OSS-Motorsports

PROJECT REPORT: *BYU_FSAE_1* ISSUE#1

Computational Fluid Dynamic Development of the Turbo System for the 2007 Brigham Young University Formula SAE Racecar

PROJECT ENGINEER(S): Miles Jackson (OSS) **DATE:** April 16, 2007

SIGNATURE:

APPROVED BY: Mark Landon Ph.D., President, Optimal Solutions Software, LLC

SUMMARY

This report presents the results of a Computational Fluid Dynamics (CFD) study to design a turbo charger system for Brigham Young University's (BYU) 2007 Formula SAE (FSAE) Racecar. A new exhaust was designed to meet theoretical performance calculations. An intake comparison of four different designs was done seeking to balance the massflow to each cylinder.

Sculptor, developed by Optimal Solutions Software, LLC (OSS) was used to tune the massflow of the individual engine runners to each cylinder. The effect of the CFD and Sculptor developed intake design and turbo system with exhaust was to balance the flow to each cylinder and to reduce the pressure drop to each cylinder

DISCLAIMER

Brigham Young University's Mechanical Engineering Department (CUSTOMER) acknowledges that the studies performed under this contract are an estimation of possible future performance and design enhancements. CUSTOMER acknowledges that further testing and analysis, independent of the delivered results by Optimal Solutions Software, LLC., must be performed before any product can be fully developed and commercially introduced or used in actual manufacture of components or vehicles. CUSTOMER agrees that it will not rely upon the results of this study in determining the final design, composition or structure of any component or product. CUSTOMER accepts full responsibility for the application of any results from this study to the design of any component or product.

CONTENTS

1. INTRODUCTION

This report presents the results of a Computational Fluid Dynamics (CFD) study to design a turbo charger system for Brigham Young University's (BYU) 2007 Formula SAE (FSAE) Racecar. A new exhaust was designed to meet theoretical performance calculations. An intake comparison of four different designs was done seeking to balance the mass flow to each cylinder.

1.1. Description of the Design Constraints - 2007 FSAE Rules

Although not repeated word for word, a brief explanation of the design constraints contained in the 2007 FSAE rules will follow. For exact rules and clarification one should consult with the 2007 FSAE Rules and SAE individually.

The intake manifold must be securely mounted to the engine besides just the rubber grommets that seal the airway.

The packaging of the entire turbo system must lie within the envelope created by the roll hoop and the outsides of the tires in all directions.

All the air must pass through a 20mm restrictor and this must be upstream the compressor and downstream the throttle body.

Cars may have turbo chargers but the system must be designed by the students. This is the focus of this paper: the design of the exhaust pipes and the intake manifold.

1.2. Design Process

We will take the results from the 2006 FSAE Car as a baseline for improvements for the engine performance. The car did fairly well at the 2006 competition placing 11th in the acceleration event.

Last year's exhaust was designed under time constraints that allowed for really only two design features. It fit in the car with the packaging constraints set by the chassis designer and the pipes were designed to have equal length until they all came into one tube that fed into the exhaust manifold. It carried over the same tube diameter as the stock bike had and the length was also left stock length.

Because the 2007 FSAE car was to have the added benefit of a turbo charged system, a few more design features were implemented into the design of the exhaust. We wanted to keep equal length exhaust runners, but we wanted to vary the length and diameter of the tubing to increase performance. Packaging was a bigger problem on the turbo system as the position and orientation of the turbo charger determines the layout of the exhaust and since the turbo charger position also determines the intake manifold design, it becomes a coupled design problem. Other than these constraints and the constraints set by the new chassis design the design was open.

The 2006 FSAE Car had a log style intake manifold made from PCV plastic with the intake coming from one side. The runners from the log plenum ran straight down into the intake ports of the engine with the injectors mounted just up from the ports set at an angle pointed into the airflow at 45 degrees. A number of design questions arise when converting to a turbo system. The log style may not be the best design for mass flow on a turbo system.

The intake from the 2006 FSAE Car was re-tuned on the dyno and the results were recorded in a torque curve and horse power curve. The temperatures from each exhaust port were also compared during the dyno testing.

An improved log style intake was built out of aluminum with smoothed fillets where each runner met the log plenum. This had the same basic layout as the PVC intake from 2006, but it was aluminum so that it could be safely tested under the pressures that the turbo would induce. This first improved design was modeled in CFD, results of which will be discussed in a later section.

The engine was tuned with this intake and a mock turbo system utilizing a mocked exhaust. Measurements were recorded and compared with the baseline.

The overall turbo system layout was decided upon considering all the constraints and packaging problems that arise from a complete car design.

The new exhaust was designed in CAD and drawings were made and the tubing was bent. The final exhaust design was welded and mounted to the engine for final placement of the turbo. The final orientation and position of the turbo was put into CAD. The compressor outlet was set and the intake design could begin.

There were several iterations of the intake summarized in the appendix but the three prominent designs will be discussed in this report.

The first had four runners blend into each other smoothly as they turned a ninety degree bend up from the compressor outlet. The runners, then completely split, divided around the thermostat housing and cooling system filler cap, two on each side. These then turned a ninety degree bend into the individual engine ports. The injectors set in this last ninety degree bend directed straight down the runners. This design was then run in CFD and sent off to be rapid prototyped.

As the first was being rapid prototyped, the CFD results indicated a problem with the design. Although still a great improvement over the log plenum, it was determined that more should be done to improve the flow.

The second design was similar to the first but the ninety degree bend directly out from the compressor was turned into a large plenum box that would turn the flow but allow mixing completely around the corner and then split into four runners that ran around the thermostat housing as before.

This was then modeled in CFD and Sculptor was used to deform the plenum shape in an attempt to balance the mass flow for each runner. Although improving the mass flow balance the behavior of the flow still could not be fixed entirely.

During this design the dyno testing and tuning on the first design was completed and confirmed the results from the CFD that there was still a misbalance in the mass flow.

A third design was one that basically had the large plenum box split with a vane to turn the flow around the ninety degree bend. The vane was then tuned using Sculptor to change the shape until the mass flow between all cylinders was balanced. This design will be sent off to be rapid prototyped. This design will be tuned and compared with the others and the best will be the one that is used.

1.3. Turbo System Layout

The turbo was placed to the right rear of the engine so that the oil return line (which is gravity fed) ran directly down into the crack case filler. The outlet of the turbo was placed just above the gearbox and directed across the car to the left. Exhaust ran from each cylinder together and down below the transmission housing and below the turbo and then up to the turbo exhaust inlet. The intake manifold ran from the compressor outlet of the turbo around a ninety degree bend up and around the thermostat housing and filler cap and down into the cylinder ports. The injectors are placed directly in-line with the runner center line.

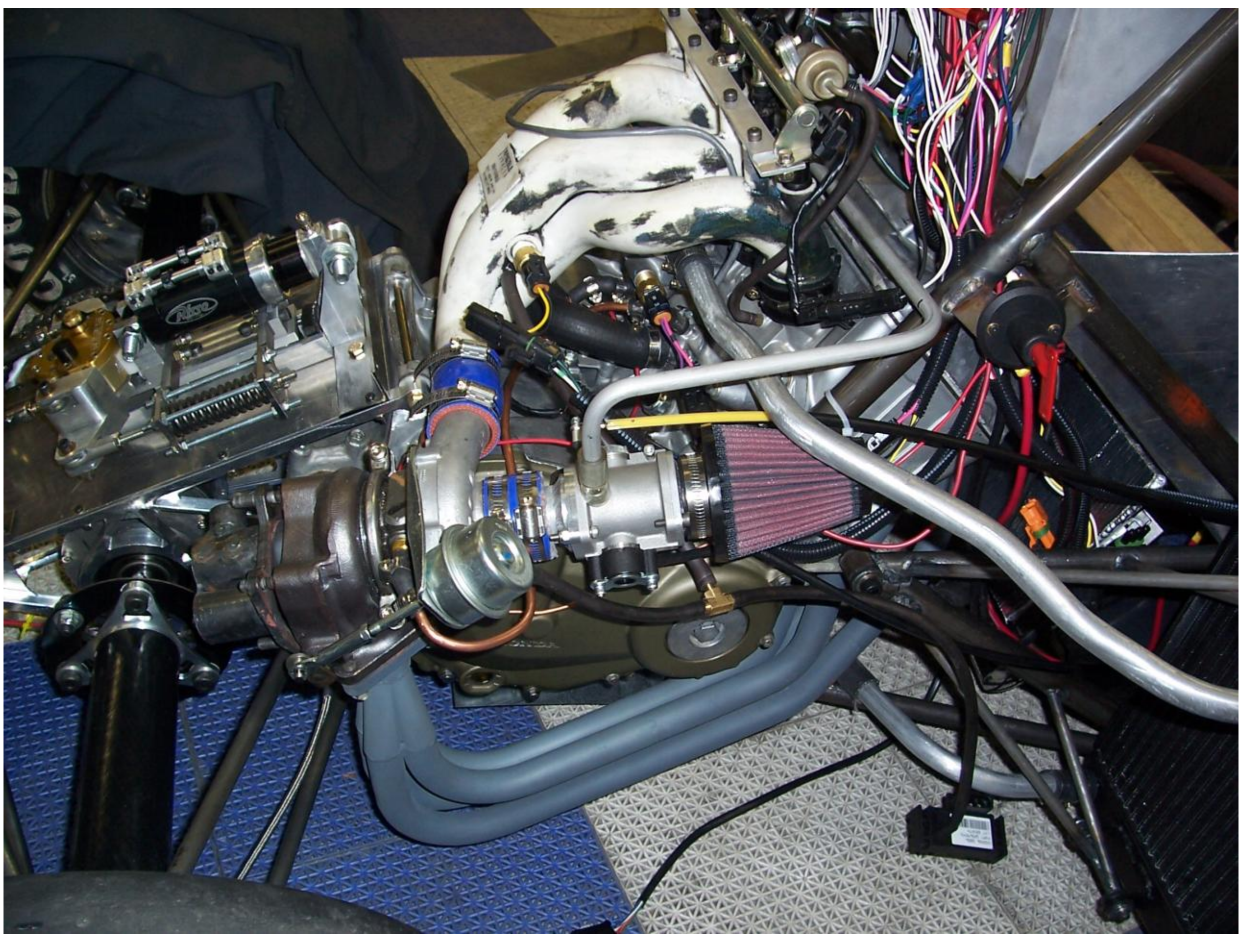

Figure 1 – Overall layout of the turbo system and positions of all components. The intake shown is the first to be rapid prototyped. Notice the exhaust runners coming from the front of the engine

under the transmission case and out and up into the turbo. All intake designs incorporated this layout for the turbo.

2. DETAILED EXHAUST DESIGN

2.1. Length and Diameter Tuning

To increase the velocity of the exhaust air as it runs into the turbo the engine tuner determined that the diameter of the tubing should be 1 inch instead of the 1.25 inch from the 2006 FSAE Car. To help increase the torque at lower RPMs over the stock configuration a length of about 31 inches was also specified by the engine tuner.

2.2. Packaging in CAD and Reality

The smaller diameter tubing would make it easier to package the exhaust especially around corners, but the added length would be hard to work with. A solution was found by taking the exhaust port furthest from the turbo and starting with that one and then moving to the next longest and wrap that one close to the first but outside as it goes around the corners to increase the length to match the first. This was done progressively from port to port until they were all packaged and an equal length of thirty-one inches and directed straight into the turbo.

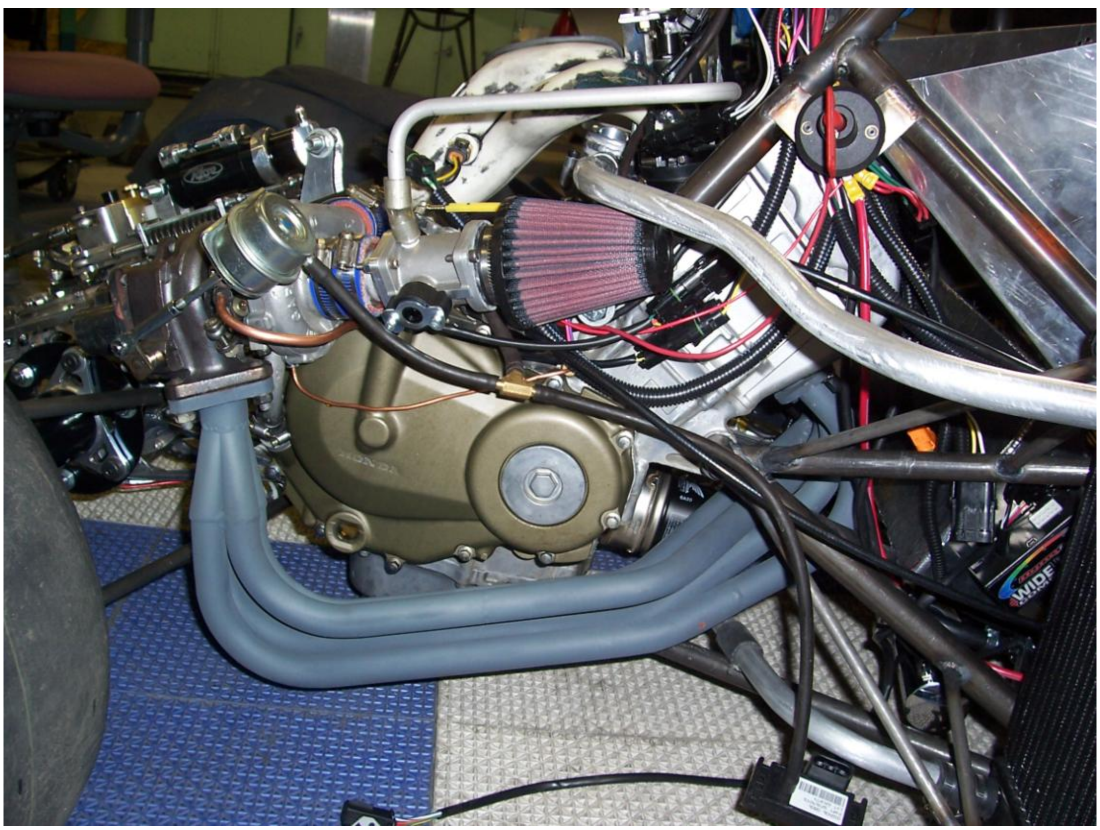

Figure 2 – Final exhaust design welded and mounted in place. Notice how the design follows the crank case shape along the bottom and just clears the oil filter located on the front of the engine and below the pipes.

2.3. CFD on Exhaust

A quick CFD model was done to confirm the balance of the flow as it goes around all the corners in each tube and merges as it reaches the turbo. The assumption was made that if in CFD the flow is steady and they all flow in together that when on the engine and with the alternating flows between the cylinders that the flow impulses will allow the flow to again alternate as it flows into the turbo to reduce the back pressure created from the flow impulses impeding on each other as they meld into one flow just before the turbo.

3. DETAILED INTAKE DESIGNS

Each CFD model was solved steady state with the inlet set at a velocity of 76.4 meters per second and each cylinder outlet was set to a pressure outlet of 0psi gauge. Balanced flow was determined by measuring the mass flow for each cylinder outlet.

3.1. Log Plenum

The log plenum did not perform well under the boundary conditions. The flow was good for cylinders 3 and okay for cylinder 1, but cylinder 2 had reversed flow that would then flow into the fourth cylinder.

Figure 3 – The aluminum log plenum intake. Notice the angle of the injectors mounted just above the rubber boots.

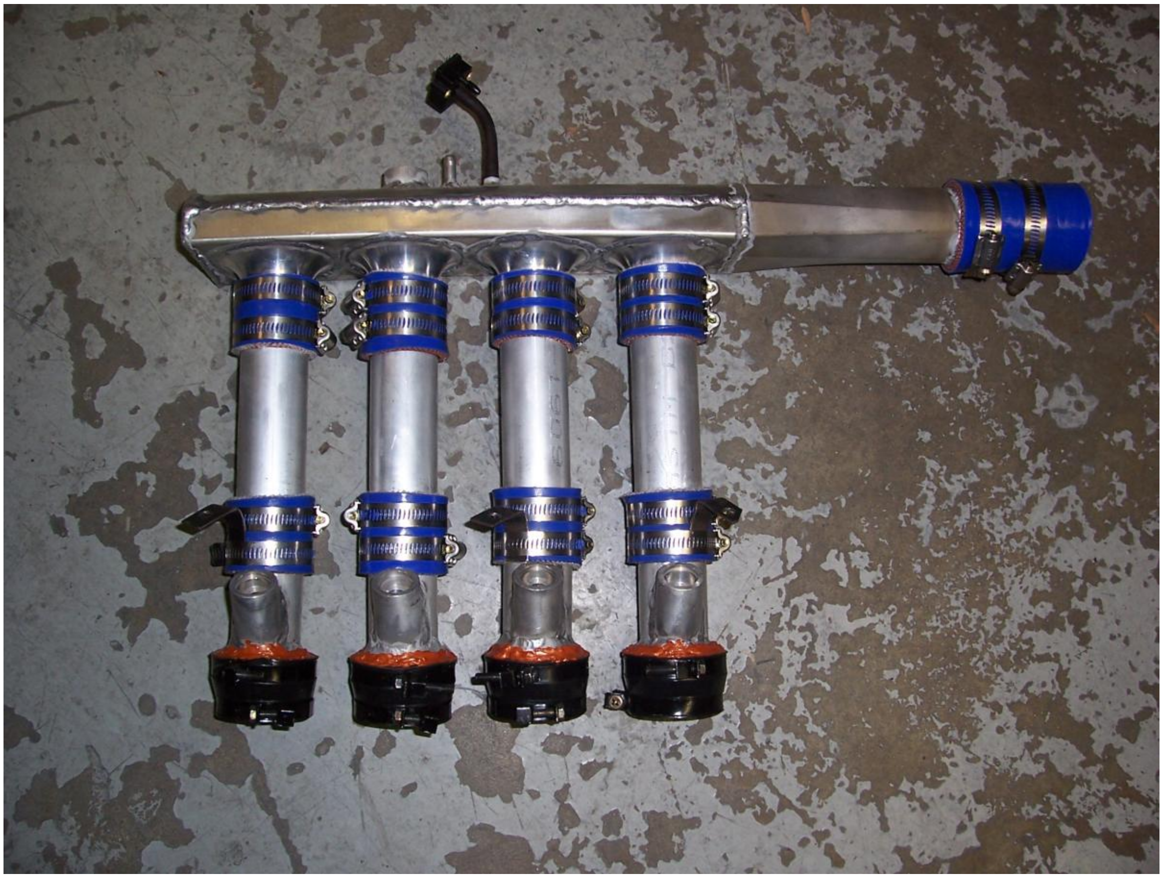

Figure 4 – Front view of the log plenum intake used for baseline measurements

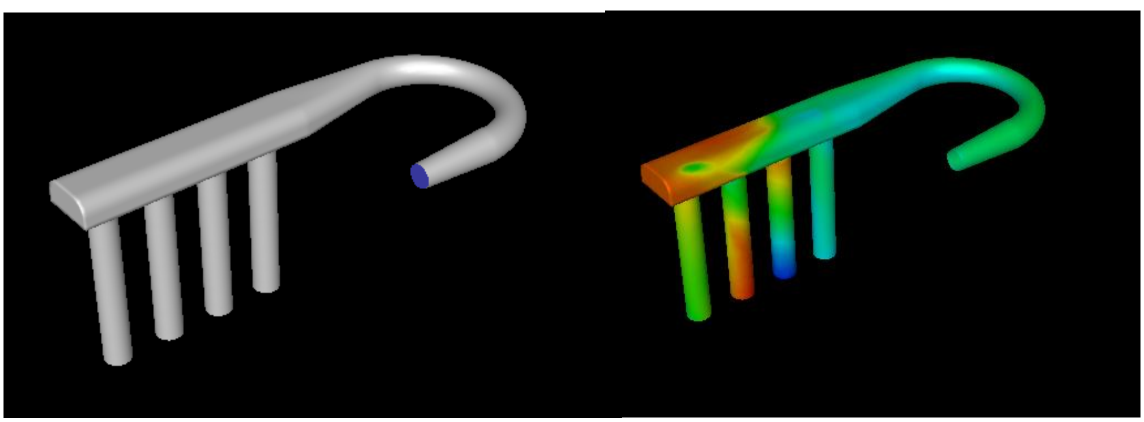

Figure 5 – Modeled geometry in CFD on the left and the pressure contours on the right. Notice the presence of back flow in the second cylinder (blue color).

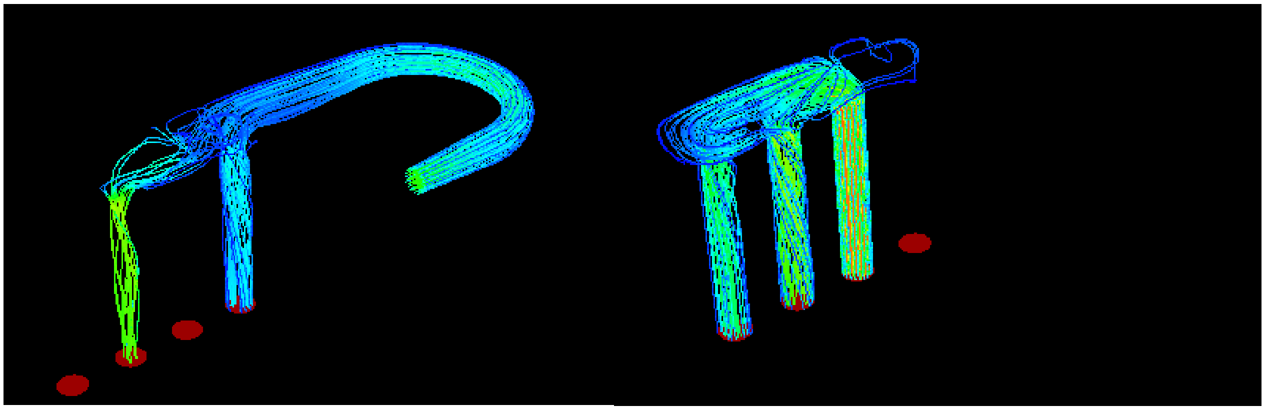

Figure 6 – Notice the pathlines from the inlet only serving two cylinders (left). The back flow from cylinder 2 is depicted on the right.

3.2. Smoothed 4-1, No Plenum

The flow improved significantly, but still was not completely balanced. The flow was dominant on the far side (cylinders 3 and 4) and didn't have reversed flow on either cylinder 1 or 2, but the difference was still about eighty percent between the worst (cylinder 1) and best (cylinder 3). This was confirmed by the temperature differences found when dyno testing the engine. The first and second cylinders were running much leaner than the 3rd and 4th as evident from the 200 degree difference in the exhaust temperatures.

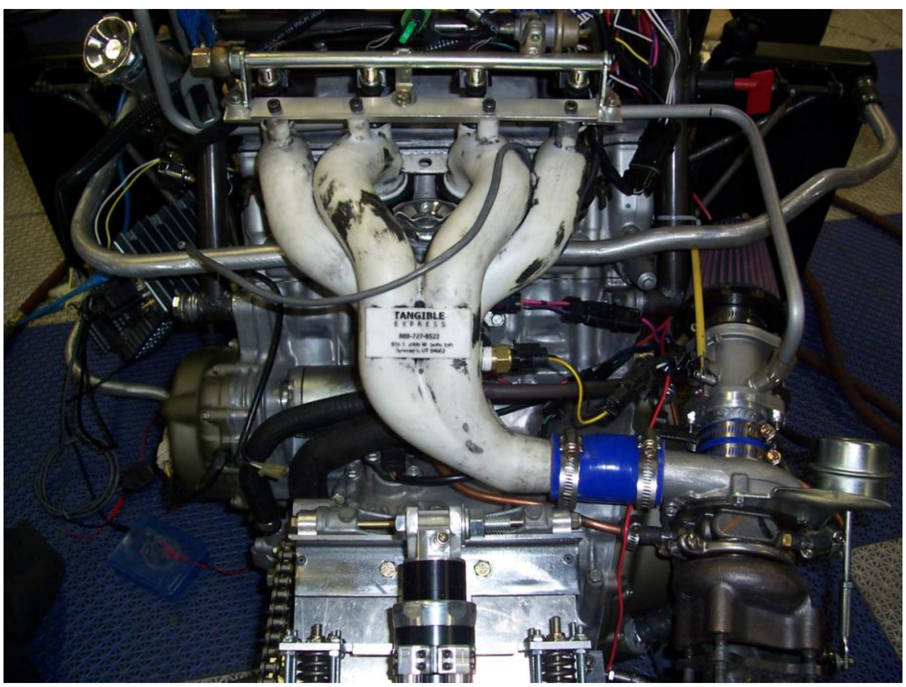

Figure 7 – Notice the ninety degree bend that the flow must go through. Notice how the runners spread as they go around the thermostat housing and coolant filler cap (barely visible). This spread is just enough to allow the mechanic's hands to have access to fill the coolant system or replace the thermostat as needed without having to remove the intake manifold.

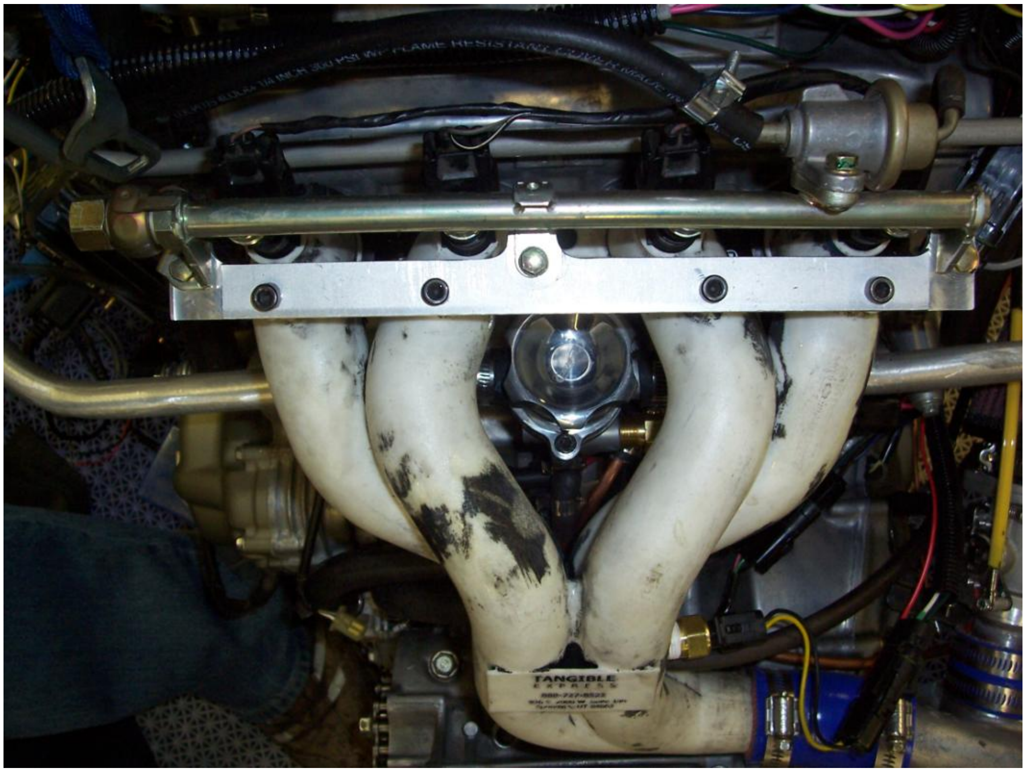

Figure 8 – A top view showing better the access allowed for refilling the coolant system. Notice the injectors are placed on the top of each port directly inline with the port in the head.

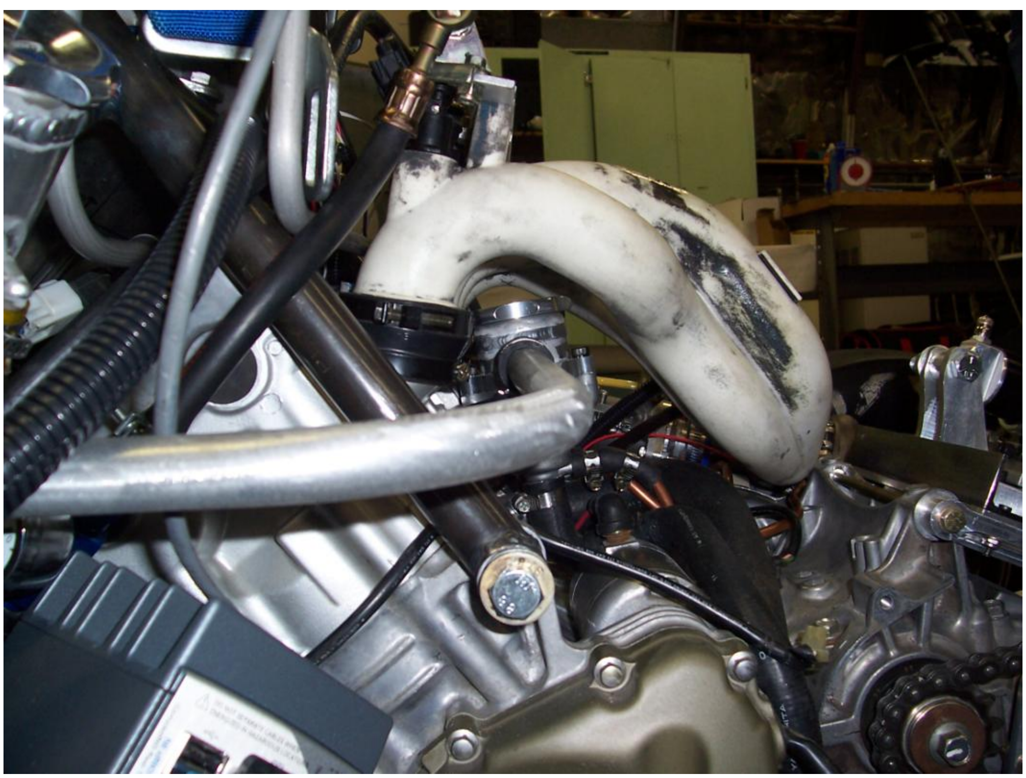

Figure 9 – Notice the clearance of the radiator lines that run underneath the intake manifold out to each radiator. Again the injectors are positioned directly inline with the ports.

3.3. Smoothed 4-1, Large Plenum

For this design a little more freedom for balancing was allowed because the plenum was larger as it went around the corner. The initial design with the large plenum had better balance than the previous intake design that was rapid prototyped, the worst case being about 40% difference. Then using Sculptor the flow was able to be balanced to about a 20% difference. This was much better than the original design but further improvement was desired.

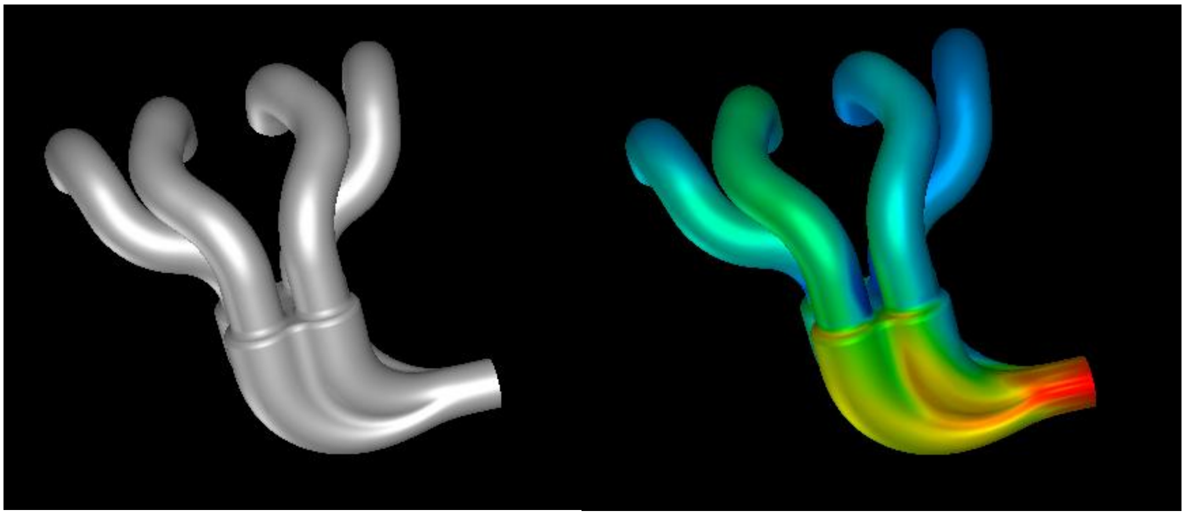

Figure 10 – This is the basic geometry before any balancing has taken place (left). The right image shows the pressure contours on the surface.

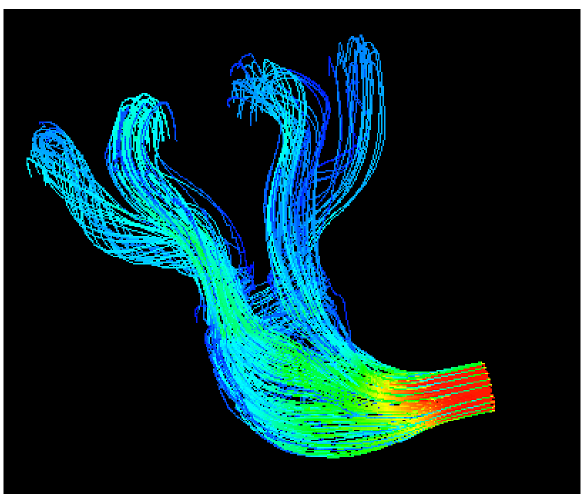

Figure 11 – This shows the pathlines of the flow in the large plenum. Notice that cylinders 3 and 4 are getting most of the flow while cylinder 1 and 2 are starving.

3.4. Smoothed 4-2, 2-1 Vane

The initial design was excellent because it decoupled trying to balance four mass flows at once into balancing only the two sides. Initially the design had 3 and 4 balanced and 1 and 2 balanced but 1 and 2 was getting the best flow. Using Sculptor the vane was moved up and down until the flow was perfectly balanced between the two sides and then the flow was balanced on all four.

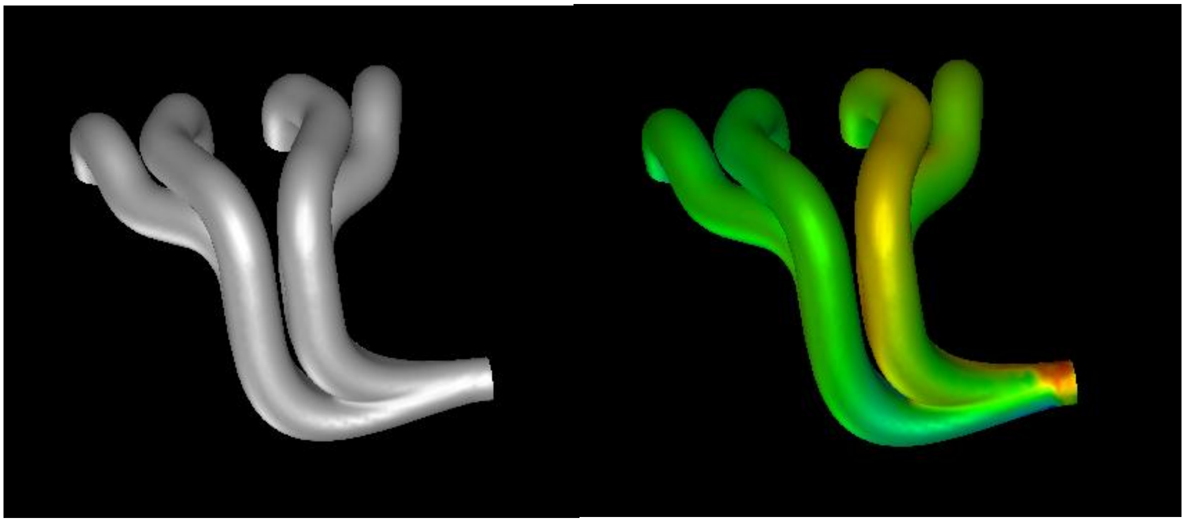

Figure 12 – This is the geometry of the fourth design with the vane coming down between the cylinders until it starts to go around the bend. In the right image notice the more balanced pressure contours.

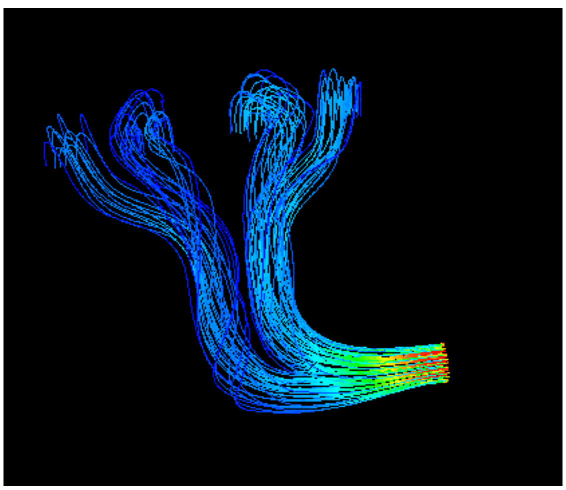

Figure 13 – Notice in these pathlines that the balance between 3 and 4 are balanced as well as 1 and 2, but notice that 3 and 4 are not balanced with 1 and 2. 1 and 2 are getting more mass flow.

4. BALANCING THE FLOW

To balance the flow Sculptor software produced by Optimal Solutions LLC allows CFD mesh geometry to be quickly deformed and then the new geometry can be fed directly into the solver. The design can then be optimized using a gradient based optimization algorithm imbedded in Sculptor.

4.1. Introduction to Sculptor

Mesh deformation techniques were implemented by using the Sculptor™ software package.

Sculptor™ removes the requirement to re-CAD and re-mesh each new design iteration by modifying the shape of the CFD model directly. This reduces the man-time requirement significantly and also allows a consistent volume mesh to be used.

The figures below identify the process that is undertaken to define an Arbitrary Shape Deformation (ASD) volume and create some mesh deformation parameters around a sample CFD model of a generic elbow in Sculptor™. An initial three-dimensional volume is constructed around the CFD model directly which is then subdivided and positioned to fit the geometry. Relationships between the nodes of the ASD volumes can then be created which form the shape deformation parameters as shown.

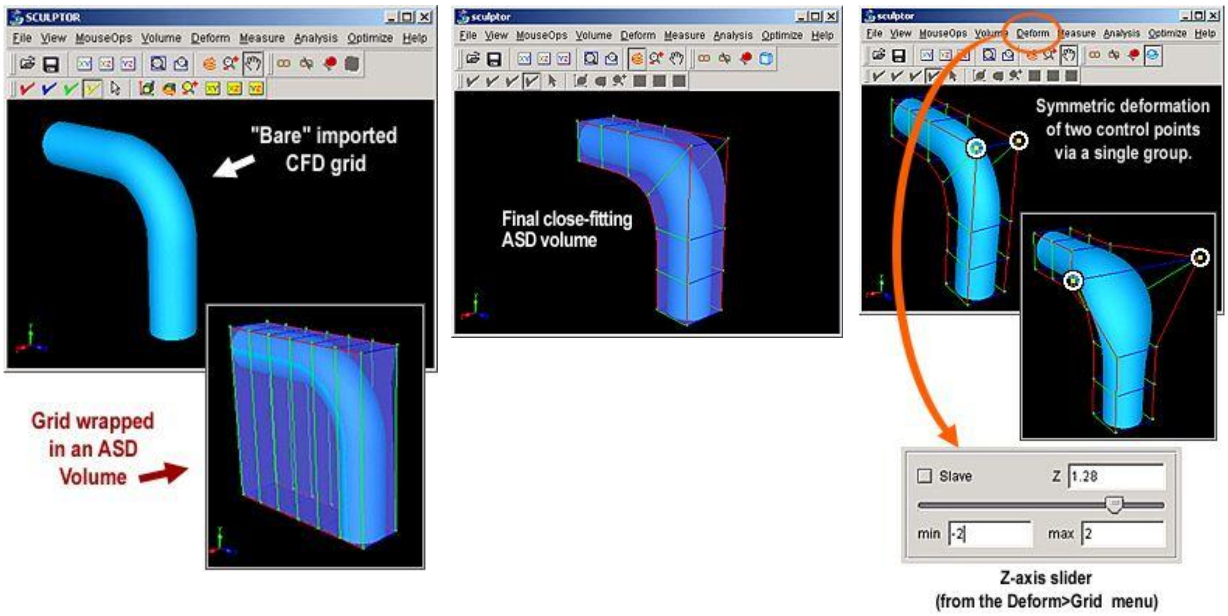

Figure 14 – Here a CFD model of an elbow is imported and an ASD volume is created around it. The ASD volume is fitted to the elbow. Points are grouped and become the parameters in which to deform the CFD mesh.

4.2. Smoothed 4-1, Large Plenum Balancing

For balancing the flow each corner of the plenum was parameterized to allow each to be shrunk towards the center of the plenum. This was set up and allowed to run over night, solving many different designs. The best it could get the optimization found a design that balance two cylinders but still 3 and 1 were 20 percent off.

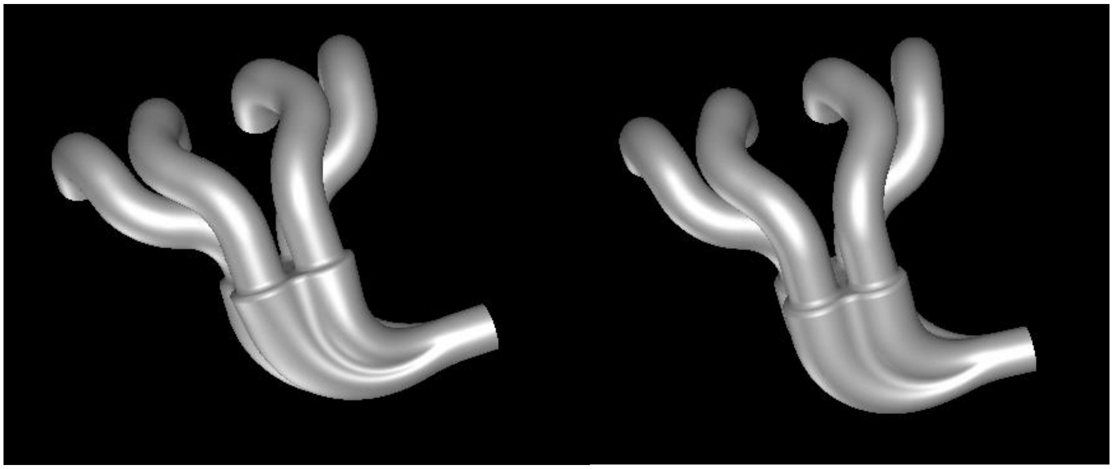

Figure 15 - The balanced geometry is on the left with the baseline shown on the right. Notice that cylinder 3's plenum is pinched in slightly while cylinder 4's is stretched slightly out. Cylinder 1 is also pushed inwards. While this balanced the flow slightly, it still didn't get the results we were looking for.

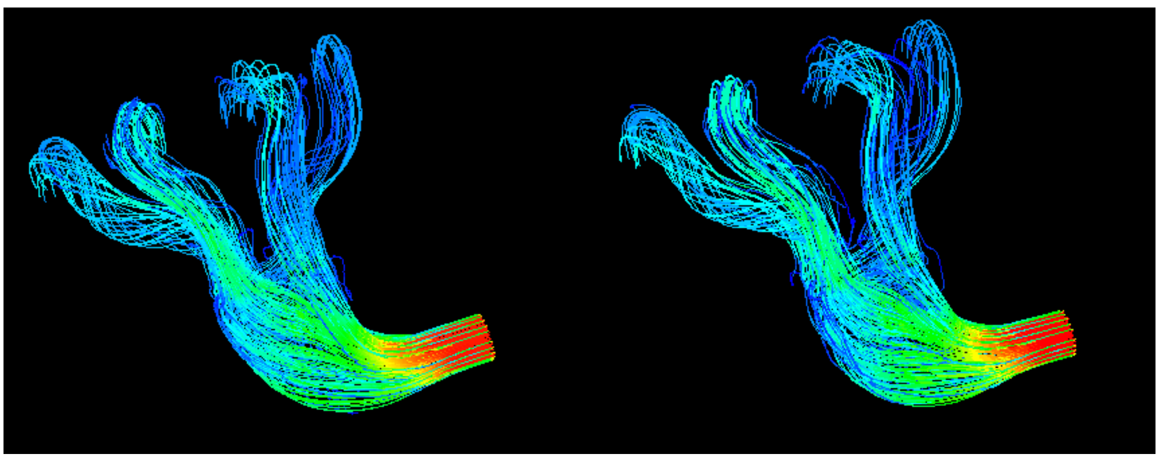

Figure 16 - Although hard to see in this picture the flow to the individual cylinders is slightly more balanced.

4.3. Smoothed 4-2, 2-1 Vane Balancing

For this parameters that would raise the vane up and down and move it further along the tube were set and allowed to run. In one hour the optimizer found a design that balanced the flow almost perfectly. This was then the design used for the next design stage.

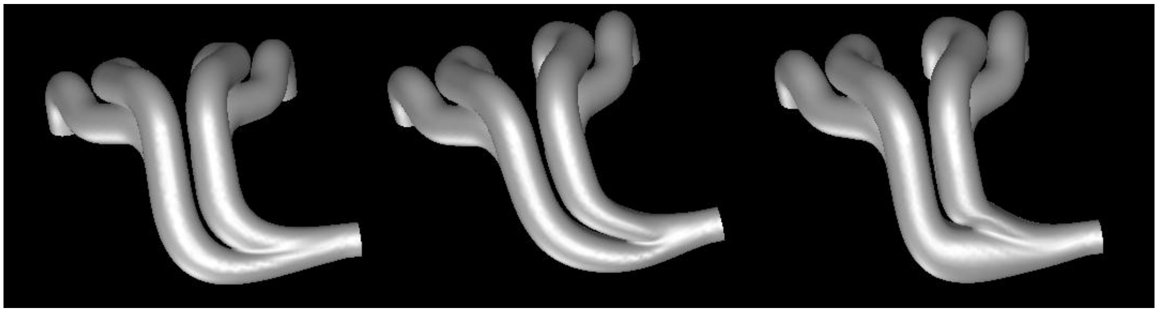

Figure 17 – With the vane design a balanced solution was easier to find. Left is the original shape, middle is one balanced solution by bringing the vane further down towards the turbo, right is a balanced solution allowing the vane only to move up and down. The middle one is the design that we will use.

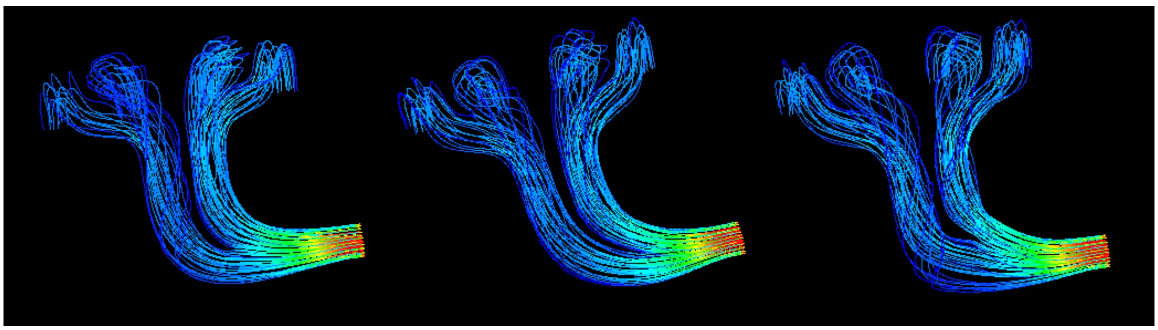

Figure 18 – Notice the balanced flow in the middle and right solutions. Baseline is to the left.

4.4. Pressure Drop Minimization

As air flows around each of the bends the change in direction causes a pressure drop. To reduce this each corner was deformed outward perpendicular to the bend plane. This bulging reduced the pressure drop.

5. SCULPTOR TO MANUFACTURE

After Sculptor produces the optimized geometry, it must be read back into CAD so that it can be detail designed and then exported to the rapid prototype machine.

5.1. Sculptor to CAD – 3Matic

Using 3Matic software produced by Materialise, the mesh was skinned with surfaces and exported to CAD using iges file format. Then in CAD outer surfaces were put on and all the correct sized bungs were added for the mounting of the injectors and sensors. The interfaces for mounting to the engine and turbo were also created.

5.3. CAD to Rapid Prototyping

After the intake is completely designed in CAD it is exported using the stl file format. This is read directly by the rapid prototype machine which ‘prints’ out the intake design. This is then sealed with a special sealant so air cannot pass through the intake wall. It was painted. All the bungs were drilled out for the injectors and pressure sensors. It was then mounted to the engine and tuned.