Exhaust optimization for Viking Motorsports


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Due: March 8th, 2016
Executive Summary

The VMS capstone group is currently designing the exhaust system for the PSU FSAE combustion car. The major goals are passing the Formula SAE noise emission test requirements with the lowest noise levels possible while attaining the highest engine performance, decreasing the overall weight and having a modular design that is easier to modify or repair. Given the team is creating a new exhaust for an existing Formula car, the final design of the exhaust is physically constrained by the space available between the frame of the car and its engine. The FSAE rules and regulations are used as a guideline for the design. The design is further constrained by a minimal budget of $1000.

Throughout the past 11 weeks, the mission was divided into two stages. The first stage focused on header design and included internal and external research, performing calculations for exhaust pipe diameter and length, and making a decision on the header design. Extensive theoretical research was conducted using fluid dynamics to understand the combustion engine process and how the frequency of the four stroke cycle changes the fluid flow characteristics. Special attention was given to the “scavenging” phenomenon, which explains how the exhaust system is a critical link to the engines ultimate performance. The diameter of the header was determined using tabulated data from Smith et al. (1972) to provide sufficient flow for the engine speed. Smith et al. (1972) and Bell et al. (1988) equations were used to determine pipe length. The header design was semi-finalized and a computer animated model was created and a CFD simulation conducted for the exhaust primary pipes. Further simulation still needs to be conducted on the rest of the model.

The second stage is focused on muffler design. External and internal research is still being conducted for the muffler design. The research considered both absorptive and reflective methods for reducing exhaust noise and identified certain absorptive material for additional research which includes: fiberglass mat, stainless steel wool, sintered metals, and porous ceramics. It was determined that the final muffler design will include a combination of reflective and absorptive sound attenuating elements that will reduce the noise adequately over the full range of frequencies. The group determined the best design using the design matrix method. The team will be manufacturing both the header and the muffler using the PSU machine shop.
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1. Introduction and Background ::

Formula SAE dictates that all competition cars entering an event must pass a noise control test before being accepted into any dynamic driving events. In 2015, Viking Motorsports struggled to pass the required limits of 110 decibels at maximum engine speed and 100 decibels at idle. Without passing the noise emission test, the team would not have been able to compete in the rest of the competition. The current capstone team is redesigning the complete exhaust system to ensure that the Formula SAE regulations are met and performance characteristics of the engine are conserved.

2. Mission Statement ::

The current capstone team is designing and building a new exhaust system that will not exceed 110 decibels at a maximum of 11250 RPM and 100 decibels at idle speed. The new design needs to produce a system with a decrease in weight and increase in overall engine performance (i.e. horsepower and torque). Horsepower and torque increases will be validated by using a dynamometer with comparison to the existing design. Evaluation of the weight and performance of the previous model is necessary in order to provide confirmation of the stated objectives completion.

3. Schedule Update ::

Current progress scheduling is represented in Fig. 1 for the header (top) and muffler (bottom). Weeks 1 through 11 are focused on researching, brainstorming, designing, and down selecting both header and muffler concepts. Weeks 12 through the final deliverable date on June 18th represent the purchasing, manufacturing, and testing stages of both exhaust components. Weeks 9 through 11 represent a turning point in the design stage from a focus on header design to muffler design. Currently in week 10, a header design has been finished and is currently being evaluated using simulation tools for testing of any design flaws. Muffler development is under way. The first test of the existing exhaust system has been scheduled to be conducted on March
5th, for which a baseline horsepower and torque curve will be recorded via a dynamometer. Temperature, intake and exhaust velocity, and volumetric efficiencies will be recorded at the dynamometer to help aid in calculations.

![Fig. 1: Project plan for header (top) and muffler (bottom) as planned out from week 1 of winter term (January 28th). Weeks 9 - 11 represent a focus turn towards muffler design Project plan for header in progress.](image)

4. PDS Review

The Product Design Specification includes the requirements, plans, and final objectives for the capstone project. The document represents the entire scope of the project and tracks the progress of the team’s ability to achieve its goal of redesigning the existing exhaust system to increase the car’s performance, while meeting FSAE rules and regulations, and developing proper documentation and a validated design. The team can utilize the PDS document to assess whether specific design requirements and specifications have been met. In doing so, the focus can be shifted towards areas that are in need of improvement.

The criterion for the design of the exhaust is developed from internal and external research while prioritizing the requirements of both internal and external customers. The project will span a variety of engineering concepts including mechanical system design, fluid dynamics, acoustics, and material science. The sponsor, Viking Motorsports, has proposed a budget of
$1000 for the completion of the project. Although the money provided will assist in fulfilling the requirements of the project, it certainly is not enough for numerous prototypes and testing phases. The final product will predominantly be the result of extensive efforts in the development of calculations and engineering concepts.

The project will take into account proper documentation of all phases of the design/build process in hopes of creating a product manual that can be utilized in the future by VMS members as well as other Capstone groups. While shooting for a decrease in sound, the design team will also focus on improving the muffler package, decreasing overall weight, and creating a modular design. The ultimate goal of the design team is to produce an exhaust system that stays within the decibel rating set by FSAE competition rules while maintaining and/or increasing the performance of the car. The performance of the car is based on peak horsepower and torque output. A dynamometer test will be conducted on the current exhaust system to obtain a baseline for the performance of the current exhaust system. This information will then be used for a comparison when the new design of the exhaust system is prototyped and validated via dynamometer testing.

5. Progress Details ::

5.1 The Exhaust Process Research:

In order to characterize the flow and acoustic properties of a 4-stroke combustion engine it is necessary to understand the combustion process. The four unique processes in an ignition cycle of a 4-stroke engine are intake, compression, power, and exhaust. The frequency of these cycles control dynamics of the flow such as mean fluid velocity, acoustic frequency, and fluid density. The exhaust stroke is of particular importance to this project. During the exhaust stroke there is a period of approximately 10° where both the intake and exhaust valve are open; this overlap time is critical to performance because it provides an opportunity to actively pull the reacted gas out of the cylinders. The reacted gases are extracted from the cylinder if the pressure in the exhaust manifold is less than the pressure in the intake manifold; this phenomena is known
as scavenging. A thorough discussion of the physics relating to scavenging is included in the header design section. Figure 2 demonstrates the combustion cycle as (a) cylinder expansion for intake of air and fuel; (b) cylinder compression for proper pressure and temperature of air and fuel; (c) expansion of combusted gases post ignition for transfer of power to cylinder shaft; and (d) compression of cylinder to expel reacted gases out of the cylinders. Process (d) represents the cycle of interest for the current project. The exhaust system under design is directly connected to the valve with which the reactants are leaving. Further expansion of each exhaust component is discussed in the following sections.

5.2 Header Design Research and Development

Header design is primarily focused on length and diameter. At low RPMs, high exhaust gas velocities are necessary to achieve quick throttle response. This is achieved by using a small diameter exhaust pipe. However, a restriction in pipe diameter can limit the flow rate needed to expel all combusted gas at higher RPMs. Pipe length is vital for proper scavenging effects. Due to restricted spacing and controversial theories behind proper primary lengths, a modular design was chosen for testing of best response from different designed modules. Using tabulated data from Smith et al. (1972), a pipe diameter of 1.5 in. was found to provide sufficient flow for engine speeds up to 8,000 RPMs. Furthermore, pipe lengths for the the primary sections to the

![Combustion Cycle Diagram](image)

**FIG. (2):** Figure shows the 4-stroke combustion cycle.
first collectors were calculated using two estimating equations by Smith et al. (1972) and Bell et al. (1988)

\[
P = \frac{ASD^2}{1,400d^2}
\]  

(1)

\[
P = \frac{850 \cdot (180 + B)}{R} - 3
\]  

(2)

where \( P \) represents pipe length in ft, \( A \) is exhaust open period in degrees, \( S \) is stroke length in inches, \( D \) is cylinder bore in inches, \( d \) is exhaust valve port diameter in inches, \( B \) is 180 plus the number of degrees the exhaust opens before BDC (bottom dead center), and \( R \) is the target rpm. Equations (1) and (2) result in a pipe length estimates of 18 in. and 21.24 in. respectively. The preceding values represent the target diameter and length for the header design.

The header geometry is largely restricted by the amount of space between the car frame and the engine itself. Primary header curves are radiused to minimize the amount of redirection that the exhaust flow sees, which can produce flow separation and recirculations, and thus potential performance losses. However, the limited space between the engine and firewall has promoted a simple design. The current model can be seen in Fig. (3).

FIG. (3): Current Header design with pipe diameter 1.5” and length to first collectors at 18”. 
Computational fluid modeling is being pursued using STAR CCM+ available through Portland State University. Flow models are simplified and primarily used to gage any possible recirculation zones. An example Vector plane cutting through the centerline of the pipes can be seen in Fig. (4). Current CFD models assume a clean, smooth surface. Further expansion on CFD modeling will use a notched surface for points where piping will be welded together to simulate flow obstructions imparted by the welds.

FIG. (4): CFD simulation vector fields for inlet pipes 1 and 4 (top) and 2 and 3 (bottom). Current model assumes a 207m/s inlet velocity with a outlet pressure of 101.3 kPa absolute. Red spots represent increased velocities due to radiused pipes.
5.3 Muffler Design Research and Development:

Sound attenuation of an IC engine provides a unique challenge because of the noise spectrum variation. A muffler must perform well at all engine speeds and therefore must be able to adequately attenuate many frequencies present in the system. Exhaust system frequencies vary between 50 and 4000 Hz (Sullivan 1978). Most exhaust noise is limited to the firing frequency and its first few harmonics.

There are two common approaches to the design of internal combustion muffler designs: absorptive and reflective. An absorptive muffler uses a sound absorbing material like fiberglass or stainless steel wool, to capture sound waves and convert their energy into heat. Reflective mufflers induce a destructive wave interference in the exhaust stream to reduce the wave intensity. For complete destructive interference to occur a reflected pressure wave of equal amplitude that is 180° out of phase needs to collide with the transmitted pressure wave (Potente 2005). A reflective muffler can be designed to pinpoint certain frequencies that are the primary contributors to exhaust noise while an absorptive muffler reduces intensity across a large frequency range.

In general most automotive mufflers have both absorptive and reactive components. The final muffler design will be a combination of single sound attenuating elements that will reduce the noise adequately over the full range of frequencies. A discussion of the unique single muffler elements follows.

Helmholtz

A Helmholtz resonator consists of an acoustic chamber that is branched off of the main header piping. As the exhaust wave passes the resonator it induces a cavity wall oscillation that introduces a forced frequency. The cavity can be tuned to create a destructive interference with the passing wave. Variables that affect the induced Helmholtz frequency include the neck diameter, wall thickness and wall rigidity.
Perforated elements with interacting ducts

A solution for the sound attenuation of two concentric interacting ducts of diameter D1 and D2 and length L, as shown in Fig. 6, has been presented by Sullivan et al. (1978), and will be discussed in this section. The continuity and momentum equation can be solved as second-order, inhomogeneous differential equations with constant coefficients for control volume 1 and 2 as shown in Fig. 6. A solution by eigenfunction expansion is presented by Sullivan et al. (1978). This solution satisfies the rigid wall boundary condition. Impedance of a perforated cylindrical chamber can be determined from experimental data presented by Sullivan et al. (1978). For a meaningful solution to be approached additional data must be collected or approximated for use as the inlet and outlet boundary conditions including inlet and outlet space average velocity and density. Solutions similar to that shown for perforated elements with two interacting ducts have been found for systems of three ducts with additional complexity.
Absorptive

An absorptive silencer reduces noise considerably over the entire spectrum and more so at higher frequencies (Potente 2005). An absorptive muffler usually consists of a perforated tube with a layer of sound absorptive material around it and a housing as shown in fig. (7). A descriptive analysis of an acoustically lined cylindrical “duct” is prohibitively complex. Thankfully the mechanical design of these mufflers is sufficiently simple and the acoustic material is sufficiently cheap to allow testing of multiple absorptive muffler arrangements. Some simple analysis may be done regarding the pore structure of the acoustic materials. Materials that can be used include fiberglass mat, stainless wool, sintered metals and porous ceramics.

FIG. (7): Exploded view of typical absorptive muffler.

Remarks on hybrid system and current stage of design

The aforementioned muffler geometries are just a small selection of the many geometries that are used in the industry. A considerable amount of additional research must be done in order to effectively approach the problem of absorbing and reflecting the exhaust pressure waves in a predictable manner.

5.4 Manufacturing Research and Development:

The scope of this project includes the manufacturing of both the exhaust header and muffler. Although the external research regarding the manufacturing of these items is different in
nature than the fluid, heat transfer, and acoustics research, it is no less important to the final product. The following is a brief discussion of the critical aspects of manufacturing and their associated challenges.

**Welding**

Tungsten Inert Gas (TIG) welding is, in all mechanical aspects, considered to be the superior to Metal Inert Gas (MIG) welding. Two important aspects of the TIG welding process are the cleanliness and focused heat that it provides. Because of the high quality inert gas shielding used, the filler material used is an alloy of very similar properties to the parent material. This is not the case with MIG welding where the filler materials often have detergents and cleaners to help create a homogenous weld with contaminated parent materials. The trade off is that the TIG welding process requires extremely clean parent materials free of contaminants. The second main benefit of TIG welding is that it localizes the heat input which reduces the Heat-Affected Zone (HAZ). The HAZ is the region around the weld that has reduced mechanical strength because of the intense heat input that takes place during the welding process. TIG welding causes a much smaller HAZ than MIG welding. Team members have been dedicating considerable time to learning the TIG welding process.

**Cutting**

The process of cutting the stainless tubing is very important because the welding process requires almost watertight fit between tube components. The cutting and finishing process may be just as time consuming as the actual welding. Using a vertical bandsaw with a high tooth count blade such as 18 Teeth-Per-Inch (TPI) will yield clean, consistent and precise cuts. A precision angle cutting jig will be necessary for angled cuts. This jig will likely be comprised of two laser cut plates. The tubing component will mount to the top plate which will pivot about the bend centerpoint of the pipe to allow angled cuts. A similar jig is shown in fig. (8).
6. Evaluation Update

The following design matrices are based off a 1-5 scale where 5 is optimal and 1 is the worst.

Table (1): Header Design Matrix

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<th>Cost</th>
<th>Complexity</th>
<th>Applicability</th>
<th>Efficiency</th>
<th>Performance</th>
<th>Torque Band</th>
<th>Manufacturability</th>
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<td>5</td>
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<td>24</td>
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<tr>
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<td>3</td>
<td>5</td>
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<td>5</td>
<td>5</td>
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Table (2): Header Material Selection Matrix

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<th>Cost</th>
<th>Durability</th>
<th>Maintenance</th>
<th>Aesthetics</th>
<th>Life in Service</th>
<th>Performance</th>
<th>Manufacturability</th>
<th>Standards</th>
<th>Total</th>
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<tr>
<td>Stainless Steel</td>
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<td>5</td>
<td>5</td>
<td>5</td>
<td>3</td>
<td>5</td>
<td>36</td>
</tr>
<tr>
<td>Mild Steel</td>
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<td>3</td>
<td>2</td>
<td>3</td>
<td>3</td>
<td>5</td>
<td>2</td>
<td>25</td>
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Selection between a 4-1 and a 4-2-1 header design is based on the desired power bands. A 4-1 header design offers the best flow characteristics at high engine speeds which gives the most top end power but usually leaves the bottom of the power band quite weak. A 4-2-1 header design gives the most mid range power but sacrifices power at the top end of the band. The track at the FSAE competition is full of turns with very few straight runs. Hence the car will almost be constantly coming in and out of turns and will rarely have the distance necessary to reach full power output. Therefore the operating rpm range that the car will experience must be tuned to maximize horsepower and torque within that range which happens to be the midrange which will
help accelerate out of turns. Considering these aspects and the performance differences, a 4-2-1 design offers the best fit for the application.

The industry standard for performance exhaust systems calls for the use of 304 stainless steel tubing. The main benefits in using stainless steel rather than mild steel are the increased lifetime of the product due to its resistance to corrosion as well as its superior aesthetics. Downsides to using stainless steel include the advanced skill required for the welding process, and the increased material cost as well as the propensity for cracking due to a combination of hardness and the heat cycles that an exhaust system experiences. Stainless Steel was chosen based on the desired lifetime of the product and the available skill of group members.

Since the exhaust build is done as a capstone, the header and muffler are designed to be modular. Having a modular design will allow for rapid modifications to the system while testing. Testing various configurations of the exhaust system will increase the chances of selecting the optimum design for the system. In addition, future capstone teams will have an easier time modifying the existing system.

There are two basic designs for a muffler, reflective or absorptive. The reflective design uses baffles to create deconstructive wave pattern within a cylinder. The reflective design is very effective at noise cancellation but also restricts the exhaust flow inherently by nature of its design. The absorptive design incorporates a perforated cylinder within another cylinder with sound deadening material packaged in between. The absorptive design naturally has less restriction to the flow but is not as effective at cancelling noise. However the noise cancelling properties of the absorptive and reflective design can change depending on the design of the baffles or the selection of the packing material used. Considering this complexity, a combination of the two will be used for the muffler design. A modular design using the combination of a reflective and absorptive muffler will allow for the testing of various configurations of the muffler in order to determine the optimal Muffler design and maximize performance.

8. Conclusion and Recommendations

Taking the discussed topics into consideration, the choices are made to achieve the best possible outcomes based on internal and external research. It was concluded that 1.50 in.
Stainless 304, 16 gauge piping will be used for the header due to its superior properties when compared to mild steel. Additionally, a 4 to 2 to 1 configuration for the headers will be used based on the operating rpm range of the engine.

Based on the gathered information, it was concluded that the muffler will be manufactured out of aluminum alloy. This alloy was chosen mainly due to its material and machinability properties. The current exhaust design is composed of mild steel, thus switching to aluminum will allow for a lighter package. The machinability (welding, bending, cutting, etc.) and overall ease to work with of aluminum is better when compared to that of 304 SS. The final muffler design will be modular so that the VMS team can make rapid and sudden modifications for testing in attempts to meet the Formula SAE noise requirements. The team will have pre-manufactured muffler subsections that will allow for easy maintenance to take place at competition and/or during practice runs.

The supplier for the materials will be Columbia Mandrel Bending and the sponsor for the project is the VMS team. Columbia Mandrel Bending was chosen by the capstone team due to their local location in St. Helens, Oregon. This allows for the materials to be readily available to pick up when needed. The designs for the header have been finalized and the parts list containing the tubing, bends, and collectors have been ordered. With a total budget of around $800-$1000, the header parts list totalled out to $450 which leaves around $550 left for the muffler budget.

The team is up to date on the gantt chart, and everything is going as planned. As soon as the supplies arrive (argon gas & mandrel bends) fabrication will take place. The muffler is in the design process and the team is currently designing a prototype via calculations and 3D modeling. The main goal of this muffler is to exceed the Formula SAE noise requirement specifications and aim around 6-7lbs or half the weight of the current one on the car.

So far the team has not had to make any compromises to meet the sponsor’s needs with the current design. Both parties are happy and are anxious to see the final product. One of the current obstacles the team faces is not compromising the welds during the header manufacturing. Stainless round tubing can be hard to weld, especially on the collectors where two pipes come into one. They are around $75 a piece so failure in the welding would come out of the muffler budget. The motive behind this project is to be budget conscious, while exceeding the
expectations of the sponsor. The team is working cohesively and will have a fabricated header model to present at the end of March. In the meantime, the team is finalizing on the muffler design and getting ready to start getting a materials parts list ordered.
Bibliography
