Design and CFD simulation of the exhaust manifold of the Formula Student vehicle

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Abstract: *One of the biggest challenges in the FSAE competition is adapting the power unit to the strict regulations of the competition. The task of the exhaust manifold is to enable the best possible flow of exhaust gases from the engine to the environment. A properly designed vehicle exhaust manifold is of great importance for enabling better performance of the power unit. There are several different concepts for designing exhaust manifolds. Each concept has its advantages and disadvantages. One of the main guidelines when designing the exhaust manifold is to enable air flow with as little local resistance as possible so that the exhaust gases are released into the environment as soon as possible. In this work, a 3D model of three types of exhaust manifolds was created, and then a CFD simulation of airflow through exhaust manifolds was performed using ANSYS Fluent software. CFD simulations help to a great extent with a better design of the exhaust manifold.*
***Keywords**: CFD, EXHAUST MANIFOLD, VEHICLE, IC ENGINES, FORMULA STUDENT*

1. Introduction

The design of the exhaust manifold is one of the biggest challenges when designing a Formula Student vehicle, as evidenced by a large number of scientific works on the mentioned topic [1-6]. Ref. [7] showed that with a proper design of the exhaust manifold, the exhaust emission can be reduced. In this paper, a CFD analysis of several different models of the exhaust manifold was performed. In the first chapter, what was done in the work itself was defined. The second chapter deals with the Formula Student rulebook with special reference to the part of the rulebook related to the driving system of the vehicle. The third chapter talks about exhaust manifolds in general. A CFD analysis of various Exhaust System concepts is presented in chapter four. In chapter five, the results of CFD analyzes of different concepts of exhaust branches are presented, while in chapter six, a conclusion related to the topic of the paper is given. Chapter seven lists the literature used in this paper.

2. Exhaust design limitations for a Formula Student vehicle

As the topic of this paper is the CFD analysis of the exhaust manifold of the engine used in the Formula Student competition, this chapter will talk about the competition itself. Formula Student or formerly "Formula SAE" (FSAE) is the most complex, demanding, and attractive student engineering competition in the world organized by the Society of Automotive Engineers (SAE). One of the biggest challenges of the Formula Student competition is the design of the exhaust system. The restrictions related to the internal combustion engine are shown in the Formula Student Rules [8]. By this regulation, the internal combustion engine that powers the FSAE vehicle is limited to a four-stroke, internal combustion piston engine with a volume of no more than 710 cm^3 per cycle. Given the previously mentioned limitation, the choice of internal combustion engines is limited to those that are usually installed in racing motorcycles. Another major limitation of the internal combustion engine that applies is related to the air intake. Rulebook [8] stipulates that all air sucked into the engine must pass through the restrictor. The maximum restrictor diameters which must be respected at all times during the competition are 20 mm for gasoline-fueled vehicles or 19 mm for E 85-fueled vehicles. The exhaust opening must be directed to the side or rear of the vehicle so that the driver is not exposed to the fumes at any speed given the vehicle's ground clearance. The exhaust port(s) must not extend more than 450 mm beyond the center line of the rear axle and must not be more than 600 mm above the ground. All exhaust components (headers, mufflers, etc.) protruding from the side of the body in front of the main hoop must be protected to prevent contact by persons approaching the vehicle or the driver exiting the vehicle. The temperature of the outer surface must not be harmful to the person touching it. The maximum sound level test speed for a given engine will be the engine speed that corresponds to an average piston speed of 15.25 m/s. The calculated speed will be rounded to the nearest 500 rpm. The maximum permitted sound level up to this calculated speed is 110 dB(C), fast weighing. The exhaust manifold used on racing motorcycle engines must be changed and another must be designed and manufactured that will be more suitable for use on a four-wheeled vehicle. When choosing an internal combustion engine to be used, it is necessary to carry out detailed analyses, primarily about the number of cylinders, but also other analyzes related to construction parameters. Analysis of the kinematics of a four-cylinder engine with internal combustion using CATIA software is presented in the paper [9].

3. Exhaust manifolds and exhaust headers

The exhaust manifold is somewhat similar to the intake manifold. The intake manifold receives incoming air from a central point, be it the throttle body or carburetor. Using the intake manifold, the air is distributed to the individual cylinders. The exhaust manifold allows the exhaust gases of individual cylinders to exit the cylinder head immediately into a single collection path or chamber. An exhaust manifold is not the most efficient design solution, but it is the simplest, most direct, and cheapest solution for ejecting exhaust gases from the engine. In the automotive industry, exhaust manifolds were made of cast iron for decades because they were cheaper to produce, but also because of their compact size compared to steel tubular exhaust manifolds. The major disadvantages of cast-iron exhaust manifolds are almost no tuning potential for internal combustion engines. Tubular structures that required assembly and welding have been avoided for years. There were rare cases where exhaust manifolds were made from steel pipes that were joined into a single outlet pipe. Tubular exhaust manifolds offer the possibility of better engine customization and have great potential for extracting additional power and torque, while cast-iron exhaust manifolds have significant design limitations. The positive side of cast-iron exhaust manifolds is that they are made from one piece, require less proctor in the vehicle, and are usually significantly thicker, so they better insulate the noise and temperatures of the exhaust gases of internal combustion engines. Cast-iron exhaust manifolds due to very sharp curves can cause a bottleneck effect which can have a very unfavorable effect on the engine. Tubular headers have a weight advantage over cast-iron manifolds. The single most important advantage is that tubular exhaust headers can increase the power and torque of the engine. Tubular headers are available in several configurations. Tubular headers with different tube lengths are used for simpler and easier installation. Tubular headers with the same pipe lengths provide a significant advantage in terms of more efficient balancing of exhaust flow and pressure. Tubular headers are made with significantly less sharp corners of the pipes in contrast to cast-iron manifolds and thus allow better flows. The big disadvantage of tubular headers is the very high price, especially if they are made of stainless steel. This cost can be very justified if you consider the performance advantage over manifolds. Depending on the specific vehicle, the installation of tubular headers represents an additional challenge due to the space limitations of where it should be placed. Also, the disadvantage of tubular headers about manifolds is the tendency to create more noise due to the wear of smaller pipes [10].

4. CFD simulation

In this paper, CFD analysis of several different models of the exhaust system for the internal combustion engine used to drive the Formula Student vehicle was performed. The geometry of the exhaust systems analyzed in this paper corresponds to the engine that is installed in the motorcycle of the Japanese manufacturer Yamaha, trademark YZF-R6. Figures 1 to 3 show the models analyzed in this paper. 3D models of exhaust systems were created in Solid Works software. CFD analysis of exhaust systems was done in ANSYS Fluent software. Exhaust manifolds analyzed in this paper are marked with the marks A, B, and C. Manifold A has equal lengths of cylindrical pipes that connect to the main pipe under the same radius (Figure 1). Exhaust manifold B has different lengths of cylinder pipes that join the main pipe at the same radius (Figure 2). Manifold C represents a classic exhaust manifold design (Figure 3).

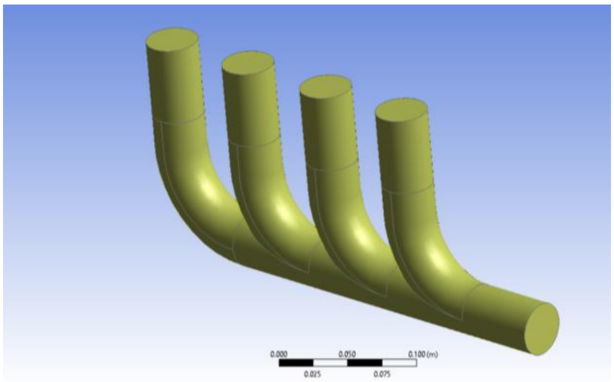

Fig. 1 *Exhaust manifold A*

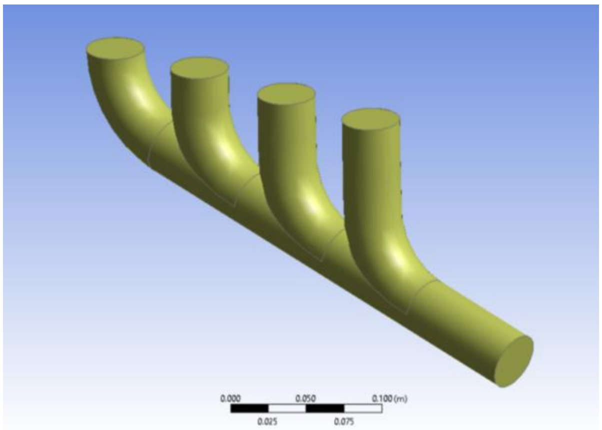

Fig. 2 *Exhaust manifold B*

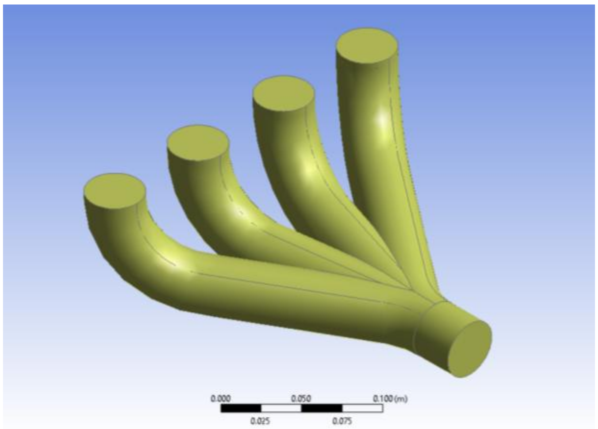

Fig. 3 *Exhaust manifold C*

After generating the fluid domain, a mesh was created for each of the models. The appearance of the created network is shown in Figures 4 to 6. Setting up the network for models during CFD simulation is a very demanding and complex job.

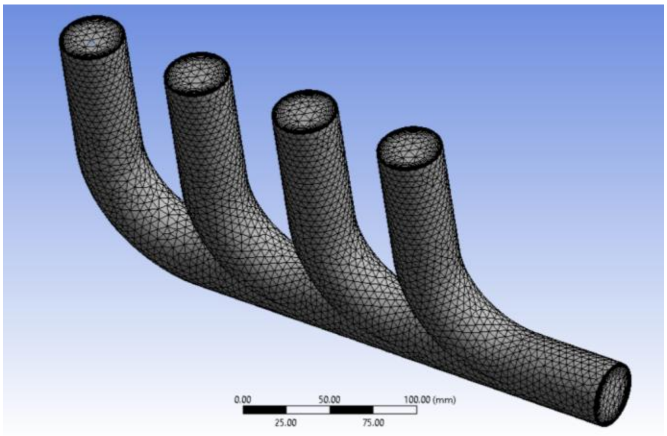

Fig. 4 *Mesh for Exhaust Manifold A*

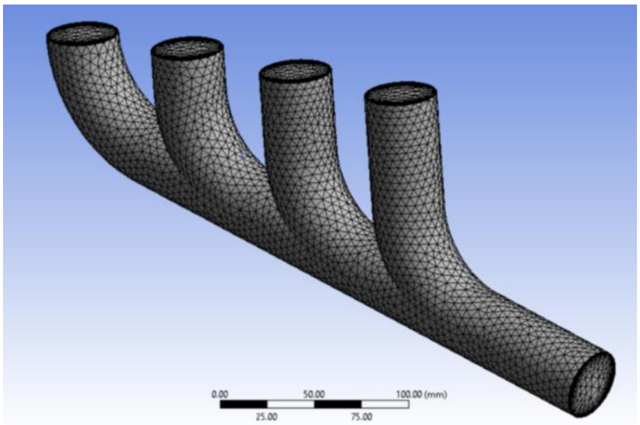

Fig. 5 *Mesh for Exhaust Manifold B*

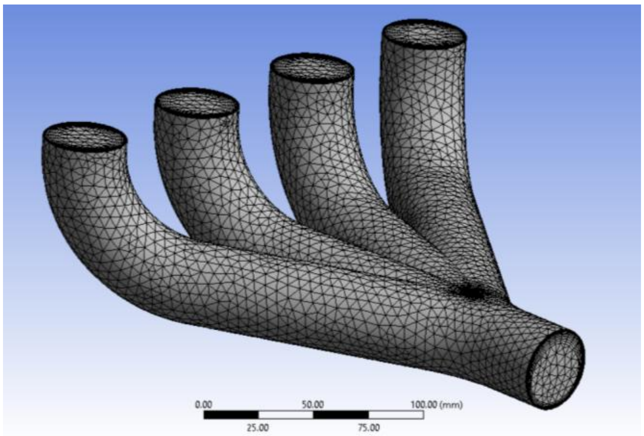

Fig. 6 *Mesh for Exhaust Manifold C*

After creating the network for the generated models of exhaust manifolds, it is necessary to set up the CFD simulation. For the CFD simulation, the standard k-epsilon turbulence model with standard constants was used: Cmu=0.09, C1-Epsilon=1.44, C2-epsilon=1.92, TKE Prandtl Number=,1 and TDE Prandtl Number=1.3. Enhanced wall treatment with pressure gradient effects was also used. Material fluid properties are shown in Table 1.

***Table 1:** Material fluid properties*

Material	Gasoline-vapor C8H18
Density [kg/m^3]	1.0
Viscosity [kg/m s]	1.72 x 10^{-5}
Thermal Conductivity [W/m K]	0.0454

After defining the material, boundary conditions were defined. Boundary conditions are set so that at the entrance to the exhaust manifolds we have a velocity magnitude of 30 m/s and that the temperature at the inlet is 700 K. As it is a four-cylinder engine, each of the considered exhaust manifolds has 4 inlets and one outlet. The inlets and outlets for each of the exhaust manifolds are shown in Figures 7, 8, and 9.

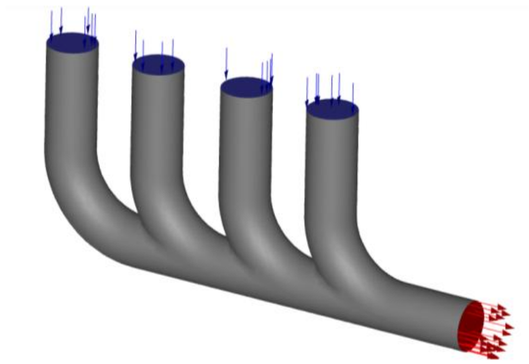

***Fig. 7** Inlets and outlet for Exhaust manifold A*

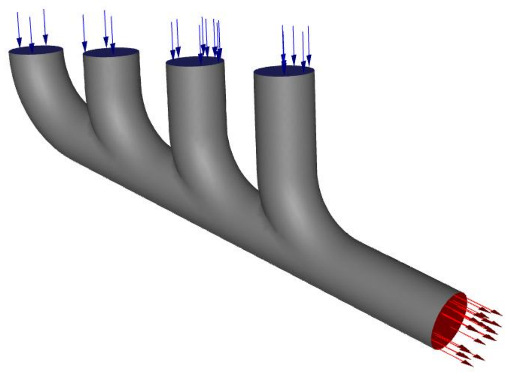

***Fig. 8** Inlets and outlet for Exhaust manifold B*

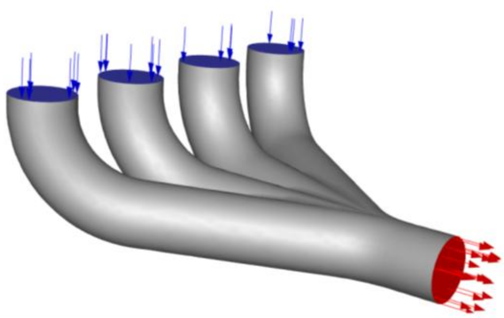

***Fig. 9** Inlets and outlet for Exhaust manifold C*

5. CFD simulation results

In this chapter, the results of the CFD analysis of the three types of exhaust manifolds that were considered (Exhaustmanifoldsd A, B, and C) are given. Figures 10 to 12 show pressure contours for the considered exhaust manifolds in this paper.

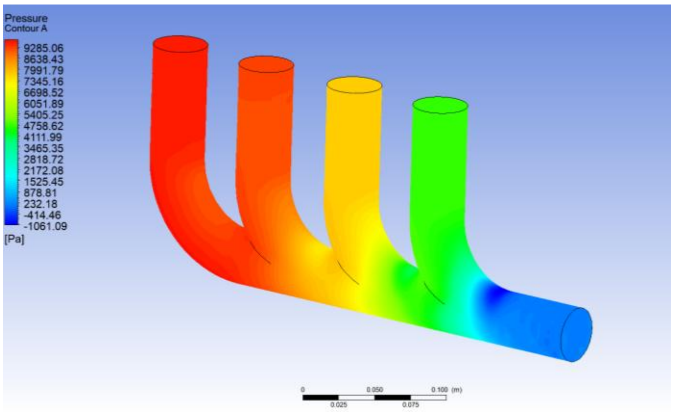

***Fig. 10** Pressure contour for Exhaust manifold A*

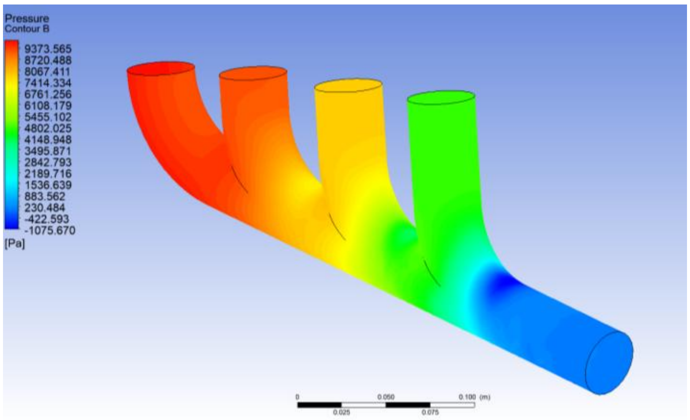

***Fig. 11** Pressure contour for Exhaust manifold B*

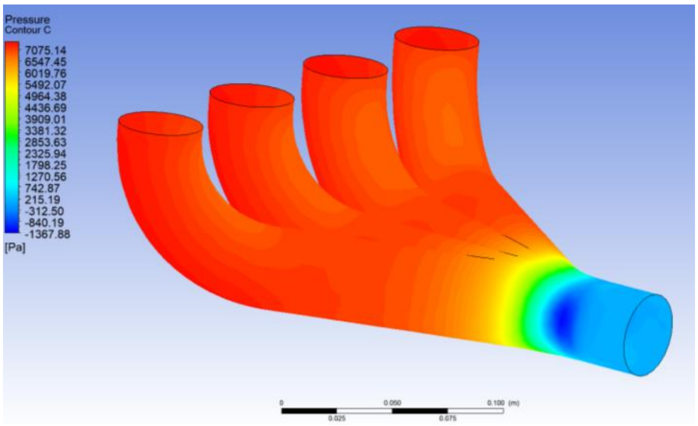

***Fig. 12** Pressure contour for Exhaust manifold C*

Figures 13 to 15 show the velocity streamlines for the considered exhaust manifolds.

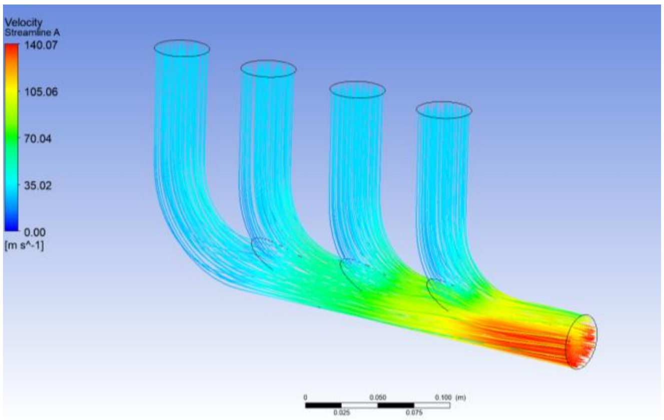

Fig. 13 *Velocity streamlines for Exhaust manifold A*

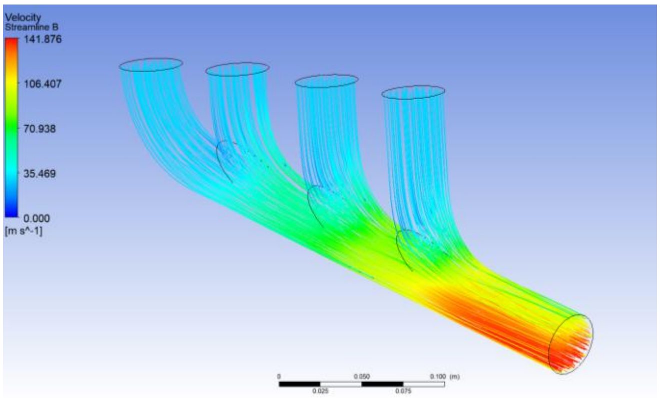

Fig. 14 *Velocity streamlines for Exhaust Manifold B*

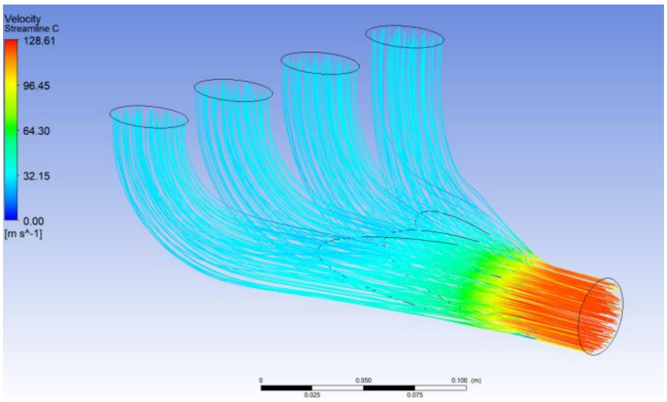

Fig. 15 *Velocity streamlines for Exhaust Manifold C*

From the previous pictures it can be seen that the results for exhaust manifolds A and B are very similar. Otherwise, these two exhaust manifolds are similar in terms of geometry, with the difference that Exhaust manifold B has pipes of different lengths that connect to the main pipe. Exhaust manifold A has a geometrically simpler construction, that is, the pipes used to distribute exhaust gas from the cylinders to the main pipe are of the same length. For these two exhaust manifolds, the pressure and flow velocity differ very little. Exhaust manifold C has significantly different results compared to the previous two. To better understand the results of the CFD analysis, the values of maximum pressure and maximum velocity for all exhaust manifolds that were considered are shown in Table 2.

Table 2: *Max values of pressure and velocity for Exhaust manifolds A, B, and C*

	Max pressure [Pa]	Max velocity [m/s]
Manifold A	9285.06	140.07
Manifold B	9373.58	141.87
Manifold C	7075.14	128.61

6. Conclusion

CFD simulations of airflow through the Exhaust manifold are of great importance because they make huge savings during the development of the system itself. CFD simulations have proven to be a very powerful tool when simulating the most realistic conditions in which the corresponding element or system being analyzed can work. These simulations can provide very important information related to the development of the exhaust manifold itself. CFD simulations of three types of exhaust manifolds were performed in the paper as a potential design solution for exhaust manifolds of Formula Student vehicles. When choosing the appropriate exhaust manifold concept, it is necessary to take into account some other parameters. One very important parameter is the production of the exhaust manifold itself, as well as the production costs. Exhaust manifold C is much more complex to manufacture compared to Exhaust manifolds A and B because it requires much more precise pipe-cutting and welding technology. Almost negligible differences in the CFD analysis results occur with Exhaust manifolds A and B because they are geometrically very similar.

7. References

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