there is no need to be a bottleneck because more air is sucked in under pressure using the supercharger or turbocharger. In this paper, an analysis of the dependence of the change in the radius of the convergent part was performed. The obtained results indicate that no linear dependence of this quantity can be defined. The best flow characteristic is provided with a radius of 46º, then with a radius of 45º, and then with 47º. The worst flow characteristic was obtained with a radius of the convergent part of 54º, and a little better than that with a radius of the convergent part of 49º. If the restrictor was chosen according to providing the best mass flow rate out of 11 analyzed solutions, then it would be a restrictor with a radius of the convergent part of 46º. CFD analysis is a very powerful tool that can simulate the real conditions in which a system works. With this kind of analysis, production costs are significantly reduced, because a large number of potential solutions can be examined using computer analysis and the best ones can be chosen. Ansys FLUENT software proved to be very good software for CFD analysis.

6. References

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