Optimization of a Single Cylinder Turbocharged FSAE Race Engine Inlet System

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The inlet system of any internal combustion engine is an often overlooked component that can be designed to provide significant increases to engine operating power in terms of horsepower and torque. This project aims to optimize the design of the inlet system of a single cylinder turbocharged Formula Society of Automotive Engineers (FSAE) race engine in order to increase engine output power throughout the operational range. Optimization of the inlet system will be constricted to and designed around the FSAE 2016 rules which introduce an inlet configuration different to conventional turbocharged setups, as well as being designed around the engine and turbocharger selected by the Australian Defence Force Academy (ADFA) FSAE team. Through the use of Computational Fluid Dynamics models verified through in depth experimentation, an intake system design has been optimized and recommendations made to the ADFA FSAE team. This includes manufacture of a restrictor pipe with a flow increase of 19%, an in depth analysis of a heat exchanger as well as validation of a tuned runner length. These modifications are designed to increase the operating power of the 4 stroke KTM 500 engine. The final step in the project will be to validate the design through the use of an engine dynamometer which has been unavailable throughout the timeline.

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Nomenclature

Terms:

- **FSAE** = Formula Society of Automotive Engineers
- **ADFA** = Australian Defence Force Academy
- **VE** = Volumetric Efficiency
- **NA** = Naturally Aspirated
- **RPM** = Revolutions Per Minute
- **RPS** = Revolutions Per Second
- **IC** = Internal Combustion
- **cc** = Cubic Centimeter
- **CFD** = Computational Fluid Dynamics
- **E85** = Ethanol Vehicle Fuel (85% Ethanol 15% ULP)
- **ULP** = Unleaded Petrol
- **CFM** = Cubic Feet per Minute

Variables:

- **A** = Cross Sectional Area (m$^2$)
- **R** = Gas Constant (J/Kg.K)
- **V** = Velocity (m/s)
- **T$_t$** = Total Temperature (K)
- **T$_i$** = Initial Temperature (K)
- **T$_\infty$** = Ambient Temperature (K)
- **r** = Density (Kg/m$^3$)
- **\(\gamma\)** = Specific Heat Ratio
- **P$_t$** = Total Pressure (Pa)
- **P$_d$** = Dynamic Pressure (Pa)
- **P$_{atm}$** = Atmospheric Pressure (Pa)
- **q** = Heat Energy Transfer (W/m)
- **L** = Length (m)
- **h** = Heat Transfer Coefficient (W/m$^2$ K)
- **D** = Tube Diameter (m)

I. Introduction

Formula School of Automotive Engineers is a design competition where roughly 80 universities partake in designing an open wheeled race vehicle that is constrained by a strict and thorough set of design requirements [1]. In this respect it is crucial that each component of the vehicle is designed in an optimized manner to achieve maximum possible performance. Roughly 20 requirements in the 2016 FSAE competition rules pertain to the design of the intake system and aim at standardizing the flow of air through the intake system and into the combustion chamber. This is where optimal design of inlet system components is crucial in providing maximum possible output power when harsh constraints such as limited mass flow must be adhered to. The order of components of the inlet system are constrained in the following order and are seen in Fig. 1; Restrictor, Compressor, Throttle Body, Heat Exchanger (Intercooler), Runner length, Injectors, Engine [2].

![Figure 1. Basic Layout of Intake System in Accordance with 2016 FSAE Competition Rules[1]](image-url)
A. Project outline
The FSAE competition rules dictate a turbocharged setup that is different from conventional setup and the technicalities of this difference will be further discussed later in the report. This difference in configuration, as well as the engine in which this intake will be attached to, provided the baseline for the motivation and inspiration for this project.

1. Purpose
The purpose of this project was to optimize the design of an intake system in accordance with the 2016 FSAE rules in order to achieve improvements on engine operating power throughout the engine operating range. This required an in depth understanding of the turbocharged configuration that is outlined in the competition rules and areas in which intuitive design will allow for increased operating power.

2. Scope
This project identified three major components of the inlet system to be analyzed and optimized that would cause the greatest increases in engine power of all the inlet components. This included the restrictor pipe design and manufacture, heat exchanger analysis and design and runner length analysis and design.

The project began through a MATLAB optimization of the restrictor pipe design using a surrogate model NSGA2 optimization code. Using a model that was developed with data gathered through SolidWorks Flow simulation of various restrictor pipe geometries, an optimized design of restrictor the restrictor pipe was developed. The optimized design was manufactured and the CFD models were verified through the use of flow bench testing by comparative methods between the original (non-optimized) and optimized restrictor pipe. The verification of the CFD models allowed more reliance to be placed on CFD when analyzing and optimizing the design of the runner length and heat exchanger.

In depth analysis of the heat exchanger and runner length was conducted and a design was developed.

3. Significance
Little analysis has been done on the configuration of a turbocharged intake configuration that is specified by the 2016 FSAE rules. Much of the previous and referenced work has relied solely on CFD methods for very basic optimization and design purposes. No published work was found on intake components for an FSAE vehicle that were optimized through mathematical optimization methods like those used in this project. Due to the sophistication of mathematical optimization methods it is expected and shown that the produced design is of better performance than those who did not use such methods. Further, unlike previous and referenced work, the method of optimization in this project has been verified through experimental methods and further work to validate the models through the use of a dynamometer is expected to occur before the 2016 FSAE competition. This will produce an optimized intake system that performs to the highest possible standard and will achieve the aim of the project as well as verifying CFD methods that can be used in future work in order to save time and costs.

II. Background
Optimization of the inlet system with respect to the 2016 FSAE rules will require raising the pressure throughout the entire inlet system in order to force more air to be ingested into the cylinder during the intake stroke. Through the use of CFD analysis techniques, pressure changes through the inlet system can be modeled and combining this method with NSGA2 optimization formed the structure by which the system was optimized and verified. ANSYS Fluent and SolidWorks Flow Simulation software were used to model inlet system components and compare how geometry changes effect pressure and momentum. The major components of the intake system that aim to increase Volumetric Efficiency (VE) included the restrictor pipe, the heat exchanger or intercooler and the runner length[3-5]. These are the components that were analyzed and optimized.

A. Inlet System
The inlet system of an IC engine is designed to deliver an air fuel mixture into the cylinders and comprises of several components [6]. The two main concepts for increasing operating power for an IC engine include increasing the amount of air entering the cylinder by raising the inlet pressure and also increasing the amount of fuel that is ingested with each intake stroke [4]. Increasing the pressure within the inlet system through geometrical design is a method of increasing the VE of the engine. VE of an engine is a percentage that quantifies how much of an engines stroke is filled with air. For example; a 500cc engine with a VE of 50% indicates that with each intake stroke 250cc of air is drawn into the cylinder. Any increase of VE allows more
energy to be consumed by the engine during combustion and subsequently operating power is increased [7-9]. In many cases the VE is limited by the design of the intake system. This is because inlet systems and manifolds are largely designed around geometrical constraints that arise when an engine is fitted into a vehicle and consequently a truly optimized design is not commonly achieved [10]. This is conventionally due to the flow restrictions that result when this design method is applied to an intake system [3]. In the case of the FSAE competition, spatial constraints are less of a hindrance on design and the main design constraints stem from the competition rules.

B. Restrictor Pipe

The purpose of the restrictor pipe in the FSAE competition is to limit and subsequently standardize the amount of air that can be ingested into IC engines no matter their capacity or number of cylinders. The type of fuel used by the engine governs the throat diameter of the restrictor pipe. E85 fueled cars are required to use a restrictor pipe with a throat diameter of 19mm and ULP fueled cars are required to use a restrictor throat diameter of 20mm[1]. The restrictor pipe throat area is what limits the amount of air that can pass through the entire inlet system. This is due to a fluid flow concept known as choked flow. Choked flow is a condition that occurs in an orifice or nozzle whereby the fluid flow through an orifice reaches sonic velocity and the absolute pressure ratio across the orifice is 52.8% of the upstream pressure [11]. At this point the airflow through the orifice is limited and will not exceed a certain flow rate unless the upstream pressure is increased greater than atmospheric pressure. Choked flow will limit the maximum operating power of the engine and will not occur until the engine reaches a certain and normally quite high RPM. Mass flow rate for a real compressible fluid flow through an orifice is represented in Eq. (1) [11].

\[ \dot{m} = \frac{AP_t}{\sqrt{\gamma R}} \left(\frac{\gamma + 1}{2}\right)^{-\frac{\gamma + 1}{2(\gamma - 1)}} \tag{1} \]

As the 20mm diameter throat has a larger cross sectional area than the 19mm throat, Eq. (1) shows it will have a greater mass flow at choked conditions.

\[
A_{19mm} = 2.835 \times 10^{-3} \text{m}^2, P_t = 101325 \text{Pa}, T_t = 300 \text{K}, \gamma = 1.4, R = 286 \text{ J/Kg.K}
\]

\[
\dot{m}_{19mm} = 0.0671 \frac{Kg}{s}
\]

\[
A_{20mm} = 3.145 \times 10^{-3} \text{m}^2, P_t = 101325 \text{Pa}, T_t = 300 \text{K}, \gamma = 1.4, R = 286 \text{ J/Kg.K}
\]

\[
\dot{m}_{20mm} = 0.0703 \frac{Kg}{s}
\]

As discussed, choked flow limits how much air will pass through the entire system and will subsequently limit the maximum power produced. Previous research has shown that different configurations of restrictor pipe geometry can induce higher mass flow rates at lower pressures. Figure 2 illustrates a pressure plot across a typical geometry of a restrictor pipe.

![Pressure Plot of Restrictor Pipe](image)

In Fig. 2, fluid flows from the right to left and the geometry consists of a diverging angle to the throat diameter (20mm in this case) and a converging angle to the intake diameter which is 44mm. Shinde compared 8 different converging and diverging angle combinations through SolidWorks CFD simulations modeled at choked flow boundary conditions with the objective to minimize pressure drop across the pipe. Despite the very
small sample size gathered by Shinde, the results showed pressure differences of over 1200Pa which demonstrates how only geometry changes can significantly influence the pressure within the inlet system[12]. Further, 49 different angle combinations were simulated via the same CFD methods by Singhal and Praveen and saw pressure differences of over 5815Pa[13]. This demonstrated that a larger sample size of angle combinations could yield an optimal geometry that would result in a lower pressure drop than those examined by Shinde, Singhal and Praveen. Also, both cited sources show that converging angle and diverging angle vs pressure drop does not necessarily follow a trend that can be easily predicted. Due to the extreme complexity to how pressure changes with these two geometric variables, an in depth interpolating model, such as NSGA2, was required to produce an accurate result.

C. Intercooler

A heat exchanger or intercooler is a common component in a turbocharged intake setup that is used to reduce the temperature of the intake air after passing through the high temperature turbocharger[4, 14]. High temperature intake air is of lower density which reduces VE and the higher temperatures can cause pre-detonation in the combustion chamber which can decrease output power. Conventional turbocharged intake system designs incorporate a large volume intercooler that is placed between the turbocharger and the throttle body[15]. This is where conventional turbocharged configuration differs from the configuration that must be used in the 2016 FSAE competition. The 2016 FSAE rules dictate that if an intercooler is used in the intake system that it must be placed between the throttle body and engine and this is seen in Fig. 1. While the principle of the intercooler is the same in this altered configuration for increasing power, this arrangement can have negative effects on how responsive the engine may be. When the throttle body is opened air flows through the final stage of the inlet system into the engine. For conventional turbocharged designs the final stage includes only on the runner length and multiple cylinder engines normally incorporate a relatively large runner volume. As the KTM500 engine that is being used is of single cylinder configuration, any large volume between the throttle body and engine are expected to increase turbo lag effects. This is because all incoming air must fill the volume after the throttle body (intercooler and runner length in this case) before entering the engine. The larger this volume is, the longer it will take for the pressure to equalize within the system and thus increase the time before high pressure air is ingested into the engine. This is may not have negative impacts on peak engine output power but will likely result in engine behavior that is unfavorable for competition use where quick throttle response with minimal turbo lag is desired. As the aim of this project is to produce a design that is optimal for an FSAE race engine, these consequences were considered during the design process.

The implementation of an intercooler will reduce the intake air temperature and hence increase engine output power. The design, however, must take the volume of the intercooler into heavy consideration due to the potential engine lagging effects that it may cause. The design of the intercooler must then be such that it reduces intake air temperature as efficiently as possible per unit volume. This will ensure that it benefits from the intake air temperature reduction effects, but is not significantly affected by turbo lag.

D. Runner Length

Tuned runner length design is the last method that shapes the flow as it enters the cylinder. In this respect, it is important that the flow properties through this pipe allow for maximum possible airflow into the cylinder with minimal pressure drop and losses [9]. A useful and widely used concept is known as ram theory. Ram theory utilizes the momentum of the air through the runner to force reflected pressure waves into the cylinder as the inlet valve opens[16].

![Figure 3. Ram Theory: Pressure Wave of Air when Intake Valve is Closed][16]

In order to increase the VE of the intake stroke of an engine, ram theory can be applied to tune the runner length to increase the output power at a certain RPM range. Ram theory relies on the inertia of the air flowing through the intake runner to achieve an increase in engine output power[17]. When the intake valve is open in
an IC engine, air is drawn from the intake runner into the cylinder due to the lower pressure inside the cylinder. As the engine continues to rotate, the intake valve eventually closes and all the air in the intake runner still moves with a high velocity towards the now blocked path. This causes the air to reflect from the intake valve in the form of a pressure wave which begins to oscillate up and down the intake runner at the speed of sound. This concept is illustrated in Fig. 3. The wave reflects off the intake valve and in the case of the 2016 ADFA FSAE intake system, it also reflects on the throttle body. If the length of the intake runner is such that it meets the intake valve precisely as it begins to open, the momentum of the pressure wave will fill the cylinder with an increased VE – subsequently increasing the output power. As the RPM of the engine changes, the time between intake valve opening and closing also changes. This restricts the runner length only being able to be tuned to a small RPM band.

Typically there are 8-12 pressure wave reflections within the runner between inlet valve closing and opening times, depending on the size of the runner [16, 18]. The fewer bounces, less energy loses will occur and more energy can be harnessed by the engine. It is often difficult to have a very long runner length to accommodate for minimal pressure wave reflections as geometrical constraints of the engine normally prohibit this. Ram theory can be applied to any RPM band but it is often tuned for an RPM band that is before the peak power output [19, 20]. This allows an engine to have a more steady power band and can be useful when significant turbo lag exists. In the case of the 2016 ADFA FSAE team, the runner may be tuned at or slightly before peak power. If applied correctly with a turbocharged intake design, the ADFA FSAE vehicle will be able to have a steadier and more useable power band throughout its operating range.

III. Optimization and Design

A. Restrictor Pipe

Developing on previous research that was discussed in the Background section of this report, the first step in developing an optimized design was to model and simulate a large sample size of angle combinations in SolidWorks Flow Simulation. The boundary conditions that each geometry was modeled under were atmospheric inlet pressure and mass flow output equivalent to choked flow (67.1g/s). This best models the restrictor pipe under maximum load when on the race engine. All simulation settings remained constant at each simulation to ensure that only the geometry changes affected the resultant pressure difference. Initially 80 different angle combinations were simulated and the pressure drop across the pipe was recorded. This data laid the foundation for developing a surrogate model using NSGA2 MATLAB optimization code. Using the data from the CFD simulations, the surrogate model was run which interpolated the data to produce a design. The design was given as a converging angle, diverging angle and the expected pressure drop. The result was then simulated in CFD along with slight variations in the design which added more substance to the surrogate model data. This new data set was then loaded into MATLAB and the larger sample size was expected to produce a more accurate result. This iterative method of MATLAB optimization and CFD simulation was done three times with over 190 simulation samples to arrive at a design which was deemed to be sufficiently accurate. The final design is outlined in Table 1.

<table>
<thead>
<tr>
<th>Table 1. Optimized Restrictor Pipe Design Specifications</th>
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</thead>
<tbody>
<tr>
<td>Diverging angle</td>
</tr>
<tr>
<td>Converging Angle</td>
</tr>
<tr>
<td>MATLAB Predicted Pressure Drop</td>
</tr>
<tr>
<td>CFD Simulated Pressure Drop</td>
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<tr>
<td>Throat Diameter</td>
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<tr>
<td>Inlet/Outlet Diameter</td>
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This design was deemed to be sufficiently accurate because further iterations would have only increased the number of significant figures of the angles. This slight variation would have caused minimal difference in resultant pressure drop and would have also been very difficult to manufacture accurately. The predicted pressure drop was also very close to the pressure drop when simulated using CFD.

Other geometry changes were also simulated to examine their effects on the resultant pressure drop. This included variables such as throat point radius, throat length as well as inlet bell mouth radius. 30 samples of different combinations of these variables were simulated using the same CFD methods and it was found that throat radius had no effect on pressure drop and adding a bell mouth did benefit pressure by roughly 300Pa but the radius of the bell mouth was not critical. All results from the simulations can be seen in Appendix A. Viewing these results it is clear that there is no definitive trend to how the pressure drop will behave as the angles change. The accuracy of the design that was generated, then, is a testament to how precisely the MATLAB surrogate model has interpreted the data.
The next step was to verify the CFD and MATLAB models by manufacturing this optimized design and comparing it with a previously used restrictor pipe on a flow bench. A two piece steel mold was turned to enable a wet layup manufacture method of the carbon fibre restrictor pipe and can be seen in Fig. 4. The mold was manufactured to a tolerance of 0.01mm and the carbon fibre was wrapped in heat shrink to ensure the pipe was impermeable to maintain its compliance to the competition rules.

A flow bench is used to measure the flow rate through a geometry at a constant downstream pressure. This allowed it to be used as a comparative testing method between the optimized and non-optimized restrictor pipes and also verified the CFD and optimization method used. The flow bench used for testing, seen in Fig. 5, was unable to be accurately calibrated due to its long service life and also was unable to achieve choked flow conditions within the restrictor pipe. Despite this, however, the flow bench testing method was still a repeatable comparative method between all test configurations. Fig. 6, 7 and 8 show the different test configurations. All tests were conducted 12 times and the average result was taken and is shown. It is important to note that the non-optimized restrictor pipe (orange in Fig. 6) has a 20mm diameter throat, whereas the optimized restrictor pipe (Fig. 7 and 8) has a 19mm throat diameter.
Despite the non-optimized pipe having a roughly 10% larger orifice area, the optimized design draws 17% more air through it at 10 inches of water pressure. Further, the addition of the bell mouth increases the flow rate by another 2% at the same downstream pressure. These flow increases are a true reflection of how optimized geometry can affect the flow rate. The only disputing factor to this statement is that the non-optimized pipe has a slightly rougher surface which is associated with flow losses, however this would be minimal. A detailed CFD view of the optimized and non-optimized pipe with the same conditions as the flow bench is included in Appendix B. It can be seen that the optimized pipe has lower levels of vorticity (energy losses) and also has a much more uniform turbulent energy profile at the outlet when compared to its non-optimized counterpart. These are the reasons as to why the optimized prototype has a greater flow rate when on the flow bench.

The flow rate increase that was achieved through the optimization process is significant and it is expected that this flow increase will cause power increases up until the flow becomes choked in the very upper limits of the RPM band. The next step is to validate these results by testing the above pipes on the engine attached to the dynamometer to quantify the power increase. Unfortunately the vehicle and dynamometer were unavailable for the duration of the project lifecycle.

B. Ram Air Geometry

Not to be confused with Ram Theory, a ram air geometry can be used as the first method to raising the inlet pressure of an inlet system. Widely used in Formula 1 racing, ram air geometry has a larger orifice that aims into the flow direction and its objective is to “catch” the air as it passes over the vehicle. At higher speeds the ram air geometry becomes more effective as the dynamic pressure at its inlet increases. This increase in pressure then raises the mass flow through the system and the operating power of the engine also increases.

A brief investigation was done into the implementation and possible optimization of a ram air geometry onto the ADFA FSAE vehicle for the 2016 competition. Two basic but widely used ram air geometries were constructed in SolidWorks and simulated under conditions similar to that of the FSAE vehicle operation at the competition and are shown in Fig. 9 and 10. The aim of these simulations was to have the pressure at the inlet of the restrictor pipe as high as possible.

![Figure 9. Large Ram Air Geometry](image1)

![Figure 10. Cylindrical Ram Air](image2)

The two ram air geometries were modeled using the same method as the restrictor pipe simulations that have been verified through the previously discussed testing. The boundary conditions of the simulations included choked mass flow outlet and an inlet condition of dynamic pressure equivalent to the vehicle travelling forward at 60km/h. This speed was chosen as it is a speed that the vehicle is likely to spend a considerable time operating at during the competition. The simulation results showed that both geometries performed to a very similar standard and only negligibly raised the pressure at the inlet of the restrictor pipe. This is due to the low speeds in which FSAE vehicles normally achieve during the competition. The dynamic pressure that is achieved at 60 or even 80km/h is not enough to raise the inlet pressure enough to cause a significant increase in the mass flow through the system. This can be shown using Eq. (1) to find the choked mass flow by using the dynamic pressure (Eq. (2)) that would occur at 60km/h.

\[
\begin{align*}
A_{\text{inlet}} &= 2.835 \times 10^{-3} \text{m}^2, \quad V = 16.67 \text{m/s} = 60 \text{km/h}, \quad T_i = 300 \text{K}, \quad \gamma = 1.4, \quad R = 286 \text{ J/Kg.K} \\
\rho V^2 &= \frac{1}{2} \rho V^2 + P_{\text{atm}} \\
V &= \frac{1}{2} \rho V^2 + P_{\text{atm}}
\end{align*}
\]

\[
P_v = 101489.5 \text{ Pa}
\]

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The above mass flow would occur at choked conditions if the ram air geometry is 100% efficient; meaning that the inlet pressure is equal to the outlet pressure. This mass flow has only increased by 0.24% from the previous mass flow. As this increase in mass flow is so insignificant and would only occur if the design was equal to or greater than 100% efficiency, the expected power increases are negligible and are likely to be outweighed by the extra weight and drag that a ram air box would add to the vehicle. Thus the decision was made after the analysis not to include a ram air box but instead to aim the inlet of the restrictor pipe into the flow path of the air over the vehicle. This would still allow the inlet system to benefit from ram air effects but would not add any extra weight to the vehicle.

C. Intercooler

Two designs were analyzed by mathematical and simulation means to test the viability of including an intercooler onto the 2016/17 vehicle. As discussed, the aim of the intercooler design was that it reduces intake air temperature as efficiently as possible per unit volume in order for engine performance not to be considerably effected by turbo lag. The designs that were analyzed can be seen in Fig. 11 and 12. The analysis of the designs included the degree of temperature change, air flow analysis using CFD and also size, weight and material considerations.

![Figure 11. 12mm Tube Intercooler Design](image1)

![Figure 12. 10mm Tube Intercooler Design](image2)

The 10mm and 12mm tube variants were simulated via CFD methods and also through mathematical methods with the same boundary conditions to determine the intercoolers suitability for the FSAE vehicle. The internal volume of both variants were very similar despite the 10mm design incorporating a longer total tube length. The 10mm design theoretically performed better than the 12mm design and the simulations showed it to cause a reduction in intake air temperature by roughly 30 degrees depending on the material and outside air temperature. Simulations of the 12mm variant showed temperature reductions of roughly 28 degrees under the same conditions. The calculations shown below, demonstrate that the 10mm design is in theory 32% better performing than the 12mm design and adding extra fins between the tubes will increase the heat transfer efficiency due to their added surface area. These calculations, however, do not accurately represent real world operation of the intercooler.

\[
q \cdot L = \pi D \bar{h} (T_1 - T_\infty) \cdot L = (W)
\]

Eq. (3) represents the heat energy transfer over a length of pipe using the thin wall approximation[21]. This can be used to determine, in a maximum efficiency case, which design will transfer more heat energy regardless of the material.

\[
L_{10\text{mm}} = 7.4\text{m}, \quad L_{12\text{mm}} = 4.2\text{m}, \quad T_1 = 368 \text{K}, \quad T_\infty = 303 \text{K}, \quad \bar{h} = \text{material constant}
\]

\[
q_{10\text{mm}} L_{10\text{mm}} = 15.11 \bar{h} = (W)
\]

\[
q_{12\text{mm}} L_{12\text{mm}} = 10.29 \bar{h} = (W)
\]

The thin wall approximation assumes that the outside of each tube is of equal temperature to the outside air which in the case of the analysis was taken to be 30 degrees Celsius. In real world application of an intercooler of this design, the tubes would begin to heat up and the tubes closer to the center of the intercooler would be of higher temperature than those on the outside. This would be more noticeable in the 10mm design as the tubes are packed closer together and would subsequently influence the neighbouring tubes temperatures more than it
would in the 12mm case. As the simulations showed very little difference in flow characteristics and temperature drop, and also considering ease of manufacture, the 12mm design will be the better performing variant of the two. At this stage of analysis, the 2016 ADFA FSAE Team decided not to implement an intercooler into the intake system due to time and geometrical constraints. This investigation has shown, however, that designs similar to those analyzed would be viable options to continue a more in depth optimization technique similar to that used for the restrictor pipe optimization.

D. Runner Length Verification

Designing a runner length for a certain RPM band is a simple process provided that the valve duration is known. Figure 13 illustrates the intake and exhaust valve lift vs engine rotation for the cam being used by the 2016 ADFA FSAE team. This aids in determining when to count the intake valve as being considered “open” and “closed”. It is important not to consider the intake valve “open” as soon as it begins to lift as this would not allow all momentum of the pressure wave to be fully harnessed. This analysis will determine the intake valve as “open” when the intake valve has a lift equal to the lift of the exhaust valve. This will ensure that all air entering as a result of pressure wave inertia will not be partly lost out of the exhaust valve as opposed to being encapsulated within the cylinder. The intake valve lift is equal to the exhaust lift at 1.04mm of lift at 2 degrees rotation. The intake valve is at 1.04mm lift again at 240 degrees rotation. This then determines that the intake valve is open for 238 degrees of rotation for a 720 degree cycle of the camshaft. From this duration an effective runner length can be calculated to be 482 degrees. Peak horsepower is expected to occur at roughly 7500 RPM and as the team wishes to increase the maximum operating horsepower, this is the length to which the runner shall be tuned to.

\[
\frac{7500\text{RPM} \times 60\text{sec}}{60\text{sec}} = 125 \text{ RPS}
\]

\[
125\text{RPS} \times 360^\circ = \frac{45'000 \text{ degrees}}{s}
\]

\[
\frac{482^\circ}{45'000} = 0.01071 \text{ s}
\]

When the intake valve closes, the pressure wave inside the runner tube will begin to oscillate at the speed of sound which is dependent on the internal conditions of the intake at that time. For the purpose of the following calculations, it will be approximated to be 340m/s. Many factors may affect the speed of sound inside the tube such as the temperature of the air, atomized fuel within the air, the surface shape and roughness factor and so on. Approximating the consequence of these parameters would take considerable time and expertise and seeing as though the majority of the aforementioned parameters will change during the operation of an engine, it was deemed unnecessary to account for these effects.

The distance travelled by the pressure wave while the valve is closed was calculated to be 3.6448m. The runner length is equal to the entire distance travelled by the wave divided by 2 as it has to return to the intake valve. Therefore the runner length distance with no bounce is equal to a distance of 1.8224m. As this length would not fit within the engine bay any division of this length would still be tuned to the same RPM band. Dividing this length by 15 reduces it to a length of 121mm; the same runner length that the vehicle is currently using.

The RPM band that was chosen to tune the runner length to was decided without seeing the power curve of the engine as a result of the dynamometer being unavailable. If a dynamometer test was conducted before the runner was tuned, a more appropriate RPM may have been identified. For example, there may have been a power lag around 6000RPM and tuning it to this RPM may have resulted in a smooth, more usable power curve. Previous engine operation, however, has shown peak power around 7500 RPM.

IV. Conclusion

This project was undertaken to conduct an analysis and design optimization of the intake system of a single cylinder turbo charged FSAE race engine in order to increase engine operating power while adhering to competition requirements. The individual intake components were optimized with respect to well researched
and understood concepts known to increase the output power of IC engines. Simulations of these components were verified through the use of flow bench testing and the flow rate through the restrictor pipe at constant downstream pressure has been increased by 19%. A significant output from the project has been the verification of the CFD method and optimization technique which allows such processes to be relied on in proceeding research and design. The optimization method adopted in the design of the major intake system components is unlike any process seen in previous work and has considered an infinite sample size due to the NSGA2 surrogate model optimization code. While the optimized system has not been validated due to the unavailability of the dynamometer, based on previous research and experience, it is expected that the optimized design will increase the engine operating power throughout the operating range and be limited by choked flow in the upper end.

V. Future Work

In order to fully reinforce the research, optimization and testing techniques of the above components with respect to the project goal, comparative dynamometer tests need to be conducted in order to quantify the engine power increase. There is also very large scope to entirely optimize the intercooler using similar methods to those used for the restrictor pipe design optimization. This would include optimizing the shape for improved flow characteristics, the selection of material and also optimizing the number, size and length of the tubes to maximize heat transfer efficiency and minimize volume and weight. NSGA2 optimization would prove to be a useful tool for managing the large number and complexity of these variables and would be able to achieve an optimal design for use in the 2017 FSAE competition. Validation of the optimized intake design through dynamometer testing is expected to occur before the 2016 competition.

VI. Acknowledgements

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