CFR Formula SAE Intake Restrictor Design and Performance

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Abstract

Cardinal Formula Racing at Saginaw Valley State University conducted a study of intake restrictor designs in an effort to improve engine performance and increase the team's competitiveness at Formula SAE competitions. The objective of the undergraduate research project was to optimize the intake restrictor geometry to maximize flow over a range of outlet pressures. Intake restrictor designs were explored using computational fluid dynamics (CFD) flow modeling software to analyze and visualize fluid flow during the design process. The intake restrictors were then manufactured and tested on a flow bench over a range of pressures. Good correlation in terms of flow rate was observed between the simulations and experiments. The prototype intake restrictor gained 4.8 CFM on average over the typical range of pressure encountered during racing compared with an earlier intake restrictor used by the team at competition.

Introduction

The performance and emissions characteristics of a spark-ignition (SI) engine are optimized from the perspective of the intake system when a fuel-air mixture is efficiently delivered and uniformly distributed to each of the combustion chambers over an RPM band. This requires a well designed intake system. The typical 600 cubic centimeter four-cylinder four-stroke Formula SAE engine has an output of about 80 horsepower with an intake restrictor installed and is fuel injected. Air travels through a throttle body and intake plenum before reaching individual runners that feed each cylinder. An optimized intake system will net the engine more airflow and more power; however, designing, machining, and testing a number of intake systems can be costly. Design improvements are incremental and the design approach is essentially a process of trial and error.

Computational fluid dynamics (CFD) flow modeling software offers an alternative to the experimental method of design. CFD is based on computer simulation, where the governing equations of fluid motion (e.g., Navier-Stokes equation) are solved numerically. CFD allows a designer to simulate a range of intake shapes and flow conditions without having to machine multiple prototypes for physical flow testing. The cost savings found through CFD can be substantial, as the manufacturing cost of a single intake system restrictor, after material and machining time, can be over $1500.

Cardinal Formula Racing conducted an experimental and numerical study of intake system restrictor designs in an effort to improve engine performance and increase the team's competitiveness at Formula SAE competitions. The specific objective of the study was to optimize the intake system restrictor geometry to maximize flow over a range of outlet pressures. Anticipating the investigation, Logan Shelagowski of Cardinal Formula Racing attended a two-day training workshop on the use of the flow modeling software SolidWorks Flow Simulation. The workshop was presented by Dassault Systèmes SolidWorks Corporation of Waltham, MA and was generously supported by the Saginaw Valley State University Foundation.

Theory

The purpose of an intake system is to flow a maximum amount of air into each cylinder during an intake stroke, as more air means more fuel can be burned to produce useful work. Improving flow through an intake system boosts overall engine efficiency. Restrictions to airflow include an air filter, throttle body, intake plenum, and intake valves. When well designed, each device is optimized for flow. Formula SAE rules mandate that an intake system restrictor (Fig. 1) be placed in the intake system between the throttle body and engine. The device is to have a maximum throat diameter of no greater than 0.787 inches (20.0 mm) for gasoline fueled engines. The restrictor serves as a design constraint for competition. The device curbs power output by impeding airflow at high RPM when airflow would typically be greatest. There are several design parameters that affect the total efficiency of the restrictor. A few of the more important include the length of the diffuser, the diffuser angle, the inlet length, and the inlet shape. Formula SAE promotes experimentation. Aside from the design constraint of the throat diameter, Formula SAE students are encouraged to improve the design of the intake system, including the restrictor. Thus finding the correct combination of lengths and angles for the restrictor is a necessary task. CFD flow modeling software offers a useful tool towards this end.

The maximum flow through an intake system under steady-flow conditions is useful as a means to gauge flow capacity. The maximum flow can be determined by performing an isentropic analysis of the flow of an ideal gas through the device[1]. The maximum flow rate is

$$\dot{m}_{\max} = A^* P_0 \sqrt{\frac{k}{RT_0}} \left(\frac{2}{k+1}\right)^{(k+1)/[2(k-1)]} \tag{1}$$

where A^* is the cross-sectional area at which the flow is sonic, P_0 is the stagnation pressure, T_0 is the stagnation temperature, R is the specific gas constant, and $k = c_p/c_v$ is the specific heat ratio of the gas. The maximum flow rate can be expressed in terms of inlet temperature T_i and inlet pressure P_i by expressing the stagnation temperature and stagnation pressure as

$$T_0 = T_i + \frac{V_i^2}{2c_p} \tag{2}$$

$$P_0 = P_i \left(\frac{T_0}{T_i}\right)^{k/(k-1)} \tag{3}$$

where V_i is the inlet velocity. The intake system is considered to be choked when the flow rate reaches $\dot{m}_{\max}$. When choked a reduction in pressure downstream of the throat will result in no additional flow through the system. Increasing the pressure at the inlet will increase flow as will decreasing temperature as shown by Eq. (1). These variables, however, are largely constrained by the ambient environment surrounding the engine. A turbocharger or supercharger (a device used to boost intake manifold pressure

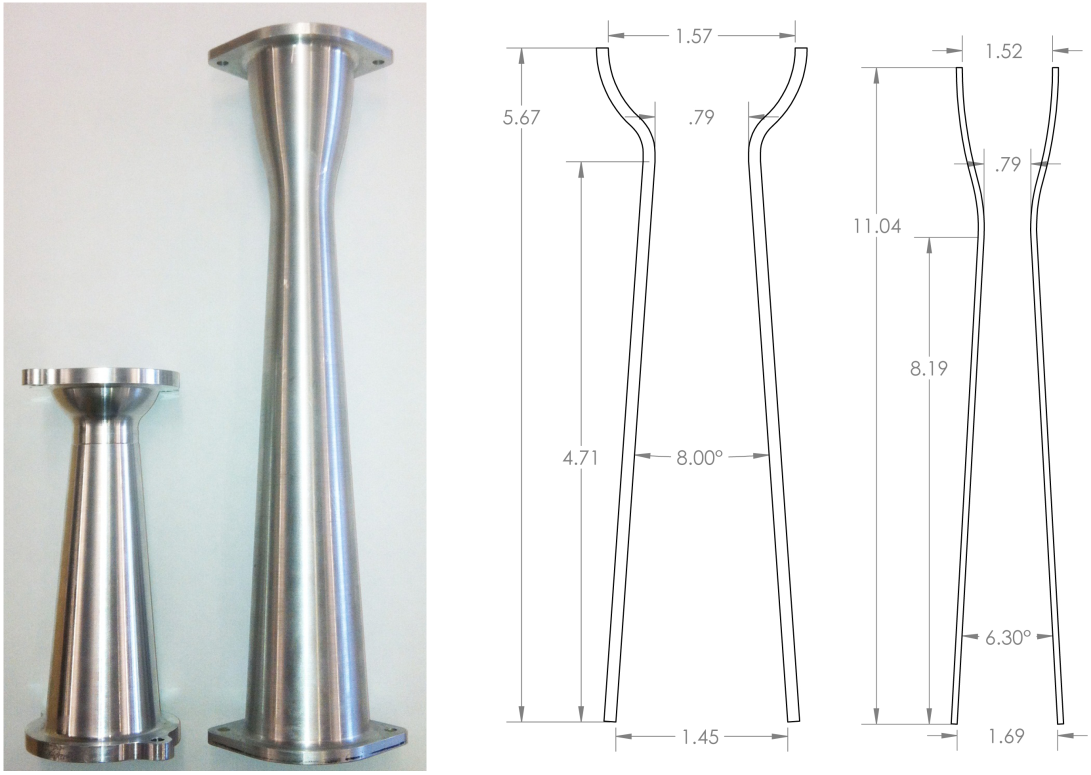

Fig. 1. Intake system restrictor prototypes: design I and II (units of inches).

and allowed under 2015 Formula SAE rules with the restriction that it must be placed downstream of the intake system restrictor) may improve low- and mid-range performance but will not improve flow once the intake system is choked because of its location downstream of the throat.

The maximum flow rate of air at choked conditions can be calculated by applying Eq. (1) at standard atmospheric conditions ($P_i = 14.7$ psi and $T_i = 70°$F). The inlet velocity is assumed to be small for the sake of the calculation ($T_0 \approx T_i$ and $P_0 \approx P_i$). The stagnation properties remain constant throughout the restrictor. The calculation yields a maximum mass flow rate $\dot{m}_{\max} = 0.165$ lbm/s. The volumetric flow rate at the inlet is calculated as $\dot{V}_i = 132$ CFM, upon applying Eq. (5) to determine the density of air at the inlet. The calculation provides an upper limit on flow rate.

An engine of high volumetric efficiency flows air well, i.e., the induction and exhaust processes are efficient and optimized from a flow perspective. The volumetric efficiency is defined as the ratio of mass drawn into the cylinder to mass displaced by the cylinder at density ρ_i referenced at the inlet of the intake system. The volumetric efficiency is[2]

$$\eta_v = \frac{2\dot{m}}{\rho_i V_d n} \tag{4}$$

where $\dot{m}$ is the mass flow rate, n is the number of revolutions per second of the crankshaft (four-stroke engine), and V_d is the engine displacement volume. The density of air

$$\rho = P/(RT) \tag{5}$$

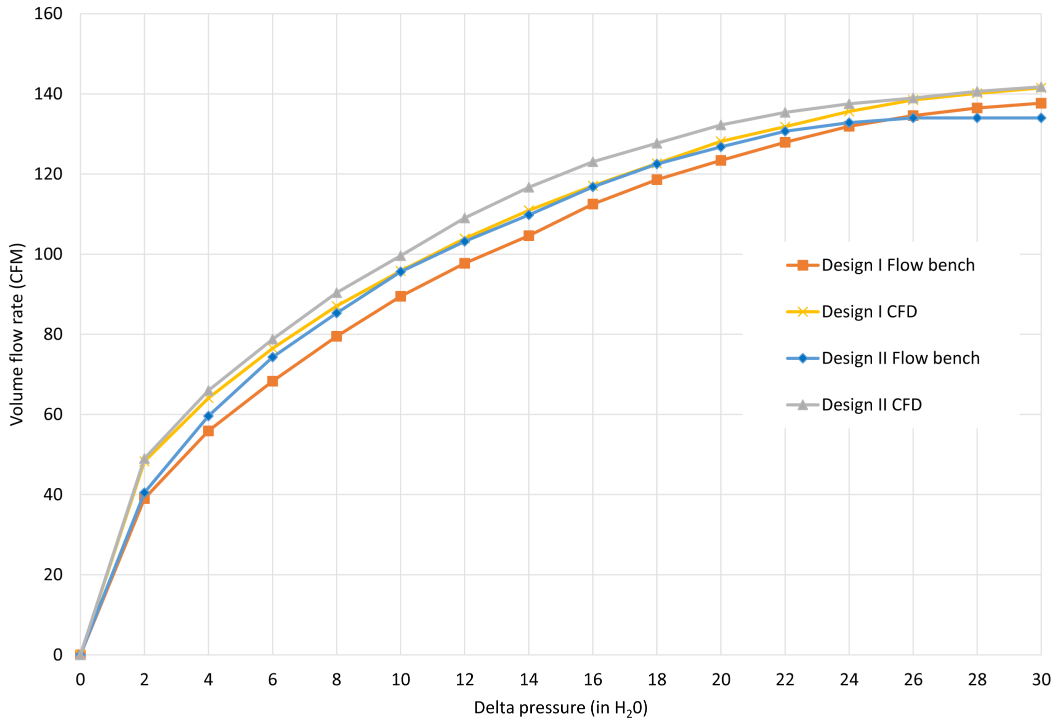

Fig. 2. Intake system restrictor performance compared based on flow bench measurements and CFD simulations.

is calculated by applying the ideal gas equation. Volumetric efficiency is a function of mass flow rate as shown by Eq. (4). A well designed engine can approach a volumetric efficiency of 100% but will not exceed it unless inlet pressure is raised above ambient pressure through the use of turbocharging, supercharging, exhaust scavenging, or Helmholtz resonance[3] to increase gas density, as mass flow rate is a function of density. Flow through an engine can be improved by streamlining intake ports and by increasing intake valve diameter. Streamlining to boost flow is a goal of Cardinal Formula Racing. Its impact was studied theoretically using CFD flow modeling software and experimentally using a flow bench.

Design of Prototypes

The flow through many potential intake system restrictors was investigated by Cardinal Formula Racing using SolidWorks Flow Simulation software as part of the academic study. The diameter at the throat of each restrictor was held at 0.787 inches (20.0 mm) while the inlet and outlet diameters and wall geometries were changed. Each iteration consisted of creating a model, specifying boundary conditions, and solving the equations of motion for pressure and velocity. The geometry of each model was then changed and the process repeated until a geometry was found that displayed optimal flow characteristics. The impact of mesh size on the solution was studied to ensure a mesh independent solution.

The restrictor is essentially a converging-diverging nozzle. The flow enters at relatively high pressure and low velocity and accelerates on its way to the throat. The maximum velocity occurs at the throat. The flow

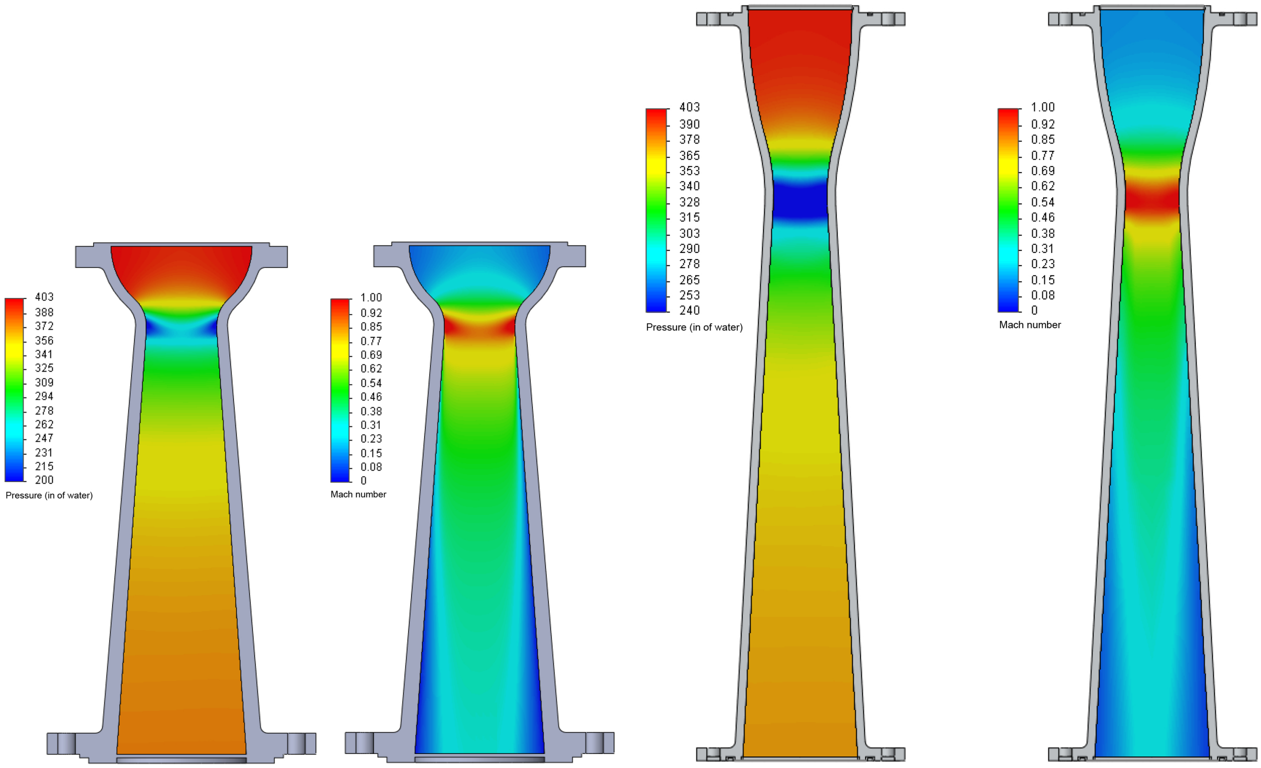

Fig. 3. Pressure and Mach number contours for sonic flow at the throat (30 inches of H_2O).

then decelerates beyond the throat and undergoes a pressure recovery. The pressure drop is large when the diameter is small, so it is beneficial to increase the diameter as soon as possible beyond the throat; however, if the diameter is increased too dramatically, flow separation may occur. Flow separation leads to an undesirable backflow that effectively reduces the cross-sectional area. The CFD analysis showed that flow separation was pronounced when the taper was increased beyond 7°. Therefore, a gradual wall taper of 6.3° from the throat to the outlet was chosen.

Figure 1 shows the two intake system restrictor prototypes: design I and II. Both were constructed of aluminum. The first was designed and built based on a paper by Byam et al.[4] and a design study by Jawad et al.[5]. It features an 8° incline taper beginning at the (0.787 inch) throat and gradually transitioning to the outlet. The inlet shape is bell mouthed. The second restrictor was designed and built upon conclusion of this CFD study. It consists of a 6.3° incline taper beginning at the (0.787 inch) throat. The more gradual transition reduces the flow separation that can occur downstream of the throat.

TABLE I

Properties of air.

Temperature T, °F	Pressure P, inches H_2O	Density ρ, lbm/ft^3	Dynamic viscosity μ, lbm/ft · s
70.0	403.0	0.07419	1.230×10^{-5}

The flow through each intake system restrictor was measured using a SuperFlow SF-600 air flow bench. An air flow bench simulates flow through an engine intake by reducing pressure below the component. Atmospheric pressure then forces air through the component. A manometer was used to measure the velocity of airflow through the intake system restrictor. The fluid properties during the experiments are given in Table I.

Design I was used as a baseline for comparison. As shown in Figure 2, the results of the CFD simulations generally show the trend in the experimental data. Design II outperforms design I over the range of pressures tested up to 26 inches of H_2O. Beyond 26 inches of H_2O the flow curves are coincident and fairly asymptotic. Pressure and Mach number contours at 30 inches of H_2O are shown in Fig. 3 (maximum pressure and Mach number are displayed in red). Sonic flow at the throat is observed in each case.

Discussion and Conclusions

Choosing one restrictor over the other depends on the application. According to the flow bench data, design I has a smoother flow curve that is more consistent than design II. This should translate into a smoother power curve, causing the car to be more driver friendly. The flow bench data also show that design I has a higher maximum volume flow of approximately 138 CFM at 30 inches of H_2O as compared with 134 CFM for design II at the same pressure. Design II reached "choked flow" (maximum flow); design I was able to deliver still more air at even higher pressures. An engine fitted with design I will create more power output at high-end than an engine fitted with design II. The data acquired from both the flow bench and CFD show that design II has a higher volume flow rate (4.8 CFM on average) compared with design I from pressures of 6 to 22 inches of H_2O. Therefore, design II will supply more air to an engine running at a low- to mid-range RPM than design I, which in turn will create a more robust low- to mid-range torque curve. For Formula SAE Racing, design II is the optimal choice. The higher maximum power output of design I would be great for the acceleration runs in competition, but this event is worth the fewest number of points compared with other events. Although design II does not have quite the high-end power of design I, the low-end power is more beneficial. The robust torque curve will provide extra power when exiting corners at competition in autocross and endurance events. As these two events are worth the greatest number of points, restrictor choice should be considered in these events. In the future, Cardinal Formula Racing plans to optimize the entire intake plenum for flow to reduce pressure loss and improve engine performance. These improvements may include flow balancing, which dictates intake runner length, to optimize engine performance.

Acknowledgments

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