ESCUELA TÉCNICA SUPERIOR DE INGENIERÍA (ICAI)

GRADO EN INGENIERÍA ELECTROMECÁNICA

Especialidad Mecánica

DESIGN AND CONVERSION OF A FOUR STROKE ENGINE TO A SIX STROKE ENGINE

Autor: Alvaro Espejo Abela
Director: Matthew McGarry

Madrid
Julio 2018

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DISEÑO Y ADAPTACIÓN DE UN MOTOR DE CUATRO TIEMPOS A UNO DE SEIS TIEMPOS

Autor: Espejo Abela, Álvaro

Director: McGarry, Matthew

Entidad Colaboradora: ICAI – Universidad Pontificia de Comillas, University of San Diego.

RESUMEN DEL PROYECTO

Introducción

El siguiente proyecto tiene como objetivo la investigación y el desarrollo de un motor de seis tiempos. Dado la delicada situación de crisis energética mundial, este proyecto pretende diseñar y crear un motor capaz de mejorar la eficiencia de los motores de cuatro tiempos actuales y que consiga conservar las demás especificaciones. Los motores de hoy en día, aunque han mejorado sustancialmente su eficiencia con el paso de los años, siguen teniendo una eficiencia muy baja (30-40% en la mayoría de los motores de combustión y compresión) puesto que no deja de ser una máquina térmica con elevadas pérdidas. El resto de la energía se entrega al ambiente por sistemas de refrigeración de aire o agua, dependiendo del tipo de motor. Esta idea revolucionaria, basada en el motor de seis tiempos diseñado por Bruce Crower, consiste en añadir dos tiempos adicionales mediante la inyección de agua. El agua tiene dos funciones principales: la refrigeración y la entrega de potencia al motor. El agua, al ser inyectada en el quinto tiempo, absorbe el calor del cilindro y lo utiliza para cambiar de estado líquido a gaseoso. A temperatura ambiente, el agua es capaz de expandirse 1600 veces el volumen que ocupa en su estado líquido. Esta expansión es la responsable de entregar potencia durante el quinto tiempo del motor. Finalmente, la energía que el agua utiliza para la expansión es energía térmica que se extrae durante el último ciclo o sexto ciclo, el de escape. El propósito de este proyecto es adaptar un motor de la forma más fácil, eficiente y económica posible. Además, se trata de responder a la siguiente pregunta: ¿Puede un motor de seis tiempos mejorar la eficiencia de un motor de combustión actual?

Metodología

Para resolver el problema, la adaptación se dividirá en cuatro subsistemas principales: el inyector de agua, el árbol de levas, el piñón de distribución y el motor base. En este proyecto se analizarán diversas posibilidades para el diseño y obtención de los distintos subsistemas que componen el motor. Antes de proceder a la elección final de cada subsistema, se hará un estudio termodinámico para calcular la cantidad necesaria de agua que debe ser inyectada para que el motor opere en todo su rango; un estudio mecánico estático y de fatiga para calcular el diámetro mínimo necesario para el árbol de levas; y un estudio mecánico para el perfil del piñón de distribución del árbol de levas.

Tras el estudio teórico y teniendo en cuenta el presupuesto y demás factores determinantes, se procederá a la elección de cada subsistema para finalmente integrarlos en un único motor. Siguiendo la integración, se realizarán pruebas con el objetivo de averiguar si se ha producido un incremento de la eficiencia en la forma de una reducción del consumo de combustible entregando la misma potencia o una mayor entrega de potencia empleando el mismo combustible.

Soluciones Propuestas

Después de un amplio estudio de distintas soluciones para cada subsistema, se llegó a la siguiente solución. En cuanto al motor base, la elección fue un motor motocicleta Honda XR250 de 250 cc, OVC, de cuatro tiempos y refrigeración por aletas. Para el árbol de levas se decidió mecanizarlo en la universidad, mientras que el piñón se encargó a la distribuidora McMaster Carr. Finalmente, para la inyección del agua se desarrolló un sistema de inyección hidráulico mediante la concatenación de una bomba hidráulica y diversas válvulas con distintas funciones.

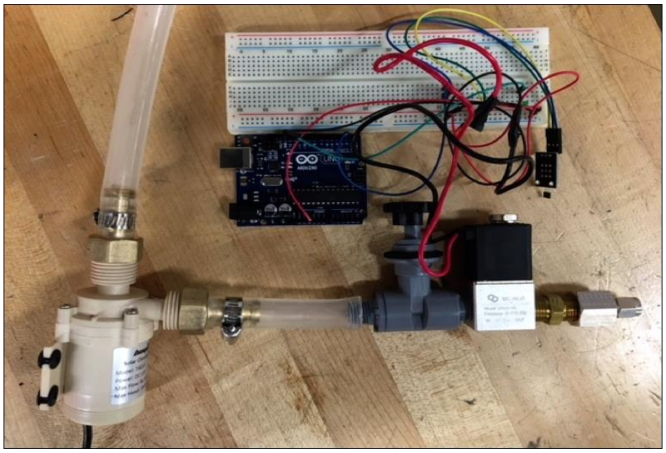

Figura A: Sistema de Inyección de Agua

Fuente: Elaboración Propia

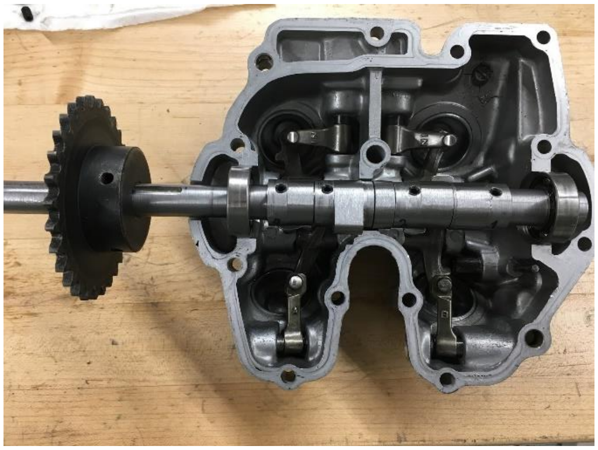

Figura B: Piñón y Árbol de Levas.

Fuente: Elaboración Propia

Figura C: Motor Honda XR250

Fuente: www.honda.com

Resultados

Para este proyecto se obtuvieron resultados teóricos y prácticos para tres de los subsistemas. Para el sistema de inyección mediante el estudio termodinámico se llegó a la siguiente tabla:

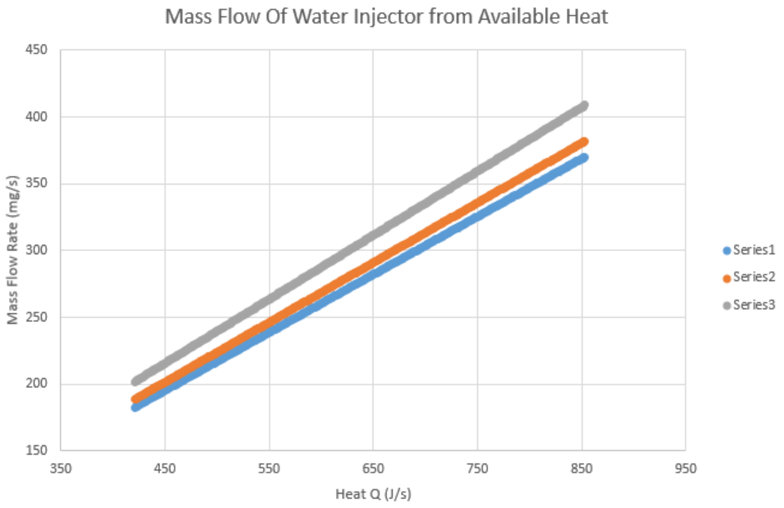

Figura D: Flujo de Agua para cada temperatura de inyección

Fuente: Elaboración Propia

Las series corresponden a la candidad de agua inyectada a tres temperaturas diferentes (25ºC,50ºC y 100ºC en este orden) necesaria para extraer el rango de flujo energético que aparece en el eje x.

En cuanto a los resultados empíricos, se midió el tiempo necesario para llenar 500ml según las vueltas de la valvula tipo aguja con el fin de calcular el flujo másico:

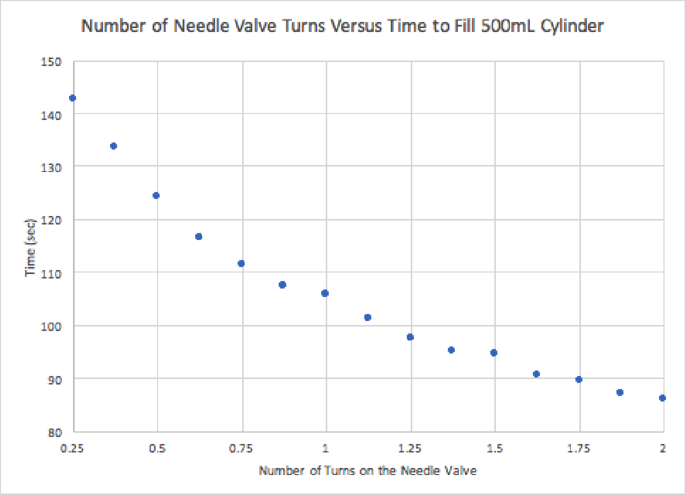

Tabla E: Numero de Vueltas de la Válvula Vs Tiempo

Fuente: Elaboración Propia

Para el arbol de levas se calculó que era necesario un eje de 1.78 pulgadas, aunque se terminó usando un eje de 0.7 pulgadas, ya que el estudio teórico se consideró demasiado conservador y el motor no tenía como objetivo sobrevivir un número elevado de ciclos.

El piñón de distribución se diseño con un diametro necesario para reducir la velocidad a un tercio del valor de la velocidad angular del cigüeñal, debido al incremento del número de tiempos. También se calculó el número de dientes necesarios que resultaron ser 54.

Tras la integración del motor, no hubo tiempo para probar si se consiguió un aumento de la eficiencia del motor, auque el motor fue capaz de arrancar durante un corto periodo de tiempo.

Conclusiones

El hecho de que los motores de seis tiempos utilicen una tecnología que aún no está arraigada en la industria del motor fue uno de los motivos para estudiar, diseñar y fabricar su propio motor de inyección de agua. Es cierto que miles de empresas de motores cuentan con equipos de I + D dedicados que buscan constantemente nuevas y efectivas formas de mejorar los motores existentes o crear otros nuevos, posible motivo por el cual no se ha desarrollado semejante tecnología. Sin embargo, a veces el beneficio que aportan las nuevas tecnologías es incapaz de desbancar a las tecnologías ya establecidas y que ya funcionan. Este cambio generalmente requiere una alta inversión inicial para lograr una buena aceptación en el mercado. Sin embargo, se ha demostrado con este proyecto que es posible crear nuevas tecnologías que mejoren la eficiencia de los motores actuales, aunque muchas veces sean incapaces de sustituir las tecnologías existentes por diversos motivos.

DESIGN AND ADAPTATION OF A FOUR-STROKE ENGINE TO A SIX STROKE ENGINE

Author: Espejo Abela, Álvaro

Director: McGarry, Matthew

Collaborating Entity: ICAI - Universidad Pontificia de Comillas, University of San Diego.

PROJECT SUMMARY

Introduction

The next project aims at the research and development of a six-stroke engine. Given the delicate situation of the world's energy crisis, this project targets at designing and creating an engine capable of improving the efficiency of current four-stroke engines while conserving the previous engine specifications. Today's engines, although they have improved their efficiency over the years, still have a low efficiency (30-40% in most combustion and compression engines) due to elevated thermal losses. The rest of the energy is delivered to the environment by air or water-cooling systems, depending on the type of engine. This revolutionary idea, based on the motor designed by Bruce Crower, works by adding two additional times using water injection. Water has two main functions: cooling and power delivery to the engine. The water, when injected in the fifth stroke, absorbs the heat of the cylinder and uses it to change from liquid to gaseous state. At room temperature, water is able to expand 1600 times the volume it occupies in its liquid state. This expansion is responsible for delivering power during the fifth stroke of the engine. Finally, the energy that the water uses for the expansion is thermal energy that is extracted during the last cycle or sixth cycle, the escape cycle. The purpose of this project is to adapt an engine as easily, efficiently and economically as possible. In addition, it is about answering the following question: Can a six-stroke engine improve the efficiency of an existing combustion engine?

Methodology

To solve the problem, the adaptation will be divided into four main subsystems: the water injector, the camshaft, the timing gear and the base engine. In this project, various possibilities for the design and obtaining of the different subsystems that make up the engine will be analyzed. Before proceeding to the final choice of each subsystem, a thermodynamic study will be made to calculate the necessary amount of water that must be injected for the engine to operate throughout its range; a static and fatigue mechanical study to calculate the minimum diameter necessary for the camshaft; and a mechanical study for the camshaft timing gear profile.

After the theoretical study and taking into account the budget and other determining factors, we will proceed with the choice of each subsystem to finally integrate them into a single engine. Following the integration, tests will be conducted in order to find out if there has been an increase in efficiency in the form of a reduction in fuel consumption by delivering the same power or greater power delivery using the same fuel.

Proposed Solutions

After an extensive study of different solutions for each subsystem, the following solution was reached. As for the base engine, the choice was a 250cc Honda XR250 motorcycle engine, OVC, four-stroke and fin cooling. For the camshaft it was decided to mechanize it in the university, while the timing gear was commissioned to the distributor McMaster Carr. Finally, for the water injection a hydraulic injection system was developed by concatenating a hydraulic pump and several valves with different functions.

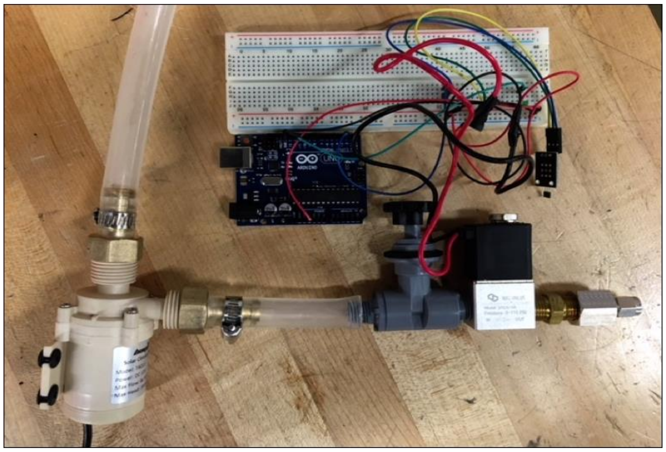

Figure A: Water Injection System

Source: Own Elaboration

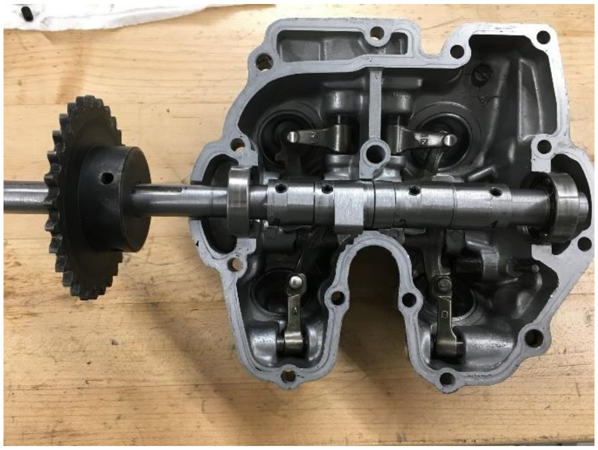

Figure B: Camshaft and Timing gear

Source: Own Elaboration

Figure C: Honda XR250 Engine Illustration

Source: www.honda.com

Results

For this project, theoretical and empirical results were obtained for three of the subsystems. For the injection system through thermodynamic study the following table was obtained:

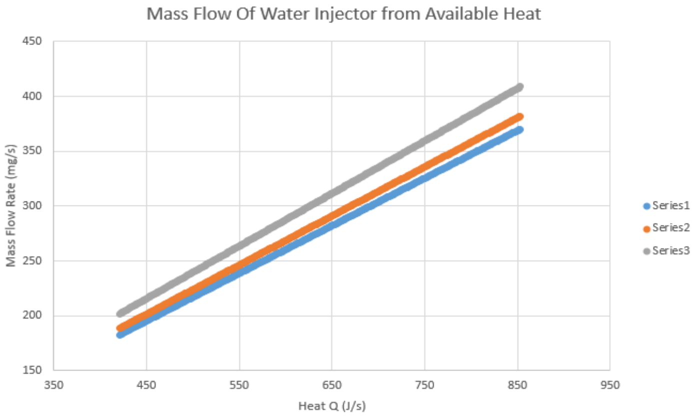

Figure D: Water Flow for each injection temperature

Origin: Own Elaboration

The series correspond to the quantity of water injected at three different temperatures (25ºC, 50ºC and 100ºC in this order) necessary to extract the energy flow range that appears on the x axis. Regarding the empirical results, the time required to fill 500ml according to the turns of the needle-type valve was measured with the purpose of measuring the mass flux:

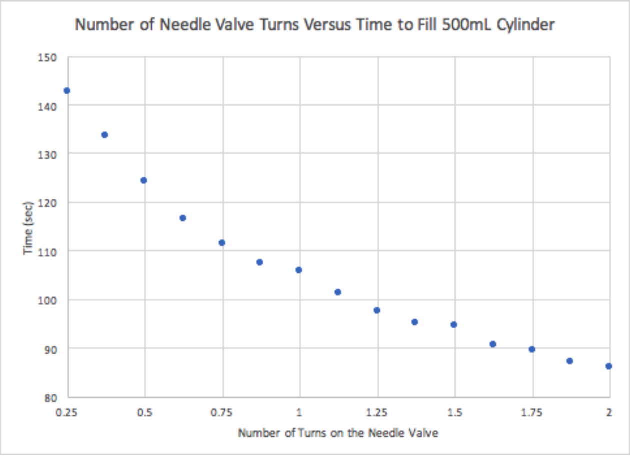

Table A: Number of Turns of the Valve Vs Time

Origin: Own Elaboration

For the camshaft, it was calculated that a 1.78-inch shaft was necessary, although it was completed using a 0.7-inch shaft, since the theoretical study was considered too conservative and the engine was not intended to survive a large number of cycles.

The timing gear was designed with a diameter necessary to reduce the speed to a third of the value of the angular speed of the crankshaft, due to the increase in the number of cycles. The number of necessary teeth turned out to be 54 was also calculated.

After the integration of the engine, there was no time to test whether an increase in engine efficiency was achieved, although the engine was able to start for a short period of time.

Conclusions

The fact that six-stroke engines use a technology that is not yet rooted in the motor industry was one of the reasons to study, design and manufacture their own water injection engine. It is true that thousands of engine companies have dedicated R & D teams that are constantly looking for new and effective ways to improve existing engines or create new ones, a possible reason why such technology has not been developed. However, sometimes the benefit provided by new technologies is unable to unseat existing technologies that already work. This change usually requires a high initial investment to achieve good market acceptance. However, this project has shown that it is possible to create new technologies that improve the efficiency of current engines at a reasonable price, although they are often unable to replace them.

The following project has been designed and manufactured at the University of San Diego, California.

Abstract

Four-stroke gasoline engines are extremely inefficient at utilizing all of the thermal energy released during combustion. Traditionally, excess thermal energy within the cylinder of the engine is simply transferred to the outside environment in order to prevent overheating. It is estimated that 62% of the energy contained in fuel is lost in the form of heat ("Where the Energy Goes", 1).

This project addresses this shortcoming by modifying an existing four-stroke gasoline engine into a prototype that demonstrates a means of recovering and using otherwise wasted heat. After analyzing many approaches, the chosen route has been to modify the engine to run the Crower cycle, a six-stroke cycle which injects water into the cylinder after the combustion products are exhausted. Thanks to the great expansion of water when changing state from liquid to steam, the excess heat produced will convert the water into steam, and the expansion of this steam provides the engine with an additional power stroke. A direct injector and additional exhaust valve are necessary to introduce and evacuate the water and steam. The prototype is broken down into four major subsystems: water injection, camshaft, timing gear and base engine. The custom camshaft is needed in order to actuate the valves at the appropriate times for the modified cycle, and the timing gear must be modified to turn the cam at a speed that allows it to control three revolutions of the crankshaft over the usual two. This project describes in detail the process that has been followed to design and manufacture an engine of these characteristics.

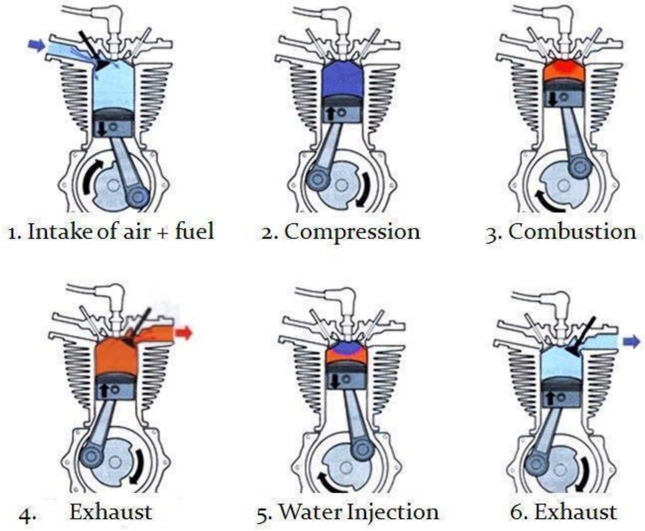

Figure 0:6-stroke Engine Cycle

Source: https://engineeringinsider.org

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1. Context

1.1. Background of Need

Traditional internal combustion engines of any type produce significant quantities of waste heat during their operation by nature of their design. Because all the energy present in an engine is derived from fuel, any heat buildup within the engine, whether from friction or combustion processes, represents fuel that has been consumed without producing any useful work. In addition to this inherent waste, heat buildup within an engine requires additional apparatus to remove it and keep the engine at operating temperature, adding weight, complexity, and points of failure while increasing the amount of back work that must be drawn from the engine's power output.

In a world where so many machines and vehicles are powered by some form of internal combustion engine, fuel efficiency is an extremely high priority and any method that can increase the amount of energy extracted from fuel is worth pursuing, from both economic and resource conservation perspectives. Since waste heat makes up such a high percentage of the energy released from burning fuel, it is a natural area of interest when seeking to eke out additional efficiency.

Because of the widespread use of internal combustion engines and the diversity of applications that employ them, any attempt to harness waste heat that hopes to have a far-reaching impact must fit the form-factor, operating characteristics, and maintenance requirements of existing engines. If capturing waste heat means significant changes to the way internal combustion engines are operated, used, or installed, users will likely forgo any performance gains to avoid investing the initial effort of conversion. Similarly, the cost of producing an engine capable of utilizing waste heat must be comparable to current production costs; if the engine is too expensive and savings from fuel efficiency take too long to outweigh the initial costs customers will not purchase it, and manufacturers have no reason to produce an engine that will not sell.

In other words, this project will serve as a tool to find out the market potential of water injection in combustion engines, without considering economic implications. Previous revolutionary ideas have been around, but they have not unseated traditional 4 stroke engines, even though inventors claim to obtain an increase in efficiency. It is a competition that looks for the balance between efficiency and cost, and 4-stroke engines are by far not the best competitors to have.

1.2. Customer Need Statement

Automotive vehicles have been the primary means of transportation for over 50 years. It has shaped the way to our society moves and operates. In 2017, close to 79 million cars were sold worldwide ("Global Car Sales", 1); the automotive industry is massive. *Auto Alliance* estimates that the automotive industry spends close to $100 billion a year on research and development alone ("Automotive Industry", 1). While it is evident that cars have become an essential building block of modern society, little development has been put towards improving the process the engine undergoes.

Almost every modern four-stroke car or motorcycle engine suffers from three major problems. The most prevalent of these is their inherent inefficiency. Only about 14%–30% of the energy produced from the combustion of the fuel within the engine is used to move it down the road. The rest of the energy created is lost via various vectors, the biggest of which is heat exhaust. A typical car engine loses upwards of 62% of the input energy to heat ("Where the Energy Goes", 1). Engines produce so much heat that an additional water or air cooling system must be implemented in order to radiate the excess and prevent the engine from overheating and failing. Additionally, traditional four-stroke Otto cycle engines release carbon dioxide and other greenhouse gases into the surrounding environment. This has been a growing issue in recent years as it is linked to global warming. Lastly, internal combustion engines run on fossil fuels, which have finite supply and are susceptible to rapid price fluctuations. There is a need for automotive engine to be redesigned to increase its thermal efficiency, fuel efficiency, and decrease its emissions.

This problem is hard to solve because significant resources are continually invested in improving and refining the current four-stroke engines, or in other forms like electric vehicles. These last ones have recently experienced a significant growth and expansion worldwide, as their characteristics are rapidly catching up traditional combustion and compression engines.

Additionally, a lot of the subsystems within an automobile are dependent on the current setup (heater, catalytic converter, etc.). With current methods of heat recapture output usually comes in the form or generated electrical power, which is difficult to convey to the wheels and has limited ancillary use.

1.3.1. Prior Work (State of the Art)

BMW M4 GTS Water Injection System

BMW has developed a water injection technology in which distilled water is sprayed as a mist into the intake manifold, lowering the air temperature for about 30 ºC. The lower temperatures increase oxygen density which at the same time increases overall power. This technology is not new, as water injection was first used in aircraft during the WII. Such system obtains a 49 horsepower increase compared to the previous BMW M4 (both have the same engine displacement). This system does not base its technology on a six-cycle engine, but it is the only market available technology that uses water injection for increasing efficiency and power.

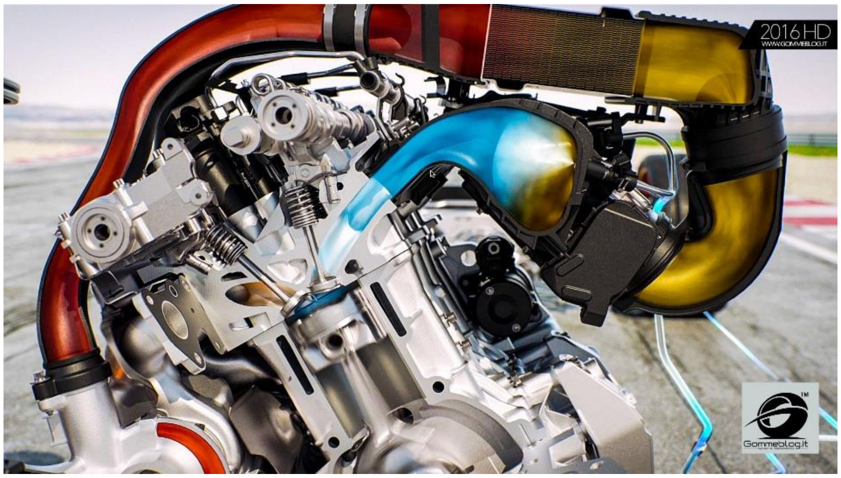


Figure 1: BMW M4 GTS water injection system illustration

Source: www.bmwblog.com

The Crower Engine (***Patent: US20070022977A1)***

Bruce Crower created a six-stroke engine prototype that used water vaporization for an additional power stroke of the Otto cycle. Water is injected into the engine cylinder right after the exhaust stroke and is vaporized into steam due to the waste heat within the engine. The expansion of the steam pushes down on the piston thus giving the engine cycle an additional power stroke. Crower claimed a 40% gain in engine efficiency. Its engine could run without the need of having a cooling system. The prototype did have fins on it, but Bruce Crower claims that the engine would be more efficient without them, because this would mean more thermal energy for the water injection/expansion stroke. Crower, in an interview with AutoWeek, an American motor magazine, said that *"It'll run for an hour and you can literally put your hand on it. It's warm, yeah, but it's not scorching hot. Any conventional engine running without a water jacket or fins, you couldn't do that."*

Just as this project intends, Crower only developed its engine in a combustion one (gasoline, 4 stroke), although he believed such technology could have the same application with diesel-based engines.

This is the type of cycle this project tries to implement without exhaust recompression; Crower himself has abandoned the project.

Figure 2: Crower with his Prototype

Source: http://autoweek.com

The Velozeta Engine (*Patent: US20160032821A1*)

A team of mechanical engineering students created a six-stroke engine, the Velozeta engine. Fresh air was injected into the engine cylinder after the exhaust stroke, which expanded due to heat and provided a second power stroke. Such engine was able to reduce fuel consumption by 40% leading to a large air pollution reduction. Although the power to weight ratio was smaller than that of a four-stroke engine, the Velozeta engine achieve a major reduction in carbon monoxide pollution. This engine was developed in 2005 at the College of Engineering, Trivandrum. The group members were the following: Mr. Boby Sebastian, Mr. U Krishnaraj, Mr. Aaron Joseph and Mr. Arun Nair George.

The Bajulaz Six-stroke Engine (*Patent: US4809511A and US4513568A)*

Roger Bajulaz created a six-stroke engine in 1989 that uses pre-heated air to provide and additional expansion stroke to the Otto cycle. The engine cylinder head is modified to have a combustion chamber and air-preheating chamber. Burning of the fuel in the combustion chamber heats the air in the chamber surrounding it. As the air is heated, it expands into high pressure which is then used to provide an addition power stroke. Such engine claimed a 40% fuel consumption reduction, to be multifuel, air pollution reduction and a comparable cost to a traditional 4 stroke engine.

Gerard B. Schmitz Six-Stroke Engine (*Patent: US4917054 A)*

Gerard B. Schmitz patented an engine design requiring multiple cylinders that splits the events of the six-stroke cycle among separate combustion chambers. 30% improvements in efficiency are claimed. Gerard B. Schmitz announced in the *International Journal of Engineering Development and Research* that the advantages of six-stroke engines would clearly outweigh its disadvantages if 4 stroke engines where to be unseated. These advantages included the fact that no cooling would be required, a reduction in fuel consumption, a reduction in pollution, two work cycles against one work cycle, increased stroke volume and high adaptability to different fuels. On the other hand, disadvantages included a high initial cost due to change in gear structure, high manufacturing costs and an increased engine size due to an increased number of strokes.

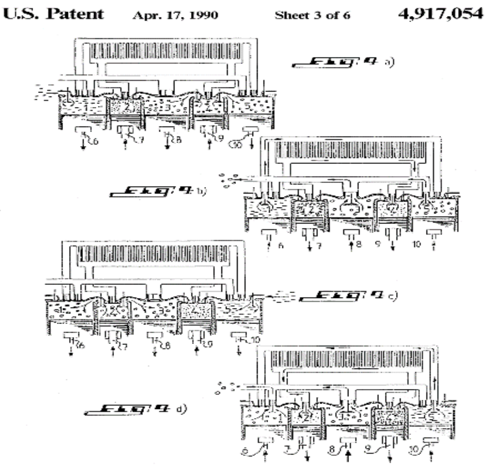


Figure 3: Gerard B. Schmitz 6 Stroke Engine

Source: http://www.ilmor.co.uk

2. Problem Definition

There are two problems that have to be addressed: finding a means to convert waste heat into useful work and deciding how best to execute that solution in the prototype.

Problem 1, Waste Heat Production:

- Traditional internal combustion engines waste as much as 62% of the fuel they consume as waste heat.
- Existing solutions to this problem generate power from heat released by the exhaust or radiator.
- These solutions only produce electrical energy, which is of limited use to a vehicle, rather than adding to the engine output.
- These solutions also require the existing cooling apparatus to remain in place, and as such only add to the complexity, weight, and cost of the system as a whole.

Problem 2, Prototype Design:

- How can waste heat be recaptured within the operation of the engine itself?
- Are there alternatives to the Crower cycle that accomplish this?
- How can the changes necessary to run such a cycle within the time and budgetary constraints of this project be implemented?
- What other problems might be brought on as a result of those modifications?

2.1.1. Functional Requirements

1. To capture waste heat produced from a standard Otto-cycle engine by modification the engine. (H)
2. The modified engine can have a similar power output compared to the original. (H)
3. Achieve a smaller fuel consumption than the non-modified engine.
4. Working prototype that demonstrates a 6-stroke Otto-cycle.

2.1.2. Physical Requirements

1. The modified engine must fit on a workshop bench.
2. The engine must have all the same material properties of a typical engine block.
3. The camshaft must be an overhead camshaft that controls each valve independently.
4. Exhaust pipe to allow for expulsion of steam and residual water.
5. Space on top of engine block to allow for machining of water injector port.
6. A water injector must be able to connect to the timing gear.

2.2. Assumptions

The following is a list of assumptions that must be presumed for the success of this project. The list includes assumptions about the original four stroke engine before it is modified, as well as, basic assumptions while operating the modified engine.

1. The prototype will use a measurable source of input power.
2. It will be possible to measure the output energy of the prototype produces.
3. It will be possible to measure the heat exchange within the prototype.
4. Mixtures used within the prototype does not have any major impurities.
5. The emissions from prototype will pass EPA standards.
6. The prototype is able to be tested in basement or parking lot of Loma Hall.
7. The engine and testing system will be able to be moved around easily.

2.3. Constraints

1. Project costs must not exceed budget of $2900.
2. Project must be completed by May 11th, 2018.
3. Project design complexity must be within the capabilities of the designer.
4. Project must meet university regulations for noise and safety, as testing will be done on campus.

5. Physical apparatus must be able to be transported by hand, limiting weight to around 100lbs.
6. Physical apparatus must fit on a workshop bench, limiting footprint to around 36”x96” conservatively.
7. Components are limited to budget constraints, market availability and University of San Diego machinery.

3. Concept Development

3.1.1. Functional Decomposition

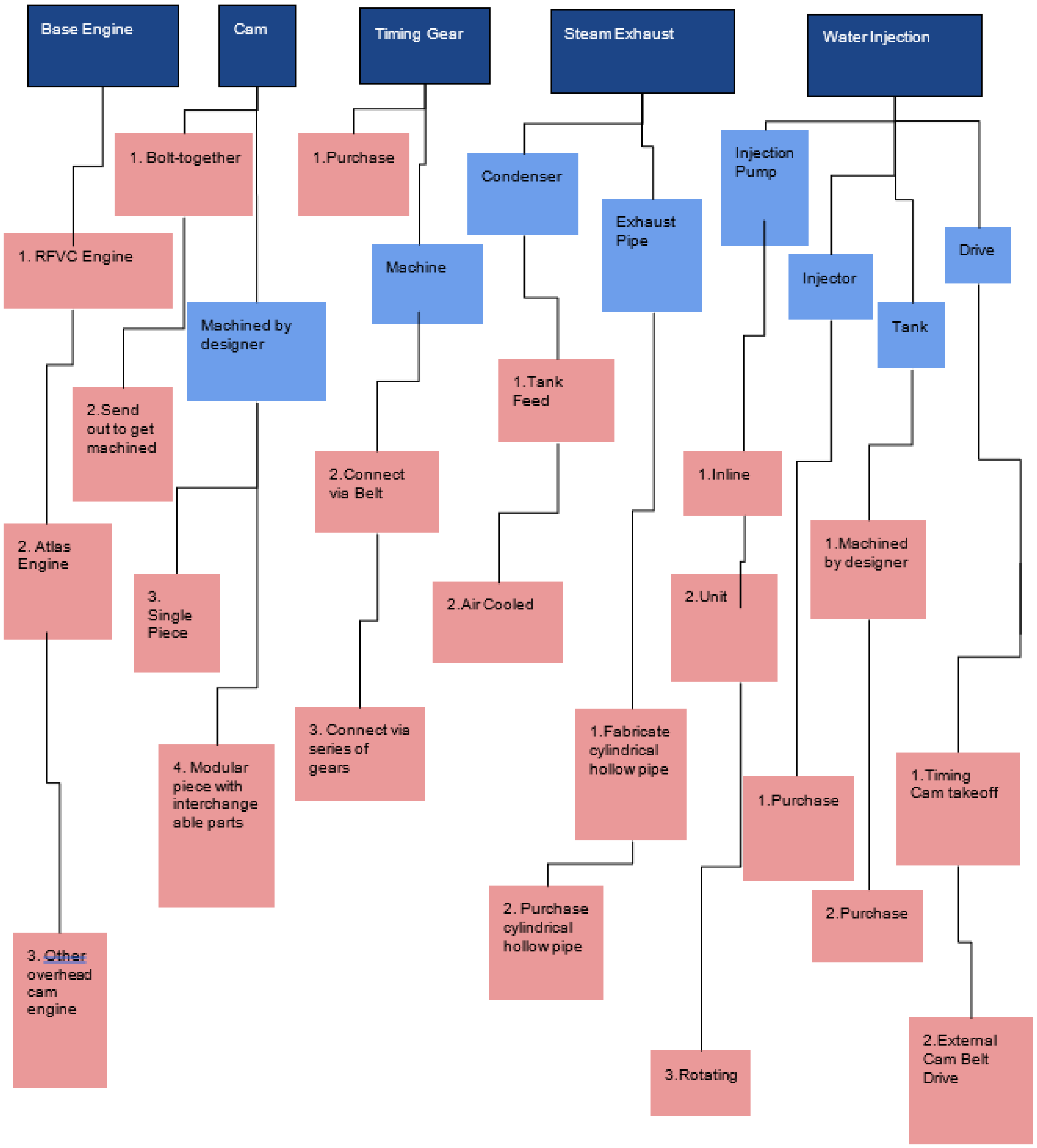


Figure 4: Engine Functional Decomposition

Source: Own Elaboration

3.1.2. Camshaft configuration

The following three sections describe potential camshaft configurations to correctly operate intake/exhaust valves in relation to piston location. This section contains the advantages and disadvantages the different components have.

3.1.2.a. Outsourced Single Piece

Design:

- Single solid machined camshaft with correct lobe locations to operate fuel intake/exhaust and water intake/exhaust.

Advantages:

- Made of high quality material.
- Made with high accuracy and precision.
- Part will be durable and reliable for application.

Disadvantages:

- Expensive to have this part machined.
- This part will not be able to be altered once changed.

3.1.2.b. Custom Machined Single Piece

Design:

- Single solid machined camshaft with correct lobe locations to operate fuel intake/exhaust and water intake/exhaust.

Advantages:

- Inexpensive to fabricate this.
- Durable and reliable for application.

Disadvantages:

- Difficult to fabricate, requires machine knowledge.
- Mistakes would be time-consuming, as alterations to part would be difficult.

3.1.2.c. Custom Machined Modular

Design:

- Machined camshaft consisting of a base cam rod and four adjustable cam lobes that can be locked in place at any location along the rod.

Advantages:

- Can be fabricated using CNC machine.
- Can be altered with ease to fit the need of application.
- Inexpensive to fabricate.

Disadvantages:

- Not as strong as a single piece camshaft.
- High number of fabricated parts to make assembly.

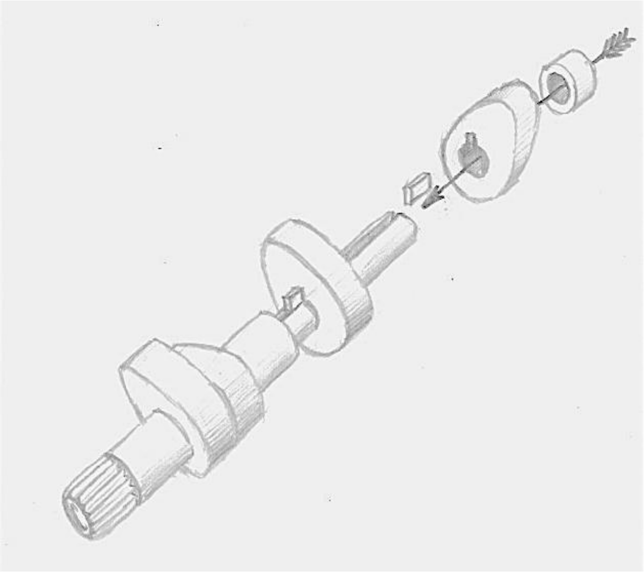


Figure 5: Custom Modular Camshaft Schematic

Source: Own Elaboration

3.1.3. Timing Drive

The following section discusses options for reducing the timing speed from ½ to ⅓ crank speed in order to allow for two additional strokes.

3.1.3.a. Fabricate

Design:

- Machine a unique custom gear matching the original tooth profile at 150% diameter.
- Machined from steel.

Advantages:

- Inexpensive to manufacture.
- Gear fit can be tested and adjusted if necessary.

Disadvantages:

- Time intensive to design and machine gear with precision.

3.1.3.b. Salvage

Design:

- Scavenge for a matching set of timing gears that will provide the desired timing speed.

Advantages:

- Inexpensive to purchase a scavenged set of timing gears.
- Large abundance of parts that can be scavenged.

Disadvantages:

- Difficulty in finding a matching pair to achieve desired timing speed.
- Difficulty in finding a gear set that will fit correctly.
- Difficulty in determining the quality of the part.

3.1.3.c. Outsource

Design:

- Commission a fabrication firm to create a custom gear matching the original tooth profile at 150% diameter.

Advantages:

- Parts will be made with high quality material.

- Parts will be machined with high accuracy and precision.
- Parts will be available in a short amount of time.

Disadvantages:

- Expensive to outsource this type of machining.
- Replacements or adjustments are equally expensive.
- Still requires time investment to design part.
- Allows for a small margin of error.

3.1.4. Water Injector Pump Types

The following section discusses different pump types that can be modified to inject precise amounts of water into the cylinder under pressure.

3.1.4.a. Unit Injector

Design:

- Combined injector and pump in single housing.
- Solenoid or cam driven.
- Mounted in injector port.

Advantages:

- Self-contained, requires no high-pressure plumbing.
- Electronic or mechanical actuation.
- Electronic or mechanical volume control.
- Inexpensive.
- Modular/individualized, install one per cylinder.
- Maintenance is relatively simple due to pump being easy to exchange.

Disadvantages:

- Takes up valuable space above the head.
- Requires dedicated local cam, or electronics.

3.1.4.b. Unit Pump

Design:

- Cam driven reciprocating pump.
- High pressure line to remote injector.
- Mounted in block.

Advantages:

- Electronic or mechanical flow control.
- Inexpensive.
- Electronic or mechanical volume control.
- Modular/individualized, install one per cylinder.

Disadvantages:

- Requires dedicated cam.
- Requires high precision purpose made housing.
- Requires high pressure plumbing to injector.

Figure 6: Unit Pump Illustration

Source: www.indiamart.com

3.1.4.c. Inline Pump

Design:

- Self-contained pump, throttle, drive, timing, and governor assembly.
- Within the pump, each cylinder has a dedicated plunger running from a shared cam and volume control.
- As the camshaft rotates, the appropriate plunger delivers fuel to its corresponding

injector at the precise time needed to ignite the charge.

- Pumps for all cylinders in the engine combined in one unit.

Advantages:

- Since it is self-contained the system is self-governing.
- Great for multiple cylinder engines that need to synchronize several injectors.
- Requires only belt or chain drive, cam is internal.
- Can be mounted anywhere.

Disadvantages:

- Expensive to purchase and maintain due to high tolerances.
- Many intricate pieces increase probability of failure.
- Requires high pressure plumbing to injector.
- Pump must match cylinder count or have wasted outputs and incorrect timing.

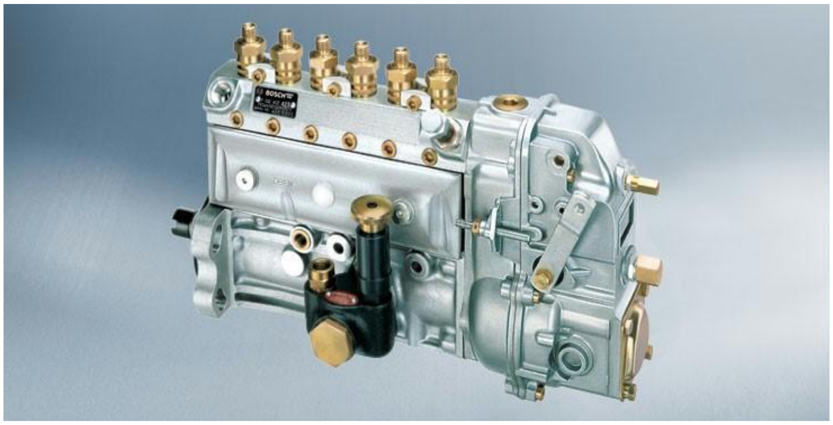


Figure 7: Inline Pump Illustration

Source: www.indiamart.com

3.1.4.d. Rotary Pump

Design:

- Radial version of inline pump.
- Multiple plungers arranged around a single cam lobe, which actuates them in order as it rotates.
- Self-contained pump, throttle, drive, timing, and governor assembly.

Advantages:

- Rotary pumps are more compact, therefore have a smaller overall package size.
- Since it is self-contained the system is self-governing.
- Can be mounted anywhere.
- Requires only chain or belt drive, cam is internal.
- Less expensive than inline pumps.

Disadvantages:

- Still expensive.
- More difficult to adapt and maintain due to less modular nature.
- Many intricate pieces increase probability of failure.
- Requires high pressure line to injector.
- Pump must match cylinder count or have wasted outputs and incorrect timing.

Figure 8: Rotary Pump Illustration

Source: www.indiamart.com

3.1.4.e. Water Pump System

Design:

- Water pump regulated by a mouse valve.
- Single directional motion of water controlled by a check valve.
- Opening/Closing of controlled by Arduino Genuino UNO.

Advantages

- Economical.
- Easy to control water injection rate by changing Arduino Genuino UNO code.
- Can be mounted anywhere.

Disadvantages

- Several intricate pieces increase probability of failure.

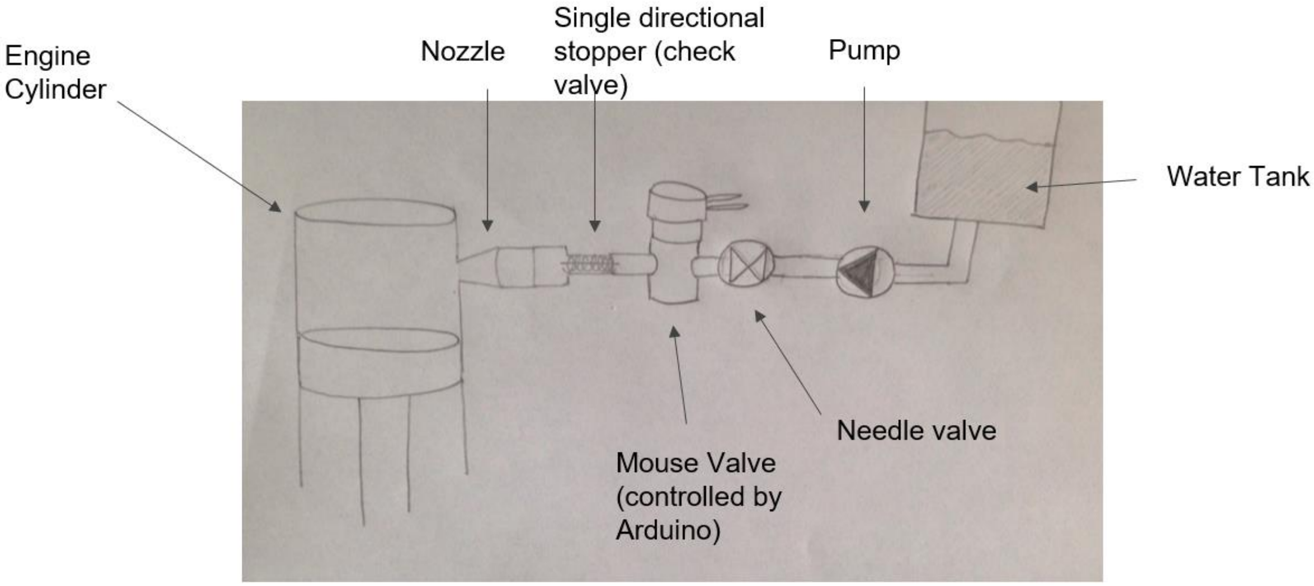


Figure 9: Water Pump System Illustration

Source: Own Elaboration

3.1.5 Base Engine Selection

There are far too many production gasoline engines that could potentially serve as the basis for this project to list all of them here, so this section will simply describe the attributes that would be most conducive to making the modifications required for this project.

1. **Single cylinder** - aside from decreased cost compared with multiple cylinders, using a single cylinder engine eliminates the need to coordinate the timing of cycle events across multiple combustion chambers.

2. **Overhead cam** – due to the increased size of the timing gear, the distance between the timing gears in a chain or belt driven overhead cam is valuable as it eliminates the need to relocate the cam bearings.
3. **Four valve** - multiple exhaust valves permits the usage of stock cam profiles at different phases since the engine must open the exhausts twice during the cycle.
4. **Dedicated cam lobes** - similarly, one cam lobe per valve enables programming of two separate exhaust events into the cam without unusual geometries by simply opening a one exhaust valve per event.
5. **Air cooled** - the absence of a water jacket means that boring injector ports into the head will not cause coolant leaks.
6. **Wasted spark** - a spark event every revolution of the crank means that the ignition timing does not need be altered to compensate for the extra revolution per cycle.

3.2. Governing Principles

Below are the areas of engineering that this project involves:

- Fluid Dynamics (Pumping and Water Injection)
- Thermodynamics (Otto-cycle and Water: Liquid to Vapor)
- Heat Transfer (Waste Heat Transfer to Injected Water)
- Solid Mechanics / FEA (Stress and Strain on Machined Components)
- Material Science (Material Selection)
- Manufacturability (Machining)
- Kinematics (Timing Gears, Camshaft, and Water Injection)
- Design of Machine Elements (Fatigue Failure for Machined Components)
- Tribology (Bearings, Lubrication, and Wear on Machined Components)

3.3. Analysis

3.3.1. Mass Flow Rate for Water Injection

The following analysis demonstrates the relationship between the amount of waste heat available in the engine and the amount of water that can be converted into vapor. To perform the analysis a few **assumptions** need to be made about the system:

- The amount of heat available to be used from combustion is at most 33% of the total heat.
- The analysis will be performed on the assumption that the injected water temperature is 25, 50, and 100 degrees Celsius.
- The mass flow rate of fuel from the fuel injector is approximately 5.5 mg/min.

The total amount of heat released from combustion is about 47 MJ/kg; approximately 66% of this heat is lost and approximately 33% of that heat is lost to engine cooling. This is the theoretical maximum amount of heat the cylinder have to convert water into steam

$$Q_{in} = (0.66)(47) \ = \ 31.02(0.3) = 9.306 \text{ MJ/kg} = 9306 \text{ kJ/kg}$$

$$m^{\cdot} = 5.5 \, \frac{mg}{min} = 0.0917 \, \frac{mg}{s}$$

$$Q_{in}^{\cdot} = m^{\cdot}(Q_{in}) \ = (0.0917 \, \tfrac{mg}{s})(9306 \, \tfrac{kJ}{s}) \ = 853.4 \text{J/s}$$

From the saturated water table, the internal energy of water is as follows:

- At 25℃: $u_f = 104.83$kJ/kg and $u_g = 2409.1$kJ/kg
- At 50℃: $u_f = 209.47$kJ/kg and $u_g = 2443.0$kJ/kg
- At 100℃: $u_f = 419.39$kJ/kg and $u_g = 2506.0$kJ/kg

Now looking at the water injection, to determine the correct mass flow rate for water the following equation is used:

$$Q_{in}^{\cdot} = m^{\cdot}(u_g - u_f) \quad \Rightarrow \quad m^{\cdot} = \frac{Q_{in}^{\cdot}}{(u_g - u_f)}$$

Here are plots of the mass flow rate of water need compared to the available heat ranging from 1421 kJ/kg (ideal) to 0 kJ/kg at the three different temperatures mentioned above:

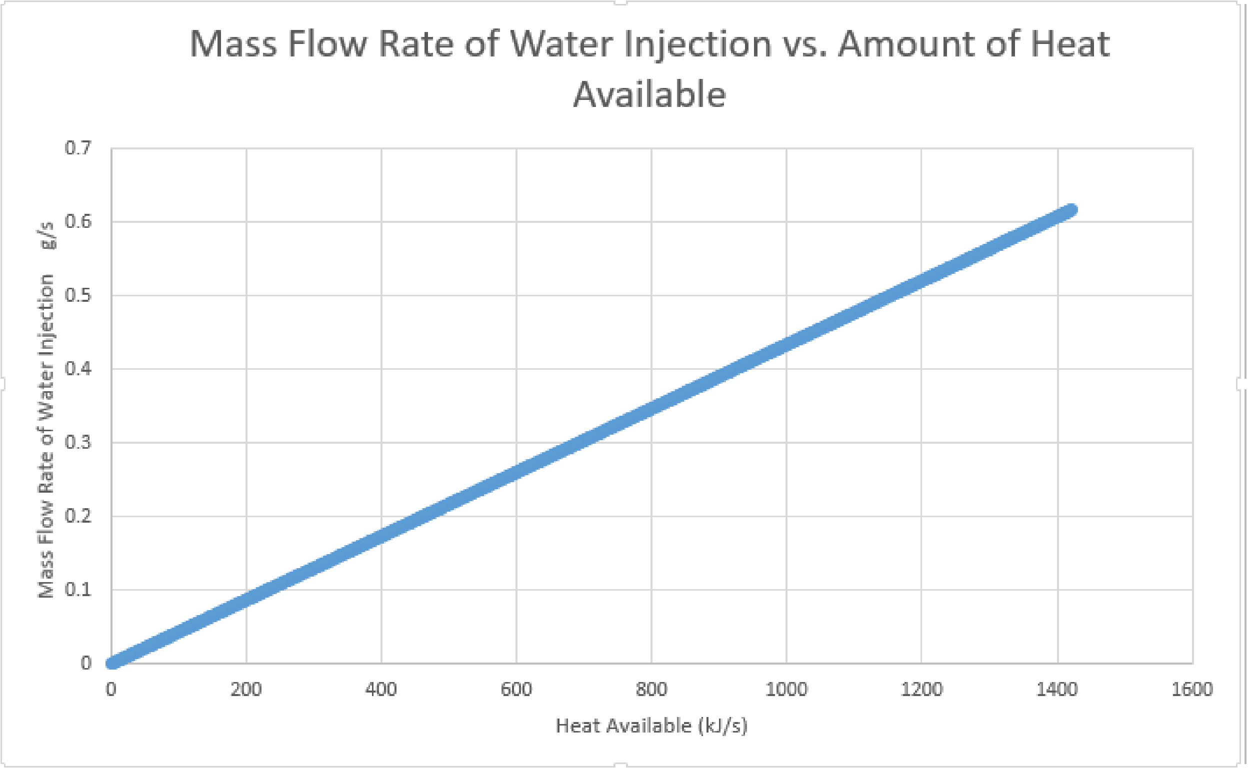


Figure 10: Mass Flow Rate of Water Injected at 25℃ versus Amount of Heat Available

Source: Own Elaboration

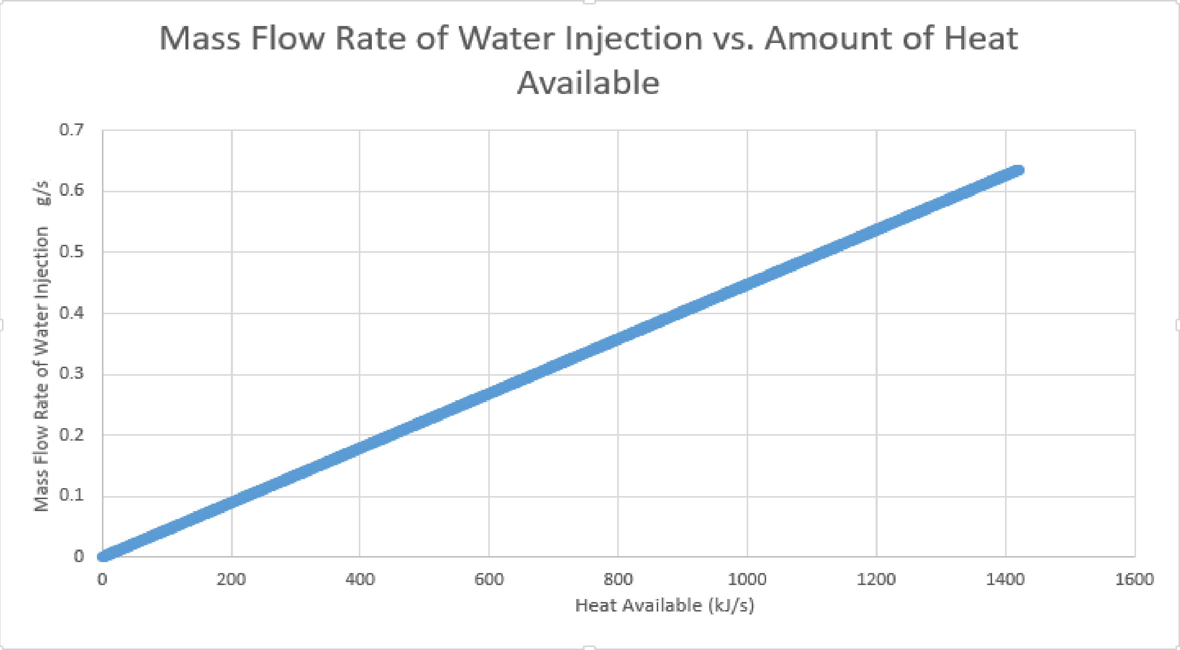


Figure 11: Mass Flow Rate of Water Injected at 50℃ vs Amount of Heat Available

Source: Own Elaboration

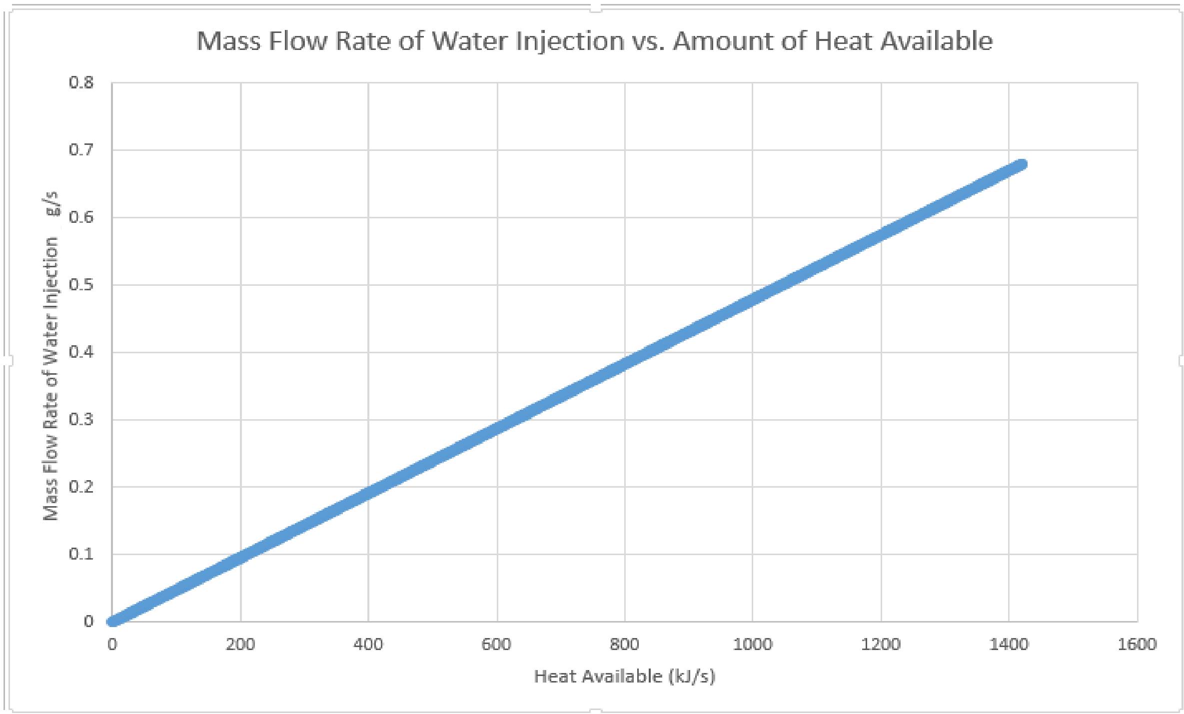


Figure 12: Mass Flow Rate of Water Injected at 100℃ vs Amount of Heat Available

Source: Own Elaboration

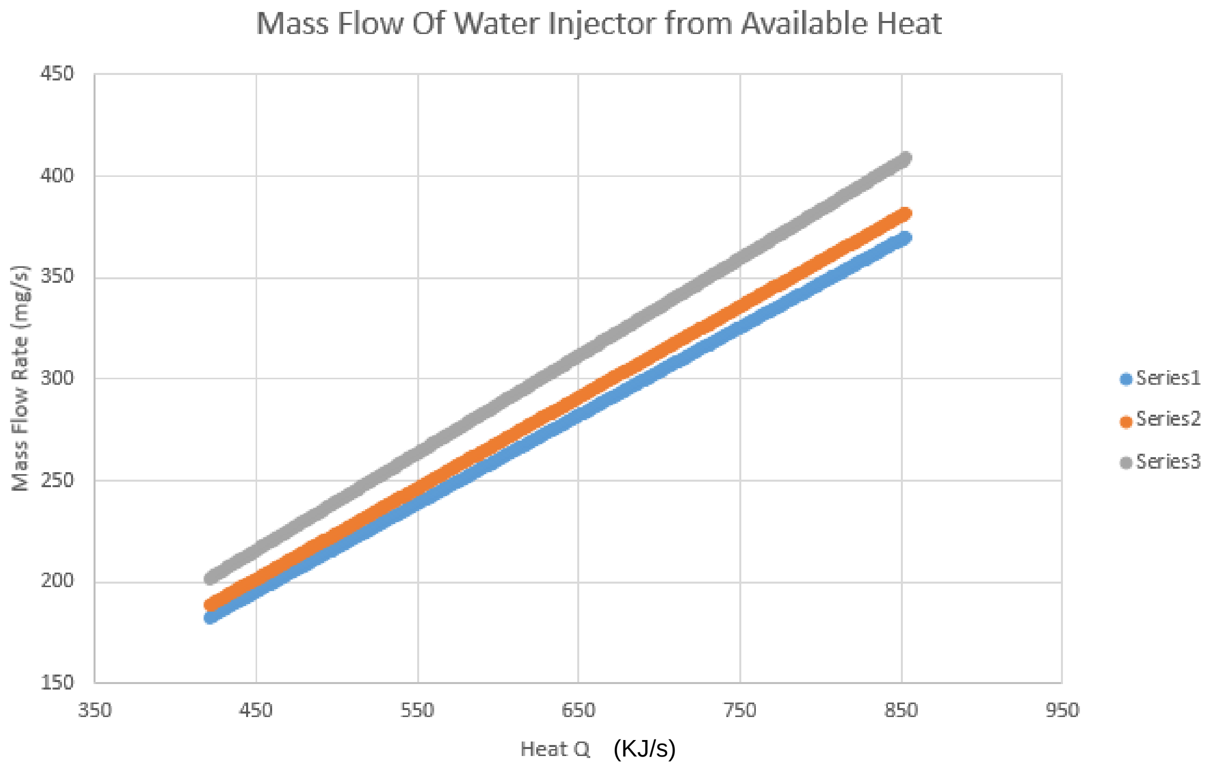


Figure 13: Mass Flow Rate of Water Injected at 25℃, 50℃ and 100℃ vs Amount of Heat Available

Source: Own Elaboration

3.3.2. Gear Ratio for Timing Drive

The following analysis demonstrates the calculations for modifying the timing drive ratio through the use of gears. The velocity ratio (m_v) between gears shows relationship between angular speed (w) and the number of teeth on each gear (N). Also, a term call diametral pitch (p_d) is used in determining the parameters for the gear teeth during the fabrication process. To perform the analysis, some assumptions have to be made:

- The velocity ratio (m_v) is equal to ⅓ due to modification from a four-stroke engine to a six-stroke engine.
- Pinion gear teeth number (N_{in}) has to be ≥19 to eliminate interference and undercutting (Norton, 725).
- The pitch diameter will vary ($75 \text{ in} \leq d_{pitch} \leq 3 \text{ in}$).

$$m_v = r_{in}/r_{out} = w_{out}/w_{in} = N_{in}/N_{out} \quad \Rightarrow \quad 0.333 = 19/N_{out} \Rightarrow N_{out} \geq 57 \text{ teeth.}$$

The number comes out to be exactly 57 teeth if the modulus of the gears are kept the same. Increasing the number of teeth would mean that the diametral pitch should be increased or the modulus would have to be changed. Increasing the diametral pitch would affect the output speed while changing the modulus would break the gearing condition. The final decision was to externally mount the timing gear, which meant that a new crankshaft gear had to be obtained.

However, only for study purposes, the following graph shows the relationship between diametral pitch and pitch diameter ($p_d = N/ d_{pitch}$). Varying the pitch diameter (0.5 in -3 in), the following graph shows different values of the diametral pitch using the minimal number of teeth required (N = 57).

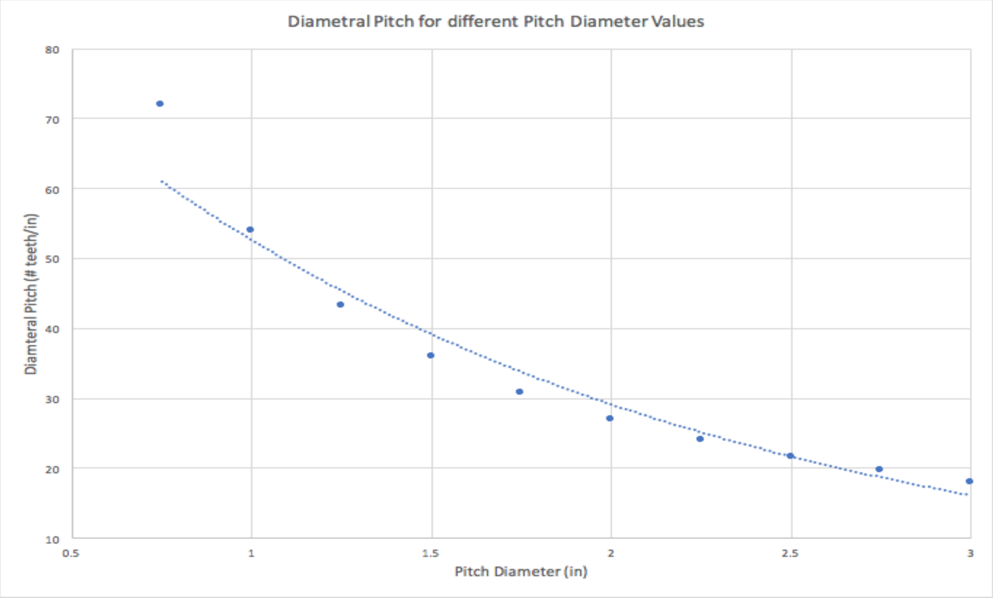


Figure 14: Diametral Pitch for Different Pitch Diameter Values

Source: Own Elaboration

To help the fabrication process, AGMA developed dimension standards gear production:

Parameter	**Coarse Pitch ($p_d < 20$)**	**Fine Pitch ($p_d \geq 20$)**
Addendum *a*	$1.000/p_d$	$1.000/p_d$
Dedendum b	$1.250/p_d$	$1.250/p_d$

Working Depth	$2.000/p_d$	$2.000/p_d$
Whole Depth	$2.250/p_d$	$2.250/p_d$ + 0.002 in
Circular Tooth Thickness	$1.571/p_d$	$1.571/p_d$
Fillet Radius	$0.300/p_d$	*not standardized*
Minimum Basic Clearance	$0.250/p_d$	$0.200/p_d$ + 0.002 in
Minimum width of Top Land	$0.250/p_d$	*not standardized*
Pressure Angle ϕ	20° or 25°	20°
Clearance	$0.350/p_d$	$0.350/p_d$ + 0.002 in

Table 1: AGMA Full-Depth Gear Tooth Specifications

Source: http://www.me.unm.edu

3.3.3 Designing Diameter of Camshaft

Due to the engine prototype design, a custom camshaft is required. In discerning a proper diameter for the custom camshaft, an analysis of the loading stresses present must be conducted. From the selected base engine, Honda XR250, the following parameters are given:

- Power (P) = 24.56 hp
- Angular velocity (ω) =8000 rpm
- Bore = 2.874 in (73 mm)

For this analysis, four cam lobes must be present to account for the four-valve system. It is assumed that the distance between the two supports are the same length of the bore (L= 2.874 in), as well as, the four cam lobes are placed even between those two supports at a distance of b= 0.575 in. Furthermore, it is assumed the camshaft timing gear will be place next to the second support at a distance of b= 0.575 in. For simplistic sake, the stress angle (ϕ) of the timing gear will be negligible. Additional assumptions are given below:

Assumptions:

- Shaft is in Steady Torsion (T_A=0) and Fully Reversed Bending (M_m=0).
- The length between the two supports are equal to the bore diameter (L= 5b= 2.874)
- Cam Lobe Max Diameter (d_{lobe})= 3 in
- Gear Pitch Diameter (d_g)= 1.5 in
- 50% reliability at preliminary stage: C_{reliab} = 1
- Cold Rolled: C_{temp} = 1
- C_{size} = 1 *May be adjusted later
- Due to bending and torsion loading: C_{load} = 1
- Notch sensitivity (q) =0.5 ; K_t = 3.5
- ASME recommendation: torsional fatigue stress factors K_{fsm}= 1

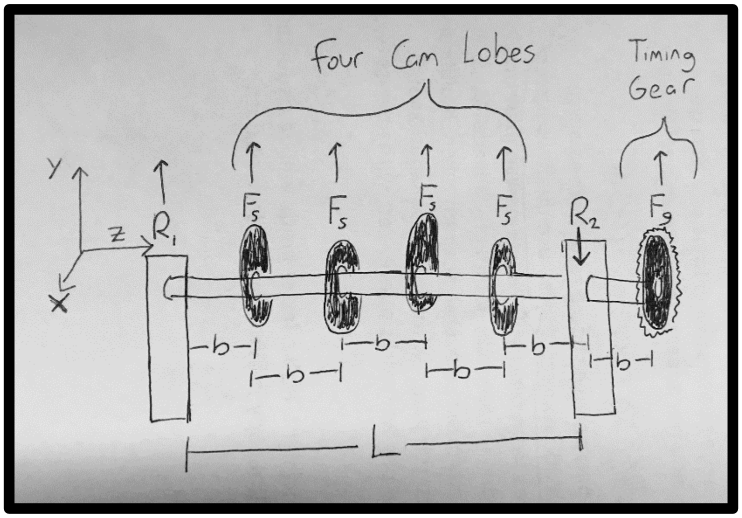


Figure 15: Camshaft Free Body Diagram

Source: Own Elaboration

Bending Stress Calculations:

- $T_m = P/\omega$ =193.48 lb-in
- $F_n= 2T_m/d_{lobe}$ = 129 lb.
- $F_s= 1.5F_n$= 193.58 lb.
- $F_g= 2T_m/d_g$ = 257.97 lb.
- $\Sigma M= 0 \Rightarrow R_2$ = -1,857.4 lb

- $\Sigma F_y = 0 \Rightarrow R_1 = 825.51$ lb

Singularity Function :

- $M = R_1\langle z-0\rangle^1 + F_s\langle z-b\rangle^1 + F_s\langle z-2b\rangle^1 + F_s\langle z-3b\rangle^1 + F_s\langle z-4b\rangle^1 – R_2\langle z-5b\rangle^1 + F_g\langle z-6b\rangle^1$

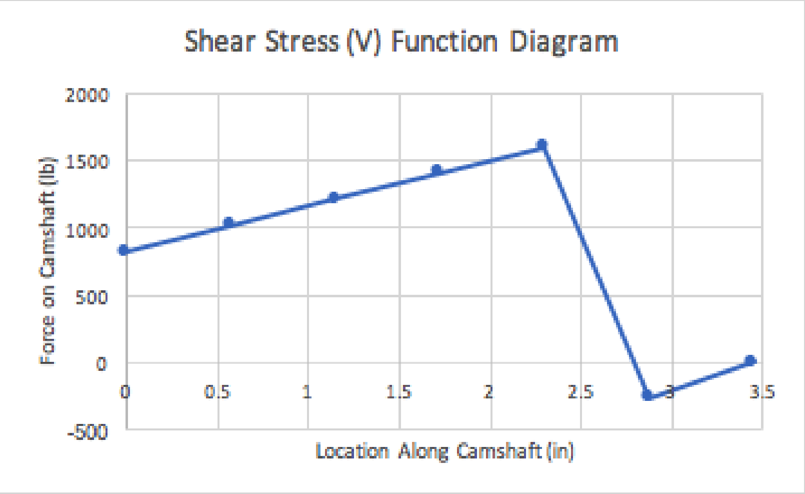


Figure 16: Shear Stress Function Diagram

Source: Own Elaboration

Moment is at a maximum when the shear diagram (V=0). This occurs @ z= L= 5b = 2.874 in. Plugging z = 2.874 in into the singularity function:

- $M_{max} = R_1(2.874) + F_s(2.874-b) + F_s\langle 2.874-2b) + F_s(2.874-3b) + F_s(2.874-4b)$
- $M_{max} = 3{,}484.22$ lb-in.

Fatigue Stress Calculations:

Before solving the corrected fatigue strength (S_f) for the shaft, first a material must be selected. Due to the availability and inexpensiveness, for these calculation SAE 1020 low-carbon, cold-rolled steel is used. This grade of steel has an ultimate tensile strength (S_{ut}) of 65 kpsi and a yield strength (S_y) of 38 kspi. This material has a low notch sensitivity which is ideal for keyways.

- $S_{f'} = 0.5S_{ut} = 32{,}500$ psi
- $C_{surf} = A(S_{ut})^b = 0.89$ where cold-rolled: A=2.7; b= -.265
- $S_f = C_{load}\ C_{size}C_{surf}C_{temp}C_{reliab}S_{f'} = 29{,}030$ psi

- $K_f = 1 + q(K_t - 1) = 2.25$

AMSE Required Diameter Calculations:

$$d = \left\{ \frac{32N_f}{\pi} \left[\left(K_f \frac{M_a}{S_f} \right)^2 + \frac{3}{4} \left(K_{fsm} \frac{T_m}{S_y} \right)^2 \right]^{1/2} \right\}^{1/3}$$

Using the equation given above, the following graph shows the relationship between the desired safety factor (N_f) and the AMSE mandated shaft diameter (d).

- @ $N_f = 2$; the required AMSE camshaft diameter = **1.78 in**

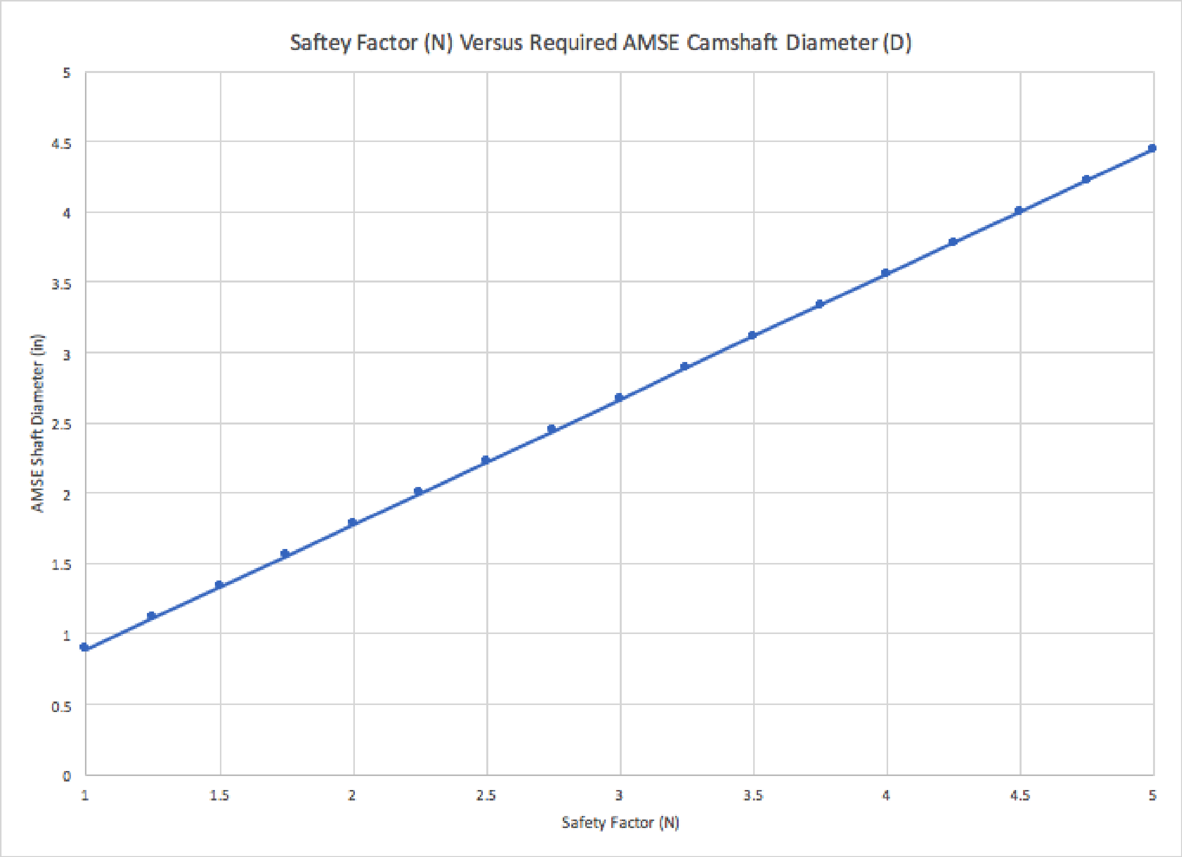


Figure 17: Safety Factor vs Required AMSE Camshaft Diameter

Source: Own Elaboration

3.3.3 Steam Power

The following analysis demonstrates the relationship between the amount of steam pressure inside the engine cylinder and amount of power it applies to the piston. To calculate power use the following equation:

$$Power = (psi) \times \left(\left(\frac{Bore}{2}\right)^2 \times \pi\right) \times \left(\frac{rpm}{3}\right) \times (Stroke)$$

Additionally, the analysis will be performed on four potential engine considerations operating at the specified maximum power output.

- **Honda MSK 125**
    - Maximum power: 7.2 kW at 7000 rpm
    - Bore / Stroke: 52.4 mm x 57.9 mm
- **Hyosung GD250N**
    - Maximum power: 20.59 kW at 9500 rpm
    - Bore / Stroke: 73 mm x 59.6 mm
- **Yamaha 500 cc**
    - Maximum power: 23.5 kW at 6500 rpm
    - Bore / Stroke: 87 mm x 84 mm
- **Honda XR250**
    - Maximum power: 18.31 kW at 8,000 rpm
    - Bore / Stroke: 73 mm × 59.5 mm

The pressure inside the engine cylinder was varied from 50 psi to 200 psi and plotted against the amount of power that steam would generate on the piston head.

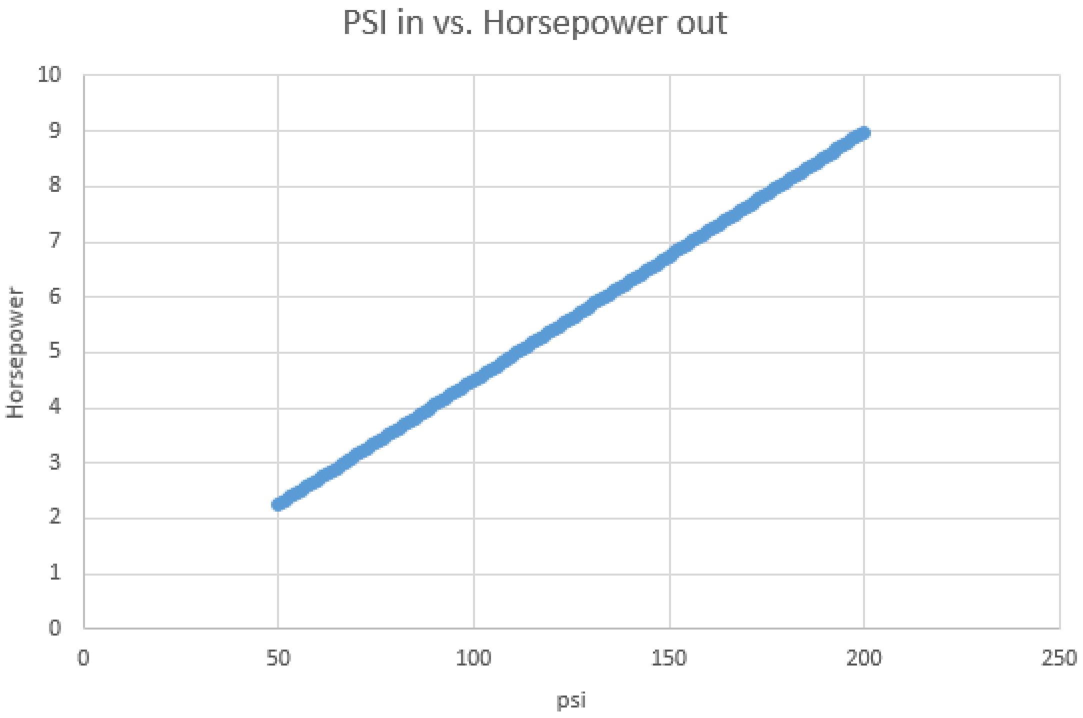


Figure 18: PSI versus Horsepower for 125cc Engine

Source: Own Elaboration

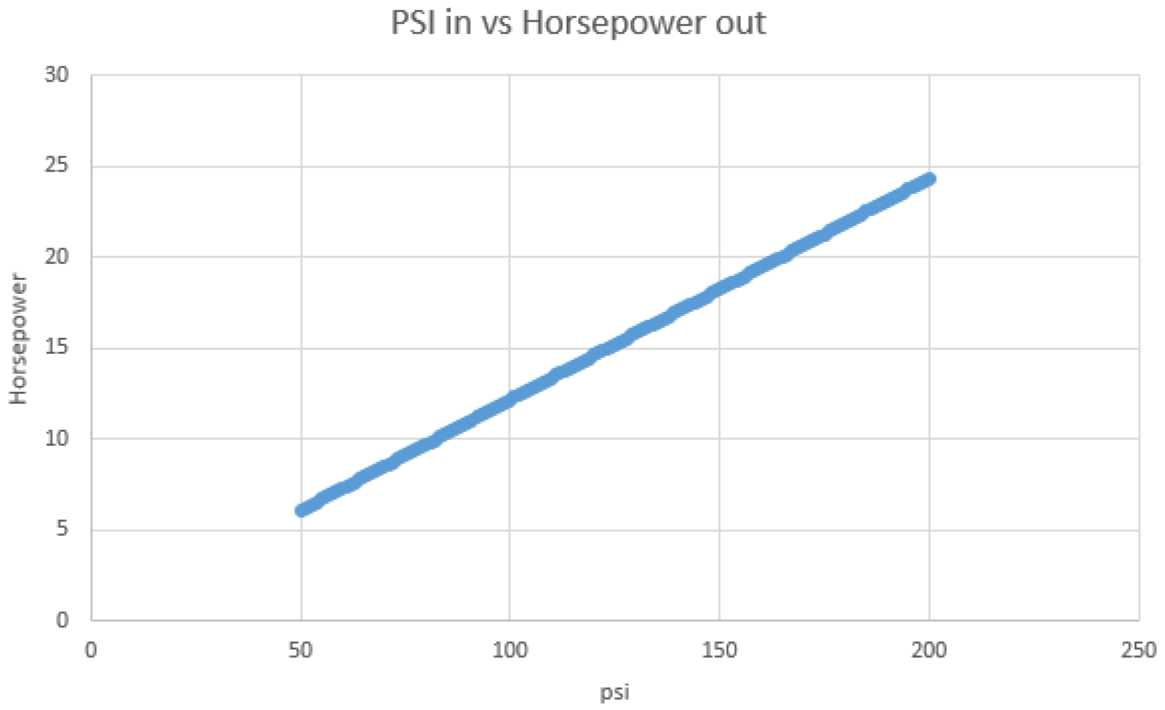


Figure 19: PSI versus Horsepower for 250cc Engine

Source: Own Elaboration

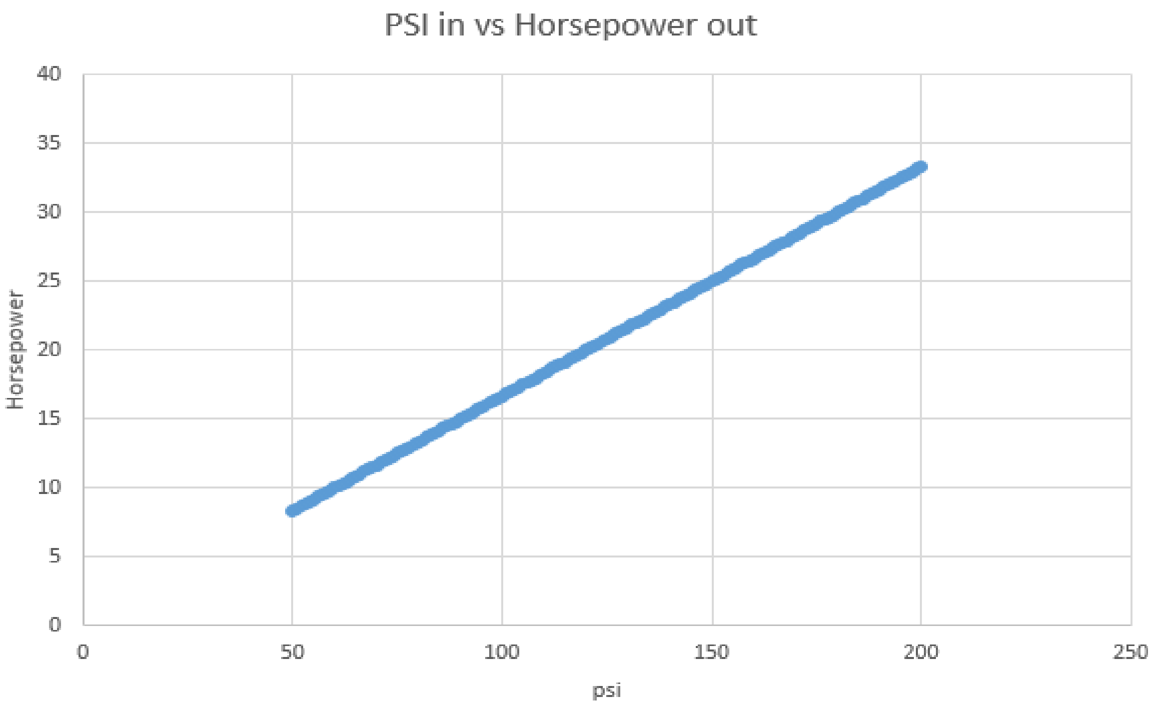


Figure 20: PSI versus Horsepower for 500cc Engine

Source: Own Elaboration

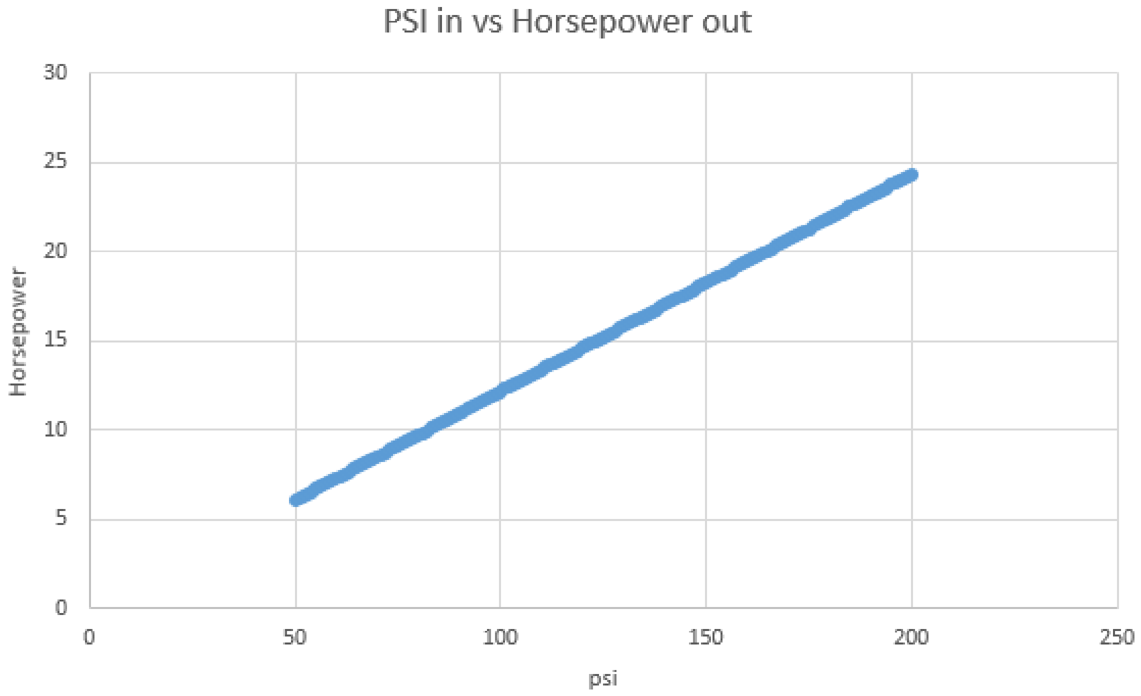


Figure 21: PSI versus Horsepower for Honda XR250

Source: Own Elaboration

Figure 22: Base Engine Illustration (Honda XR 250)

Source: http://pulpmx.com

The prototype requires several modifications to the cylinder head. The water injector must be installed including a drilled and tapped port in which to mount it. The intake valves will continue to operate as designed, but an additional steam exhaust valve is required. To easily achieve this a four-valve engine will be used and the flow from one of the two exhaust valves will be redirected. This necessitates changing the phase of the cam lobe responsible for that valve, so an engine whose cam has four dedicated cam lobes is required. For these reasons, the ideal engine choice is that of a Honda XR250 dirt bike. The following table contains the specifications of the selected engine/bike:

Model	XR250R
Engine Type	249cc air-cooled dry-sump single-cylinder four-stroke
Bore and Stroke	73mm x 59.5mm
Compression Ratio	10.2:1
Valve Train	SOHC; four-valve RFVC
Carburetion	30mm piston-valve
Ignition	Solid-state CD with electronic advance
Transmission	Six-speed
Final Drive	#520 O-ring-sealed chain; 13T/48T
Suspension	Front: 41mm leading-axle Kayaba cartridge fork with 20-position compression damping adjustability; 10.6 inches travel Rear: Pro-Link Kayaba single shock with spring preload, 20-position compression and 20-position rebound damping adjustability; 10.6 inches travel
Brakes	Front: Single disc with twin-piston caliper Rear: Single disc
Tires	Front: 80/100-21 Rear: 100/100-18
Wheelbase	55.1 inches
Rake (Caster Angle)	24.8°
Trail	92mm (3.6 inches)
Seat Height	36.0 inches
Ground Clearance	12.4 inches
Dry Weight	240 pounds
Fuel Capacity	2.4 gallons, including 0.5-gallon reserve

Table 2: Honda XR 250 Specification Sheet

Source: http://www.motorcyclespecs.co.za

Since the engine will be modified to operate from four to six strokes, the timing gear connected to the camshaft must produce the appropriate reduction in speed. This engine will require an overhead camshaft configuration to allow space for the modified timing gear, since it must be 50% larger than the original. The timing gears located on the camshaft and crankshaft will be connected via an external drive chain.

3.4. Evaluation

For the cam, cost likely prohibits outsourcing production, leaving either a single-piece or modular cam fabricated in-house. The modular cam has a significant advantage here, since it is not only easier to machine, but also easier to adjust and modify. The capability to CNC complex curves like those found on the cam lobes is invaluable as well, which combined with the other advantages offsets the decreased strength.

For the timing gear, outsourcing is implies a higher cost. While finding a mismatched set of gears that produce the correct reduction is possible and the least expensive option, it is unlikely and would require significant time to search, as well as replacement of the crank end gear which may be difficult or impossible depending on the engine. This leaves machining a gear, which is still inexpensive, allows the crank gear to be retained, and allows a higher degree of customization. However, due to time constraints, the final decision was to outsource the timing gear, as a suitable gear for a reasonable price within the budget was found.

For the injection system, an inline or rotary pump would be ideal; either of these would make installation much easier since all they require is a drive belt from the engine crank, and can be mounted externally, so if the budget was not a concern it is a very good choice. Wasted outputs are of no consequence for a demonstration of concept, and if applied to a single cylinder engine the timing issues are irrelevant. Unit pumps or injectors could be made to work, but there may not be room in the head for a unit injector drive, and the lack of an electrical engineer on the team means electronically driven versions may be too difficult to work with.

In the first semester, a diesel pump was used. Although it initially worked (it was able to spray/inject the required mass flow), water is non-lubricant. The pump was designed for diesel intake which acts as a lubricant and enables correct proper operation of the subsystem. The pump eventually rusted and became unusable. After this system failure, the developing of the water pump injection system described before was considered, as it is cheap, easily controllable and sufficiently precise. The following decision matrix accounts for a subjective grade from 1 to 10 for the different water injection system possibilities, 1 being the worst case and 10 being the best:

Criteria	**Value**	**Unit Pump**	**Unit Injector**	**Inline Pump**	**Rotary Pump**	**Common Rail**	**Water Pump System**
Cost	9	6	7	1	2	4	10
Adaptability	10	4	3	10	10	7	10
Control	6	6	6	10	10	6	6
Modularity	5	8	10	7	7	10	10
Need for EE	7	7	8	10	10	5	6
Total		**31**	**34**	**38**	**39**	**32**	**42**

Table 3: Design Decision Matrix

Source: Own Elaboration

3.5. Refinement

A possible refinement to the injection system would be common rail injection. While heavily electronics dependent, if it is possible to adjust the timing speed of the ECU it could be highly adaptable to this application and require hardly any mechanical modification compared to the other choices. Unfortunately, research has not revealed whether this can be done, and if it can it might be beyond the designer ability.

3.6. Selection

For the above reasons, it makes the most sense to self-machine the parts for the cam; the modular cam in particular has numerous advantages that make it a clear choice. The final decision was to outsource the timing gear due to time constraints. As for the water injection, the wining system was the water pump injection system described in 3.1.4.e.

4. Design Specifications

4.1. Design Overview

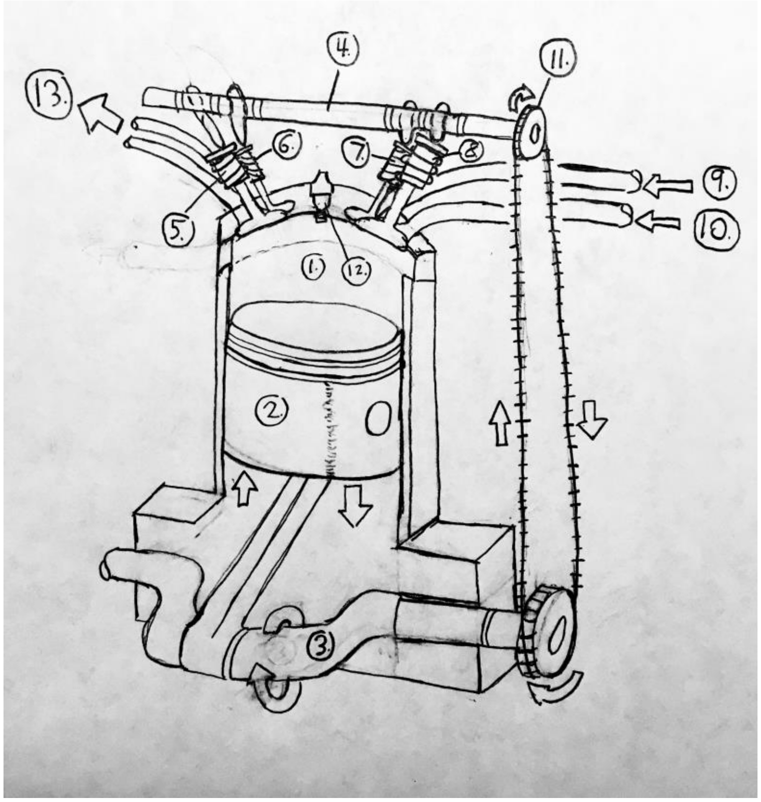
4.1.1. Description

The prototype requires several modifications to the cylinder head. A direct injector must be installed including a drilled and tapped port in which to mount it. The intake valves will continue to operate as designed, but an additional steam exhaust valve is required. To easily achieve this, a four-valve engine will be used and the flow from one of the two exhaust valves will be redirected. This necessitates changing the phase of the cam lobe responsible for that valve, so an engine whose cam has four dedicated cam lobes is required.

Since the engine will be modified to operate from four to six strokes, the timing gear connected to the camshaft must produce the appropriate reduction in speed. The engine will require an overhead camshaft configuration to allow space for the modified timing gear, since it must be 50% larger than the original. The timing gears located on the camshaft and crankshaft will be connected via the original drive chain.

4.1.2. Design Schematics

The following figure outlines the features within the modified engine prototype:



1. Cylinder
2. Piston
3. Crankshaft
4. Fuel Exhaust Valve
5. Steam Exhaust Valve
6. Water Intake Valve
7. Fuel-air Intake Valve
8. Water Feed Pipe
9. Fuel-air Feed Pipe
10. Cam Timing Drive Gear
11. Spark Plug
12. Exhaust Pipe

Figure 23: Feature Schematic of Modified Engine

Source: Own Elaboration

4.2. Functional Specifications

- To capture and use waste heat produced from a standard 4-stroke engine by injecting water into engine cylinder.
- Engine: 250 cc, naturally aspirated, air-cooled, 4-stroke, single overhead camshaft, 4 valves.
- Camshaft: actuates the four valves in a modified sequence to allow for two extra strokes.
- Timing Gear: reduces the camshaft speed from ½ to ⅓.
- Water Injector: inline or rotary will provide a controlled amount of water into the engine to be turned to steam.

The following diagram describes the stages of the 6 stroke cycle:

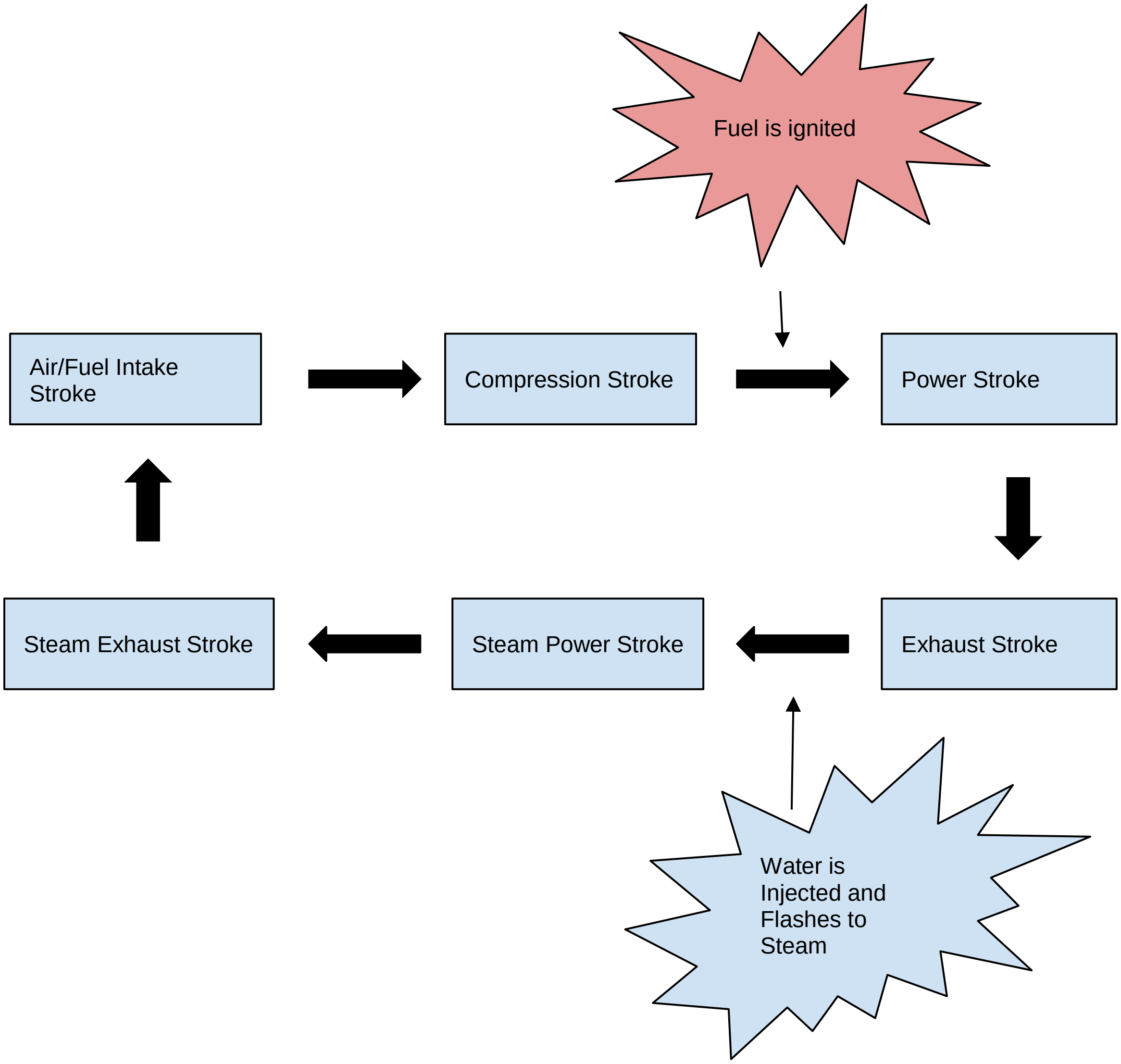


Figure 24: Process Schematic for Modified Engine

Source: Own Elaboration

4.3. Physical Specifications

- Components must fit on a workshop bench, approximately 36in x 96in.
- Modification parts shall have the same material properties of a typical engine block
- Weight (engine): 75 lbs.
- Weight (total): 100 lbs.

4.4. Subsystems

Camshaft: A custom camshaft is required in order to regulate the four-valve design. A material that is strong yet cost efficient will be used, such as low carbon steel, to fabricate the camshaft. The steel chosen is SAE 1020 low-carbon. The reason being for choosing this steel was that it was the one available for the timing gear, and its properties were then checked to see if they were suitable for the project. The physical properties of AISI 1020 steel are:

Physical Properties	Metric	Imperial
Density	7.87 g/cc	0.284 lb/in³

The mechanical properties of AISI 1020 steel are:

Mechanical Properties	Metric	Imperial
Hardness, Brinell	111	111
Hardness, Knoop (Converted from Brinell hardness)	129	129
Hardness, Rockwell B(Converted from Brinell hardness)	64	64
Hardness, Vickers (Converted from Brinell hardness)	115	115
Tensile Strength, Ultimate	394.72 MPa	57249 psi
Tensile Strength, Yield	294.74 MPa	42748 psi
Elongation at Break (in 50 mm)	36.5 %	36.5 %
Reduction of Area	66.0 %	66.0 %
Modulus of Elasticity (Typical for steel)	200 GPa	29000 ksi
Bulk Modulus (Typical for steel)	140 GPa	20300 ksi
Poissons Ratio	0.290	0.290
Charpy Impact		
@Temperature -30.0 °C/-22.0 °F	16.9 J	12.5 ft-lb
@Temperature -18.0 °C/-0.400 °F	18.0 J	13.3 ft-lb
@Temperature -3.00 °C/26.6 °F	20.0 J	14.8 ft-lb
@Temperature 10.0 °C/50.0 °F	24.0 J	17.7 ft-lb
@Temperature 38.0 °C/100 °F	41.0 J	30.2 ft-lb

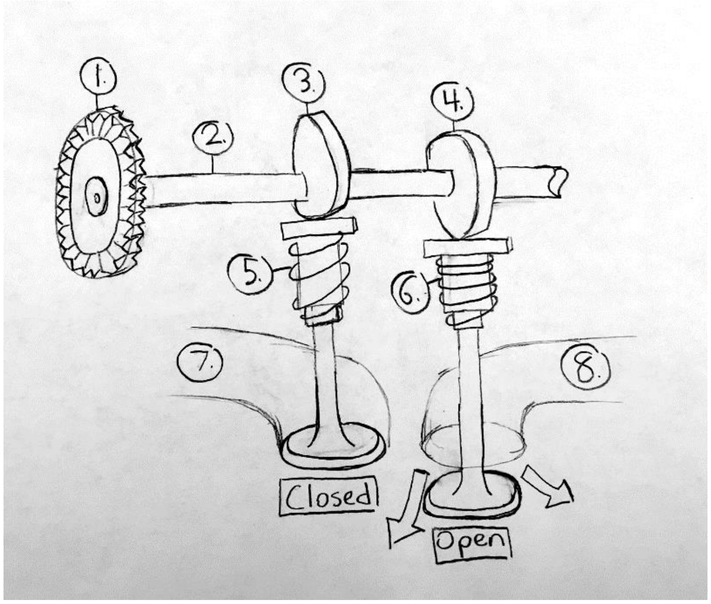
@Temperature 65.0 °C/149 °F	54.0 J	39.8 ft-lb
@Temperature 95.0 °C/203 °F	61.0 J	45.0 ft-lb
@Temperature 150 °C/302 °F	68.0 J	50.2 ft-lb
Izod Impact	125 J	92.2 ft-lb
Shear Modulus (Typical for steel)	80.0 GPa	11600 ksi

Table 4: Mechanical Properties of AISI 1020 steel

Source: https://www.azom.com

As it can be observed from the previous specification sheet, this steel has a decent hardness (111 in the Brinell Scale). Camshafts do not really require extremely high hardness requirements, 111 Brinell is more than enough. This relatively low hardness allows it to have a high machinability, very useful when machining with limited power lathes as the one available at the University of San Diego. Given its strength characteristics, (57249 psi for ultimate tensile strength), the minimum required diameter for the camshaft came out to be 1.78 in. However, due to the elevated price of the stock material and the high conservative manner of the fatigue stress analysis, the diameter was greatly reduced. In addition, the study treats the base shaft as if it was intended to endure by its own the static and fatigue forces. This is also not true, because once all the spacers and the lobes are mounted, the diameter of the assembled piece comes out to be thicker than the shaft, and in many points the conservative number 1.78 is reached. Note that fatigue stress analysis are extremely conservative studies that intend to extend the life of parts a high number of cycles. This project is only intended to design and manufacture a working prototype for a short amount of time so as to test the engine capabilities. In addition, the safety factor applied was Nf=2, which gave it extra size. With this information in mind, the base shaft diameter was designed to be 18 mm, as it this the size of the old base shaft (shaft integration would not be possible if the size of the base shaft was changed). This does not mean that the bike designer did not take into consideration fatigue mechanics, the reduced diameter is probably counter attacked by an increase in the quality of the camshaft stock material.

The camshaft will consist of a base shaft where four cam lobes can be place and adjusted if necessary. As the cam rotates, each lobe will open its corresponding valve (i.e. fuel-air cam lobe opens the fuel-air valve during the intake stroke). Each valve will be held closed by a spring. The diagram below illustrates the interconnection between the camshaft, cam lobes, valve, and timing gear:



1. Timing Gear
2. Shaft of Cam
3. Fuel-air Cam Lobe
4. Water Feed Cam Lobe
5. Closed Fuel-air Valve
6. Opened Water Feed Valve
7. Fuel-air Intake Pipe
8. Water Injection Pipe

Figure 26: Camshaft, Valve, and Timing Gear Interconnection Diagram

Source: Own Elaboration

Timing Gear: The custom timing gear, as previously stated, was constructed out of the same material as the camshaft. The fabricated timing gear was connected to the crankshaft via a drive chain. The gear ratio will provide a 3:1 reduction of the crankshaft angular velocity to the camshaft. In order to reduce interference and undercutting between the two gears, the timing gear must have a minimum of 57 teeth. This increases the torque and provide proper timing for the valves to open and close accordingly. Hardness requirements for the timing gear are higher than that for the camshaft, however, as it was obtained from McMaster-Carr, the periphery of the timing gear was heat treated (cemented) for extra hardness, while maintaining a decent toughness in the rest of the gear (nucleus).

However, due to the difficulty of fitting the new gear internally, the final decision was to externally mount the gear. This meant that a new crankshaft gear was needed, as well as the timing gear. To make the numbers easy the crankshaft gear ended up having

10 teeth and the timing gear 30, in order to make the 1/3 angular speed reduction (keeping the same modulus).

Water Injection System: The water injection system for the engine prototype is broken down into nine components. An improvement to the existing water injection system would be to include a condensation section so as to recycle the water so that the user would not have to constantly replenish the water reservoir. However, designing and developing this extra system does not help respond to the problem that this project intends to solve. Below is a list (in descending order) of all the components within the injection system:

1. Reservoir where water is pulled from the pump.
2. 12-volt DC water circulation pump that will produce a constant pressure:

Figure 27: Water Pump

Source: https://www.mcmaster.com

3. ¼” diameter needle valve to regulate the mass flow rate of the water:

Figure 28: Needle Valve

Source: https://www.mcmaster.com

4. ¼” diameter 12-volt DC fast response solenoid valve:

Figure 29: Solenoid Valve

Source: https://www.mcmaster.com

5. Arduino board attached to a magnetic sensor that will regulate the amount of water allowed to pass through the solenoid valve:

Figure 30: Arduino Genuino Uno

Source: https://www.mcmaster.com

6. ¼” diameter brass ball-check valve that will withstand pressure up to 2,000 psi from the engine to the solenoid valve and recirculation pump:

Figure 31: Ball-Check Valve

Source: https://www.mcmaster.com

7. Stainless steel female yor-lok fitting designed to step a ¼” tapped pipe down to a ⅛” tube:

Figure 32: Female Yor-Lok Fitting

Source: https://www.mcmaster.com

8. ⅛" stainless steel tube:

Figure 33: Stainless Steel Tube

Source: https://www.mcmaster.com

9. Stainless steel male yor-lok fitting that will be connected to the ⅛" tube on one side and will be tapped directly into the engine head on the other

Figure 34: Male Yor-Lok Fitting

Source: https://www.mcmaster.com

The next photograph contains an assembly mistake, as the order of components 6, 4 and 3 are badly connected. Unfortunately, no correct assembly photograph is available (see figure 9 for correct assembly schematic). The correct order would be 3, 4 and 6 instead of 6, 4, and 3 as figure 14 shows. The reason being is that the pressure of the water is generated by the water pump (2), the needle valve (3) precisely controls the water flow, the mouse valve (4) controlled by the Arduino UNO (5) decides when to inject water and finally the check valve (6) allows unidirectional water flow into the engine:

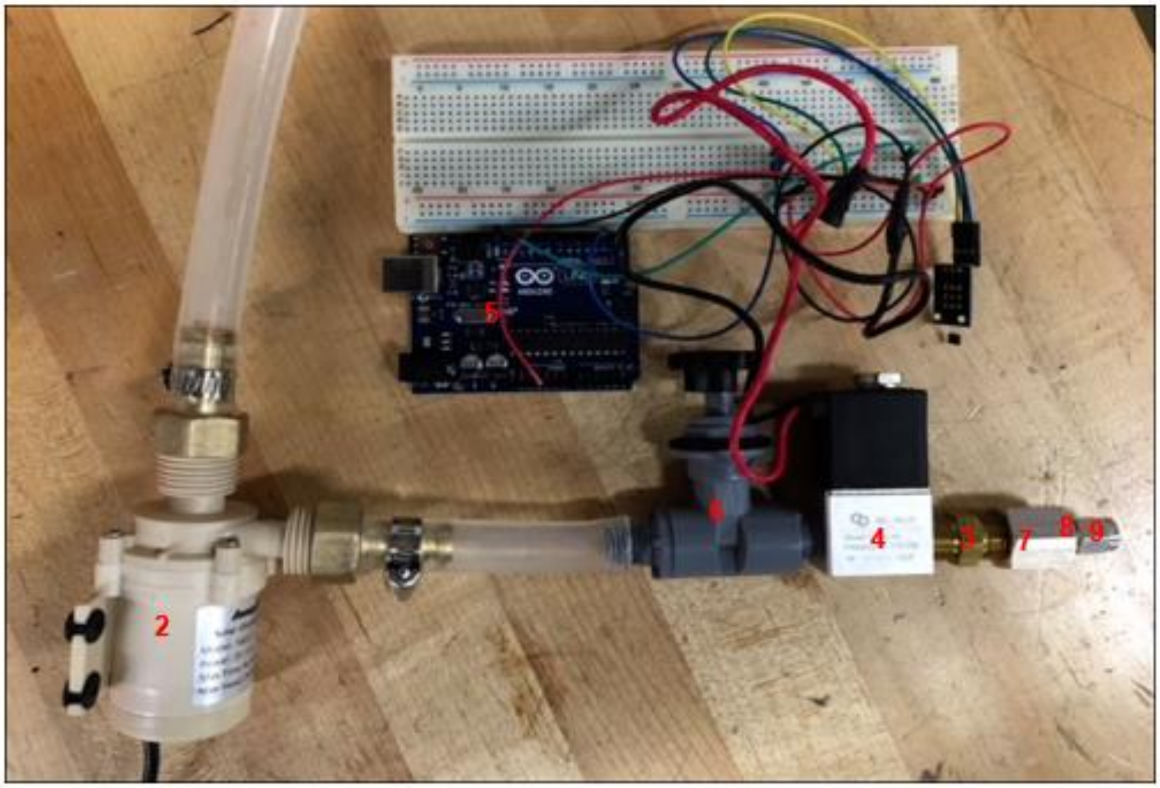


Figure 35: Full Water Pump System Integration Photograph

Source: Own Elaboration

Base Engine: The prototype design requires the base engine to have an overhead camshaft configuration. An engine with a pushrod configuration would complicate efforts as the two gears between the crankshaft and camshaft would be directly meshing or connected by a very short chain. This would not supply proper clearance for modified of a larger radius timing gear and necessitate relocating the cam bearings cast into the engine block. The chosen engine was a 4 stroke, OVC, combustion engine (Honda XR250 Dirt Bike).

5. Project Plan

5.1. Research

Thermodynamics and Heat Transfer:

Extensive calculations have been done above for the power production from steam and water volume for generalized heat production levels and engine geometry, but additional research more specific to the choice of base engine was not carried out. A more detailed thermodynamic study could include the following topics: how much heat the water will absorb when injected into the cylinder, what effects sudden temperature changes will have on the piston and other hardware, how much water the engine can vaporize given the length of the injection event and the temperature of the engine, what mass flow rates are possible with the injector setup, and how much power and pressure the engine can safely develop. Most of this can be accomplished through testing or simply applying the dimensions specific to the chosen engine to the equations that have already been derived, but some of it will can be done with physical testing. A more intensive thermodynamic study was considered not to be essential to solve the problem this project intends to respond to (can a 6-stroke engine produce an increase in engine efficiency?).

Stock Material:

While the materials that are used in the stock engine are known, the capability to machine some of those materials is limited by the University of San Diego machinery and substitutes to use for making things like the cam or timing gear had to be found. For this the properties of various available metal stock had to be researched in order to find something that would survive testing while costing as little as possible. Steel was the chosen stock material for both the camshaft and the timing gear (in particular AISI 1020, as described before), there are a variety of grades and compositions available with different heat-treating or hardening characteristics after machining is complete. However, as this project is not designed to last a high number of cycles so as to fatigue stresses to come into play, machined parts were not heat treated.

All of the stock material was obtained from **McMaster-Carr**, an excellent Industrial supply online store.

5.2. Construction

For this project, a working four stroke, overhead cam and 4-valve one-cylinder gas engine was purchased. Several modification were needed in order to transform the four-stroke base engine into a six-stroke engine prototype that utilizes water injection. A custom camshaft along with cam lobes were designed and fabricated to regulate the valves properly. Furthermore, a new timing gear system was needed to allow proper timing from the crankshaft to the camshaft. Lastly, a water injection system operated by an Arduino board was designed and assembled to allow precise amounts of water into the engine cylinder.

5.2.1 Camshaft Fabrication and Timing Gear Assembly

The final design of the camshaft is composed of five major parts: four individual cam lobes, and a one-piece shaft core to mount them on. The shaft was turned on the manual lathe and is of a stepped design allowing the cam lobes, bearings, and timing gear to slide on from the appropriate end. Machining the cam lobes was a more involved process. To analyze the stock cam, the shaft was mounted in an indexed chuck, and fitted with an analog displacement gauge positioned to read the lift of a cam lobe and zeroed at the base lobe radius. The timing marks on the stock timing gear were aligned to zero mark on the chuck for timing reference. The assembly was then rotated through a full 360 degrees, with readings taken every five degrees. This process was repeated once each for the exhaust and intake cam lobes, producing 72 data points apiece. Figure 13 illustrates the rig used to conduct the cam analysis.

Figure 36: Cam Analysis Rig Photograph

Source: Own Elaboration

The obtained data was entered into a spreadsheet application. Because it consisted of rotational position (degree) values and radial displacement (lift) values, the resulting range needed to be converted from polar coordinates to Cartesian coordinates, which was accomplished trigonometrically by multiplying each absolute radius value (obtained from the lift displacement added to half the base diameter) by the cosine and sine of the angle at which it occurred, producing *x* and *y* positional values respectively. When plotted, these values produce a to-scale representation of the lobe profile, crucially including the rotational position on the shaft and relative to the other lobes that produces the correct phasing. These tables and figures can be found in Appendix 7.2.

The new lobe profiles needed to produce the same lift and dwell as the originals, but in two-thirds of the rotational space as the crankshaft makes three revolutions instead of two but the camshaft can still only rotate once per complete engine cycle. This means the cam phasing needed to be reduced to two-thirds of its original amount, and profiles themselves also needed to be compressed into two-thirds of the space on the lobe, all while retaining the correct timing relative to the crankshaft. To accomplish this, the original 72 data points representing 360 degrees per lobe were distributed across 108 positions representing 540 degrees of travel, with the additional spaces filled by radius values equivalent to the base lobe radius. Since the cam cannot actually revolve 540 degrees, the 360 degrees of cam rotation were divided evenly over the 108 positions, resulting in a lift value every 3⅓ degrees instead of every 5. This operation compresses the lift and dwell events by the appropriate amount, as well as positioning all two-thirds sooner relative to the timing mark at the same time. These tables and figures can be found in Appendix 7.3.

Unfortunately, when the 108 adjusted values are plotted over their coordinate system, the resulting plot contains concavities due to the profile compression. The rocker arms cannot navigate concave surfaces, so each profile was manually smoothed by identifying the offending points and removing them from the final profile. Doing so leaves gaps in the surface, but because the spaces in between measured points on the profile are approximated by a straight line careful selection of the omitted values produces a smooth tangent to the surface.

The final step was to time the steam exhaust lobe since it no longer actuates in time with the combustion exhaust. To do this, one of the exhaust cams was simply phased 120 degrees earlier than its counterpart, resulting in an event that occurs at the same relative position to the piston as the combustion exhaust but two strokes earlier in the engine cycle. Counterintuitively it is the combustion exhaust that was made earlier, since it must occur before the steam exhaust, and the steam exhaust occurs in the original combustion exhaust position immediately preceding the intake event. The final profiles can be seen in Appendix 7.3.

The lobe profiles are too complex to accurately machine by hand, so a CNC program needed to be written from the spreadsheet data. To do this, the spreadsheet *x* & *y* values were stripped of any headings and notations, given artificial *z* values of zero, and exported as a comma-separated text file. This format can be read by SolidWorks and output as a continuous curve. Within the Mastercam extension of SolidWorks, these curves were converted into toolpaths that could be run by the CNC mill, and then exported as G-code. Because the lobe phasing and timing is integral to the new profiles, three programs were necessary to produce two identical intake profiles, one exhaust profile, and one steam exhaust profile identical to the exhaust but at a different phase angle.

Four cam lobe ‘blanks’ were hand turned on the lathe to the maximum lobe radius, and with sufficient extra material at either end to allow them to clamp in the mill vise and locate the lobes axially on the camshaft. Note that as a result of the different spacing of each lobe on the stock shaft, each blank was unique. The profiles were then individually CNC milled. Great difficulty was encountered at this stage, but the profiles were eventually completed. A timing mark was cut into the axial ends of each lobe along the *y* axis to allow the phase positions to be aligned when the lobes were installed on the shaft. The lobe surfaces were ground smooth after machining to limit rocker arm wear, since the linear machine paths between data values produced finely faceted profiles. The extra clamping material was then cut off and the four lobes were bored to camshaft diameter.

Aligning the timing marks to the surface of the manual mill vise, set screw holes were drilled into the non-profiled sections of each lobe. The lobes were then mocked up on the camshaft, and the set screw positions were marked. The corresponding set screw holes were then drilled into the camshaft, and the timing gear indexing keyway was milled at the same time, resulting in all mounting points occurring at the same radial position on the shaft. Finally, the lobes, set screws, bearings, timing gear, and machine key were all installed in their final positions. Figures 37 and 38 illustrate the new cam assembly compared to the stock camshaft and installed in the upper housing. Timing sprockets, roller chain, and associated hardware was purchased.

Figure 37: Cam Assembly (Left) and Stock Camshaft Photograph

Source: Own Elaboration

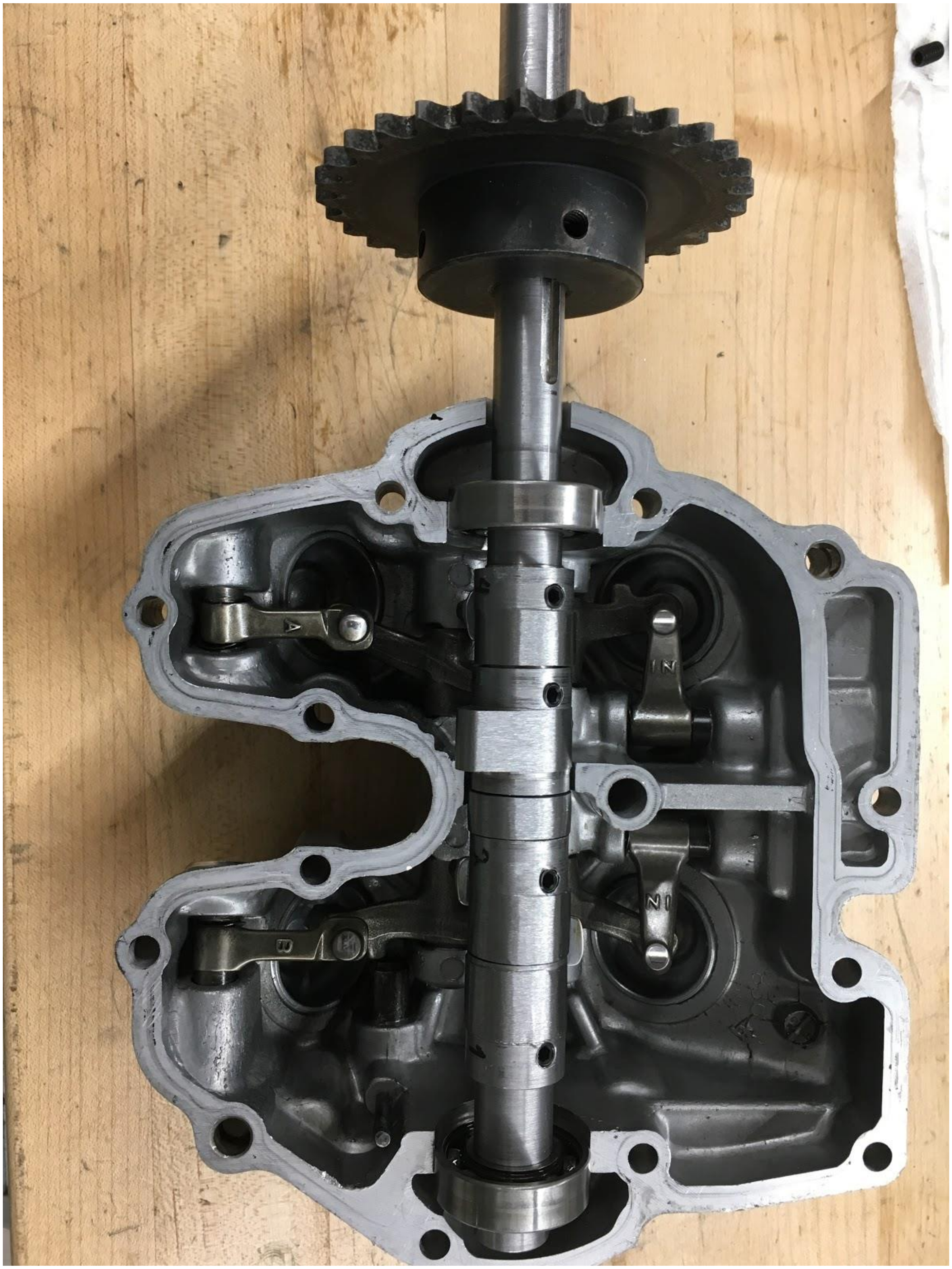


Figure 38: Cam Assembly and Timing Gear Installed

Source: Own Elaboration

5.2.2 Water Injection System Assembly

The water injection system, that is broken down into ten components as stated above (see section 3.3), will be drilled directly into the engine cylinder. Pulling water from the reservoir, a DC water circulation pump provides the system with sufficient pressure for the water to enter into the engine cylinder. The water is pumped into the needle valve to allow for a precise amount of mass flow rate of the water through the system (see section 5.2.1). Next, the water is pumped into the solenoid valve. Operated by the Arduino board, the solenoid valve will only open for short durations to allow a finite amount of water to pass through. A magnetic sensor is attached to the camshaft that will sent a signal to the Arduino during the fifth stroke.

Since the engine cylinder experiences high degrees of pressure, a ball-check valve is installed to order to stop the high levels of pressure from damaging the solenoid valve, needle valve and pump. The ball-check can withstand pressure of 2000 Psi in one direction, yet opens with pressure of 2-5 Psi in the direction of the water flow. Furthermore, the two Yor-lok fittings and ⅛” tubing can withstand pressure up to 7,000 Psi. See figure X for full water injection system assembly.

As for the microcontroller, the breadboard circuit used the following components:

1. The previously stated solenoid valve.
2. An Arduino Uno microcontroller.
3. A solderless breadboard.
4. One TIP120 Darlington Transistor.
5. One 1K Ohm Resistor.
6. One 1N4001 Diode.
7. Hookup Wires.

Using the previous components and the following schematics, the following circuit was designed:

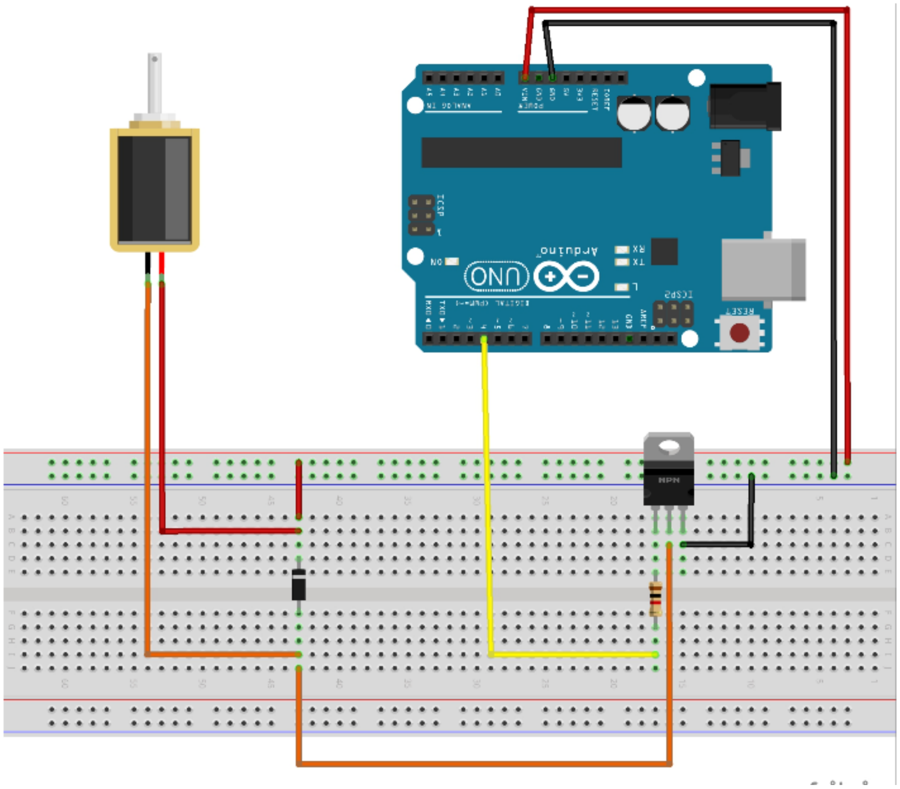


Figure 39: Full Circuit Integration

Source: https://www.bc-robotics.com

In order to test the solenoid valve, the following Arduino code was used. The program used to input the code in the microcontroller was Arduino 1.8.5, the most recent version available:

```
int solenoidPin = 4;    //This is the output pin on the Arduino for the solenoid valve


void setup() {
  // put your setup code here, to run once:
  pinMode(solenoidPin, OUTPUT);           //Sets the pin as an output
}


void loop() {
  // put your main code here, to run repeatedly:
  digitalWrite(solenoidPin, HIGH);    //Switch Solenoid ON
```

```
  delay(1000);                      //Wait 1 Second

  digitalWrite(solenoidPin, LOW);     //Switch Solenoid OFF

  delay(1000);                        // Wait 1 second
```

The purpose of this program, specifically the timing, was written to electronically test the solenoid valve. It really only turns on and off the solenoid valve, with a delay of 1000 ms seconds (1 second) between the ON and OFF states.

As stated previously, for the full 6-stroke engine integration, a magnetic sensor was introduced to the camshaft. For each cycle, the purpose of this sensor is to turn ON (during water injection) and OFF (the rest of the time) the solenoid valve. A LED light was added for visual purposes (to check when the valve is ON and OFF). The following code accounts for this modification:

```
int solenoidPin = 4;    //This is the output pin on the Arduino for the solenoid valve

int magnetic_sensor = 2;

int inputVal = 0;


void setup() {

  // put your setup code here, to run once:

  pinMode(solenoidPin, OUTPUT);           //Sets the pin as an output

  pinMode(13, OUTPUT);                    //LED (only for visual purposes)

  pinMode(magnetic_sensor, INPUT);

}


void loop() {

  if(digitalRead(magnetic_sensor)==HIGH)      //Check the sensor output

  {

    digitalWrite(13, HIGH);   // set the LED on

    digitalWrite(solenoidPin, HIGH);    //Switch Solenoid ON


  }
```

```
else

{

  digitalWrite(13, LOW);    // set the LED off

  digitalWrite(solenoidPin, LOW);     //Switch Solenoid OFF

}
```

5.2.3. Full engine Integration

Although the full integrated prototype did not get tested, engine integration was carried out. As previously shown, the camshaft correctly fitted into the cylinder head. The problem was that doubling the size of the timing gear meant that it was impossible to fit the gear inside the engine so it had to be externally mounted. Given the size, a new chain was externally implemented and connected to both axes (camshaft and crankshaft). This can be clearly seen in the photograph below:

Figure 40: Connecting Chain Between Camshaft and Driveshaft

Source: Own Elaboration

The water injection system was drilled and tapped directly into the cylinder and connected to a water reservoir.

After the three integrations, the whole engine was put together. Engine oil had to be replenished as it had been partially lost during the disassembly. Finally, the rocker cover was put back in place.

Figure 41: Complete Bike Integration at University of San Diego Expo, May 2018

Source: Own Elaboration

5.4. Safety Assessment

Internal combustion engines work at high pressures and temperatures. Although they are safe to use since engine manufacturers run many safety tests before production, modifying an existing engine can be the origin of many safety issues.

The engine will be tested in a dynamometer as a way to record any changes in horsepower, torque or fuel consumption. During testing, several hazards can take place, including fire, reduction of air quality, noise, and shrapnel.

- To avoid **air poisoning** (including carbon monoxide and other potentially harmful gases), testing will be done outside of Loma Hall.
- Once the engine is running, the tester will maintain a **prudent distance** from the engine, in order to avoid being hit by any loose engine parts. Even with the assumption that the amount of waste heat is reduced, internal combustion engines reach **high temperatures** that can be dangerous to humans, so protection should be used if the engine is manipulated. Although testing will be done on an open space (e.g parking lot) with no surrounding flammable objects, knowing the location of the closest fire extinguisher will the prevention of further engine damage and reduce the fire hazard.
- **Maximum working pressure** of the water intake stroke should be limited to a safe level (100 psi) so as to protect the engine and people around during testing.
- As testing is done on campus, to reduce **noise pollution**, a muffler will be installed at the end of the exhaust.

5.5. Testing

5.5.1 Water Pump Injection System Testing

The following section tests the mass flow rate of the needle valve. The valve handle is equipped with 16 notches. In order to calculate the mass flow rate, the amount of time it took the system to fill a 500mL cylinder with each corresponding turn of the valve handle was recorded. It is important to note that at 1/16” and ⅛” turns of the valve, the flow of water dribbled out onto the male Yor-lok fitting. Only after ¼” turns of the valve did the flow of water begin to produce a steady stream. Data resembled a logarithmic relationship, spiking at the 1/16” and ⅛” turns of the valve. After 2 turns of the valve, the amount to time that it took to fill the 500mL was negligible.

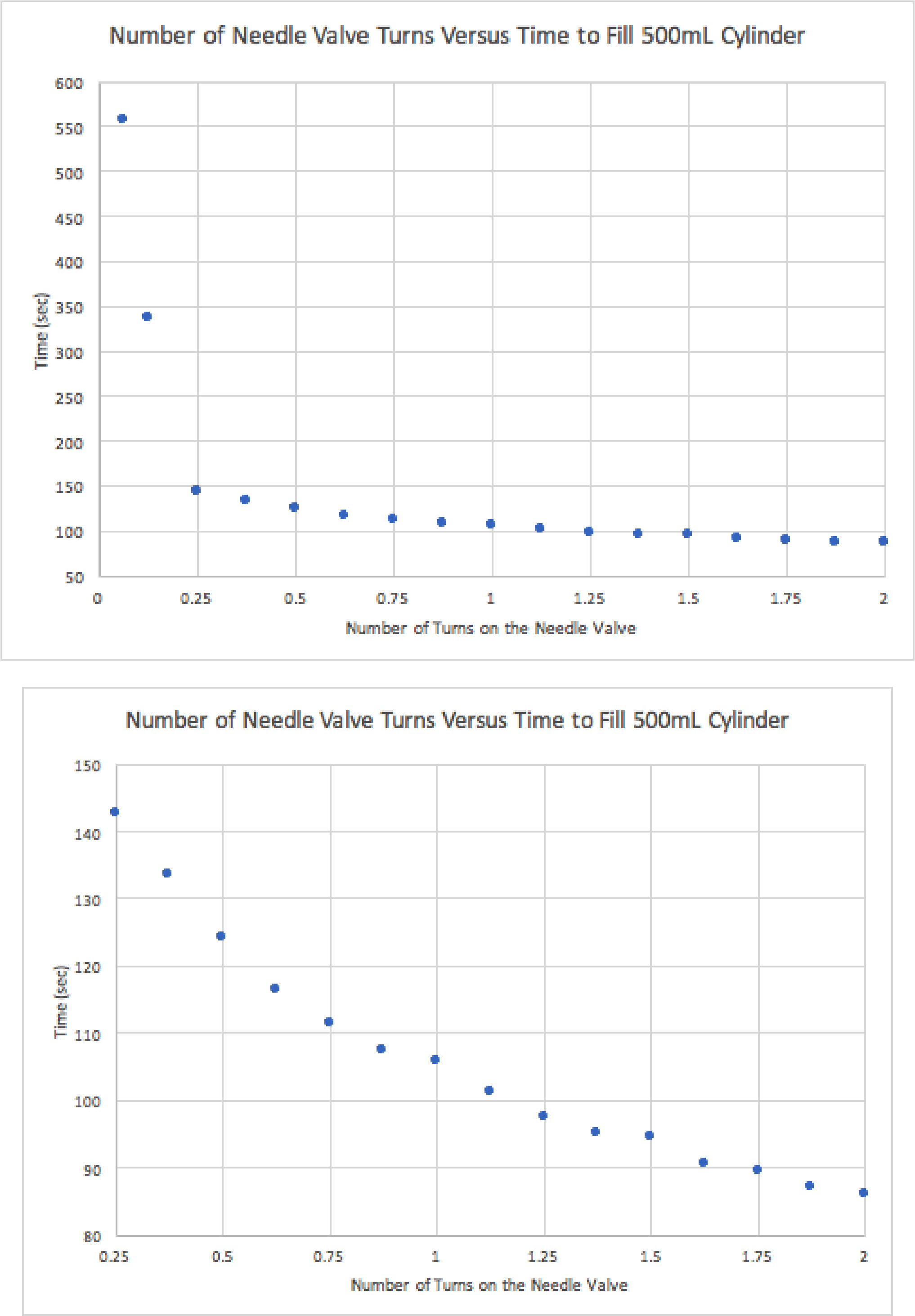


Figure 42: Number of Needle Valve Turns Vs Time to Fill 500ml Cylinder

Source: Own Elaboration

5.5.2 Camshaft and Time Gear Testing

Once the camshaft was fully assembled, it could be visually appreciated that the system was able to generate the desired valve timing.

5.5.3 Complete Integrated System Testing

The following table contains the customer requirement the product is designed to meet with the necessary test procedure:

Customer Requirement / Constraint	**Test Procedure**	**Summary of Test Results**
Increase power output with the same fuel consumption or reduce fuel consumption with the same power output.	Engine to be tested on calibrated dynamometer. (Engine must be tested before and after 6 stroke adaptation to compare results).	Not Applicable
Deliver water into engine head at high enough pressure for injector	Attach water injection system to head, fill with water, check for any leaks	Test not conducted as of yet
Camshaft must resemble the original and run in the same spot as the old one	Manually crank timing system, ensure that camshaft rotates fully and all valves open and close properly	Test not conducted as of yet

Table 5: Customer Requirement Compared to Test Procedure

Source: Own Elaboration

The project finished after the integration of the new parts and the reassembly of the bike. Due to time constraints, complete testing of the full integrated prototype was not possible. This project is still a valid attempt at studying, designing and manufacturing a six-stroke water injection engine. Unfortunately, experimental data to back up the previous customer requirements/constraints and previous theory is not available.

Nevertheless, the engine was successfully started and run for a time span of 10 minutes approximately. 5 minutes were needed for the engine to heat up before starting the water injection (the engine was still running).

Even though the bike got to work, without experimental data it is impossible to detect if the water is actually powering the bike, or if both final strokes do not produce any power (the flywheel does the work during those strokes). Unfortunately, there was no time to test on a calibrated dynamometer, which is the only way to find out about the previous statement.

5.6. Schedule

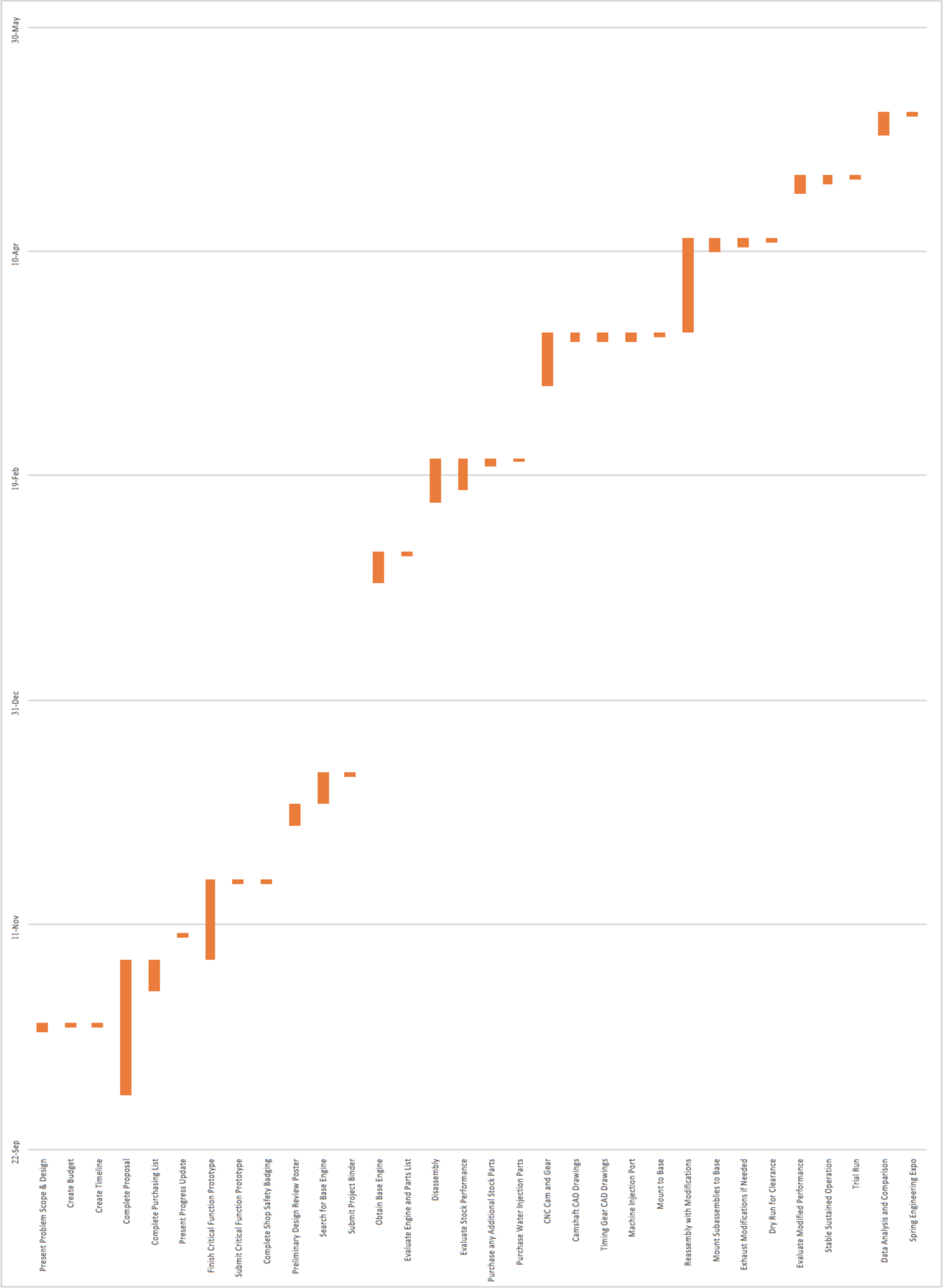
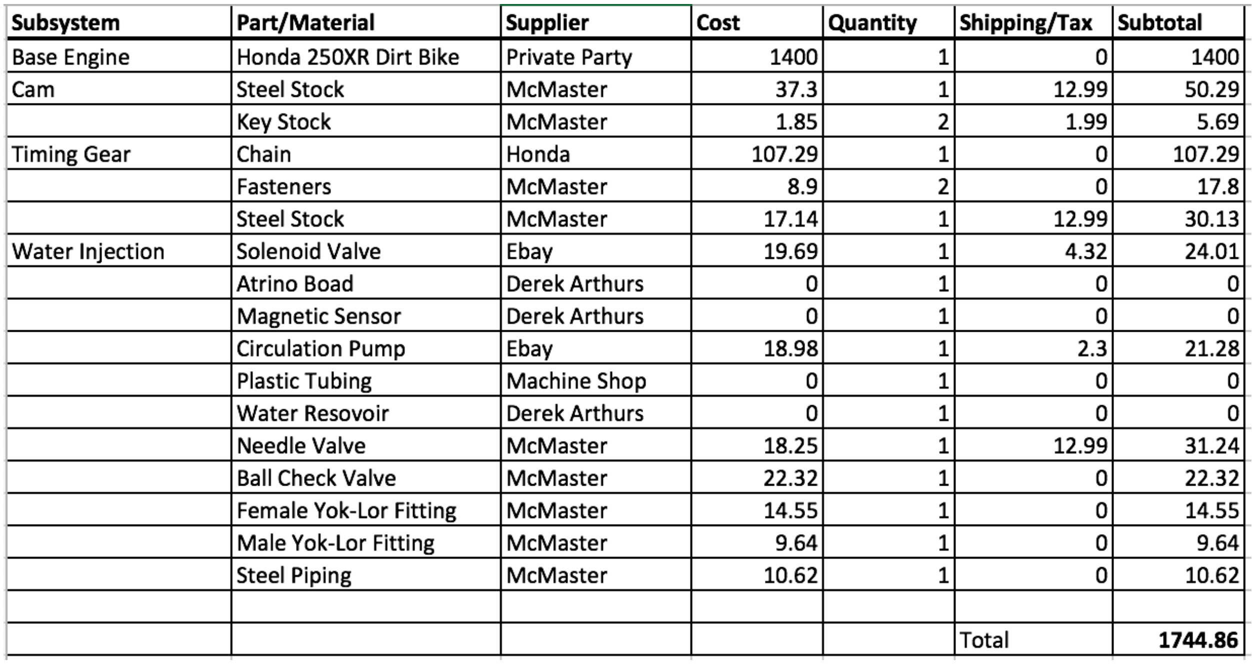


Table 6: Gantt Chart

Source: Own Elaboration

5.7. Budget

The total cost for the six-stroke engine conversion prototype and all related test equipment and materials is $$1744.86.



Subsystem	Part/Material	Supplier	Cost	Quantity	Shipping/Tax	Subtotal
Base Engine	Honda 250XR Dirt Bike	Private Party	1400	1	0	1400
Cam	Steel Stock	McMaster	37.3	1	12.99	50.29
	Key Stock	McMaster	1.85	2	1.99	5.69
Timing Gear	Chain	Honda	107.29	1	0	107.29
	Fasteners	McMaster	8.9	2	0	17.8
	Steel Stock	McMaster	17.14	1	12.99	30.13
Water Injection	Solenoid Valve	Ebay	19.69	1	4.32	24.01
	Atrino Boad	Derek Arthurs	0	1	0	0
	Magnetic Sensor	Derek Arthurs	0	1	0	0
	Circulation Pump	Ebay	18.98	1	2.3	21.28
	Plastic Tubing	Machine Shop	0	1	0	0
	Water Resovoir	Derek Arthurs	0	1	0	0
	Needle Valve	McMaster	18.25	1	12.99	31.24
	Ball Check Valve	McMaster	22.32	1	0	22.32
	Female Yok-Lor Fitting	McMaster	14.55	1	0	14.55
	Male Yok-Lor Fitting	McMaster	9.64	1	0	9.64
	Steel Piping	McMaster	10.62	1	0	10.62
					Total	**1744.86**

Table 6: Budget for Engine Prototype

Source: Own Elaboration

5.8 Final Project Conclusions

5.8.1. Professional and Ethical Responsibility of Project

Engineers have an ethical obligation not to produce designs that pose a threat to the health and safety of the general public. While the prototype could be considered hazardous if mistreated, very limited scenarios operational were outlined to prevent it from being tested in any kind of dangerous manner or environment, and its status as a nonproduction prototype means that the wider population will never have a chance abuse those boundaries. An engine of the type demonstrated here that was correctly designed from scratch and build for the purpose would pose no greater ethical problems than any existing engine currently in production.

5.8.2. Lifelong Learning Contribution of Project

This project involved fairly significant, highly involved, and widely varied mechanical engineering problems including: reverse engineering, part design, CAD design, part selection, manufacturability design, material selection, and hand and CNC machining. These problems were very appropriate for a mechanical engineering project, and it is surprising how truly interconnected the various fields are. There was also a necessity to draw heavily on fluid dynamics and electrical engineering knowledge over the course of the project. Additionally, for the construction of the bike the group realized the importance of dividing work since there was far more than any one person could do and by specializing the results were obtained easily and efficiently. In addition, the group was also surprise by how large of some impact administrative obstacles can have on timelines, and that there is a maximum number of delays and setbacks a timeline can handle. Most importantly however, from this project it was learned that even ambitious, problematic projects can be accomplished with enough planning and cooperation.

5.8.3. Global, Economic, and Environmental Impact of and to Project

The introduction of an internal combustion engine that can effectively utilize waste heat has obviously major ramifications in a world where such engines are so prevalent and essential. This combustion cycle is meant to do this by vaporizing water to convert stored and exhaust heat into pressure and usable work within the operation of the engine, producing greater and smoother power without additional fuel consumption, ancillary equipment, or undeveloped technology. Reduced consumption of hydrocarbon fuels would have wide-reaching economic consequences and direly needed environmental effects with the associated reduction in oil purchases and atmospheric emissions, but engines like the one designed prototyped for this project have existed for some time now without garnering much attention or interest. There is presumably a reason, given the high demand for efficiency it is unlikely that such developments went unnoticed by industry, and one of the main goals of this project was to understand what that reason is.

Unfortunately, while the prototype was successfully constructed, time and facilities constraints prevented proper testing, so it can only be speculated as to what that reason might be.

5.8.5. Results

As stated previously in the testing section, full integration testing was unfortunately not possible. However, the water injection system successfully produced the water injection flow the engine needed for the full integration. The camshaft and the timing gear were also both successful in producing the desired timing for a six-stroke cycle.

Even though all subsystems where correctly manufactured, it was not possible to test the bike to see if any efficiency improvements were made. However, the bike did get to run for a short amount of time (10 minutes), enough to test the injection system. However, as previously stated, without proper testing in a calibrated dynamometer, improvements in power and/or efficiency cannot be visually detected.

5.8.6. The validity of findings and recommendations for future studies

The fact that six-stroke engines utilize a technology that is not yet rooted into the engine industry was one of the motives to study, design and manufacture its own water injection engine. Someone with a glint of common sense would certain ponder upon the following question: if this technology or similar technologies like the ones described in the state of the art supposedly obtain a significant increase in efficiency, emissions and power why does not it find its way into the engine market?

Thousands of engine business have dedicated R&D teams constantly looking for new and effective ways to improve existing engines, or create new ones. However, sometimes the benefit new technologies bring is unable to unseat previous, stablished already working technologies. This unseating generally requires a high initial investment to achieve a good market acceptance. The scope of this study was straightforward: can a working 6 stroke water injection prototype be created, and can it increase efficiency or power?

Therefore, recommendations for future studies include the following. Once increases in efficiency, reduced fuel consumption or increases in power have been demonstrated, the application of such engine should be heavily studied. This will depend on the system the engine will be integrated to. Maybe the weight of the water tank it needs outweighs the efficiency improvement. Maybe the increase in size and weight makes it difficult to create small, lightweight, powerful cars. Maybe the high initial investment hinders its expansion capabilities. Thus, an exhaustive, complete integration study of the engine into an existing vehicle or machine that incorporates the previous factors and economic considerations is highly recommended.

Finally, I consider that the fact that this engine has not been developed does not necessarily mean it is the wrong way to go. In fact, in this case it is completely the opposite: this should serve as a hint for future studies to consider the downsides of the technology and find ways to improve or reduce their negative effect. I still think that even the slightest improvement in fuel efficiency can outweigh a high product price, as fuel economics (especially in commercial use) clearly surpasses the initial price of the majority of all market-available machines.

6. References

[1] *Automotive Industry*. (n.d). Retrieved on the 14 of May 2018, from www.selectusa.gov/automotive-industry-united-states.

[2] *Global Car Sales 1990-2017*. (n.d). Retrieved on the 20 of May 2018, from www.statista.com/statistics/200002/international-car-sales-since-1990/.

[3] *Where the Energy Goes: Gasoline Vehicles*. (n.d). Retrieved on the 3 of February, from www.fueleconomy.gov/feg/atv.shtml.

[4] Lyons, P. (2006, February 26). Inside Bruce Crower's Six-Stroke Engine. *Autoweek*. Retrieved on the 12 of March 2018, from http://autoweek.com/article/car-news/inside-bruce-crowers-six-stroke-engine

[5] Raza, M. (n.d). *Study and analysis of six stroke internal combustion engine.* Retrieved on the 15 of March 2018, from the Department of Mechanical Engineering of JSS Academy of Technical Education: https://www.ijedr.org/papers/IJEDR1703167.pdf

7. Appendices

7.1. Cam Analysis Tables

7.1.1. Intake Analysis

*	D	R	X	Y	Z
0	0	0.433071	0.433071	0	0
5	0	0.433071	0.4314230341	0.03774462467	0
10	0	0.433071	0.4264916784	0.07520198995	0
15	2	0.435071	0.4202463152	0.1126046608	0
20	7	0.440071	0.4135314713	0.1505131465	0
25	13	0.446071	0.4042776209	0.1885177506	0
30	23	0.456071	0.3949690719	0.2280355	0
35	35	0.468071	0.3834213165	0.2684744961	0
40	51	0.484071	0.3708198996	0.311154841	0
45	72	0.505071	0.3571391291	0.3571391291	0
50	97	0.530071	0.3407230711	0.406057944	0
55	127	0.560071	0.3212435283	0.4587833046	0
60	158	0.591071	0.2955355	0.5118825014	0
65	188	0.621071	0.2624759464	0.5628814836	0
70	218	0.651071	0.2226793967	0.6118066143	0
75	238	0.671071	0.1736859554	0.6482048102	0
80	255	0.688071	0.1194822753	0.6776176554	0
85	264	0.697071	0.06075374075	0.6944184344	0
90	270	0.703071	0	0.703071	0
95	272	0.705071	-0.06145098669	0.702387992	0

100	271	0.704071	-0.1222606461	0.6933745795	0
105	265	0.698071	-0.1806740696	0.6742848075	0
110	250	0.683071	-0.2336240413	0.6418767782	0
115	229	0.662071	-0.2798032952	0.6000401029	0
120	197	0.630071	-0.3150355	0.5456574922	0
125	163	0.596071	-0.34189228	0.4882727782	0
130	131	0.564071	-0.3625778498	0.4321034551	0
135	104	0.537071	-0.3797665461	0.3797665461	0
140	81	0.514071	-0.3938012329	0.3304384693	0
145	64	0.497071	-0.4071767258	0.2851082128	0
150	50	0.483071	-0.4183517578	0.2415355	0
155	40	0.473071	-0.4287479311	0.1999284437	0
160	33	0.466071	-0.4379634795	0.1594056702	0
165	28	0.461071	-0.4453603867	0.1193339559	0
170	26	0.459071	-0.45209668	0.07971684257	0
175	25	0.458071	-0.4563279015	0.03992351824	0
180	24	0.457071	-0.457071	0	0
185	24	0.457071	-0.4553317069	-0.03983636249	0
190	24	0.457071	-0.4501270645	-0.07936954621	0
195	24	0.457071	-0.4414966833	-0.1182986798	0
200	24	0.457071	-0.4295062459	-0.1563274889	0
205	24	0.457071	-0.4142470065	-0.1931665515	0
210	24	0.457071	-0.3958350973	-0.2285355	0
215	24	0.457071	-0.374410644	-0.2621651553	0
220	24	0.457071	-0.3501366997	-0.2937995755	0

225	24	0.457071	-0.3231980036	-0.3231980036	0
230	24	0.457071	-0.2937995755	-0.3501366997	0
235	24	0.457071	-0.2621651553	-0.374410644	0
240	24	0.457071	-0.2285355	-0.3958350973	0
245	24	0.457071	-0.1931665515	-0.4142470065	0
250	24	0.457071	-0.1563274889	-0.4295062459	0
255	24	0.457071	-0.1182986798	-0.4414966833	0
260	24	0.457071	-0.07936954621	-0.4501270645	0
265	23	0.456071	-0.03974920675	-0.4543355122	0
270	22	0.455071	0	-0.455071	0
275	20	0.453071	0.03948773952	-0.4513469281	0
280	20	0.453071	0.0786749535	-0.4461878335	0
285	19	0.452071	0.1170045845	-0.4366670542	0
290	18	0.451071	0.1542753681	-0.4238680902	0
295	17	0.450071	0.1902082237	-0.407902852	0
300	16	0.449071	0.2245355	-0.3889068941	0
305	14	0.447071	0.256429391	-0.3662191236	0
310	13	0.446071	0.2867289118	-0.3417102108	0
315	12	0.445071	0.3147127222	-0.3147127222	0
320	11	0.444071	0.3401781219	-0.2854433366	0
325	10	0.443071	0.3629425154	-0.2541350852	0
330	9	0.442071	0.3828447163	-0.2210355	0
335	7	0.440071	0.3988397741	-0.1859820411	0
340	6	0.439071	0.4125917787	-0.1501711264	0
345	4	0.437071	0.4221781668	-0.1131222989	0

350	3	0.436071	0.4294461017	-0.07572293448	0
355	2	0.435071	0.4334154235	-0.03791893615	0
360	0	0.433071	0.433071	0	0

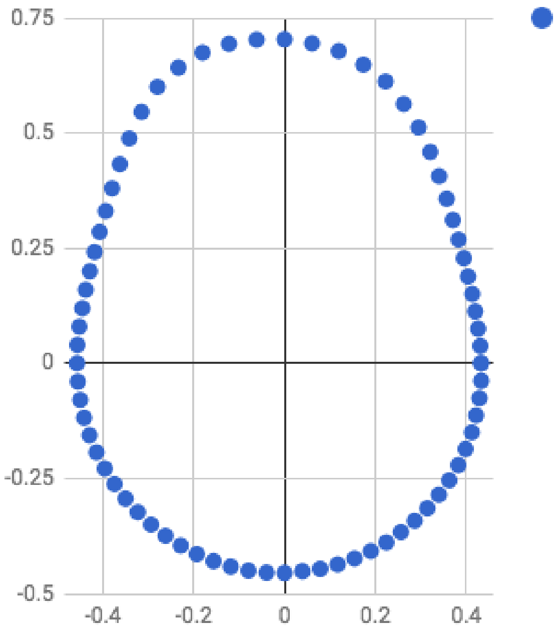


Figure 43: Intake Plot

Source: Own Elaboration

7.1.2 Exhaust Analysis

*	D	R	X	Y	Z
0	105	0.558017	0.558017	0	0
5	137	0.590017	0.5877718072	0.05142336987	0
10	172	0.625017	0.6155215874	0.1085330631	0
15	203	0.656017	0.6336637628	0.1697896935	0
20	226	0.679017	0.6380672643	0.2322374917	0
25	238	0.691017	0.6262740881	0.2920364034	0
30	242	0.695017	0.6019023781	0.3475085	0
35	243	0.696017	0.5701437484	0.3992189505	0
40	242	0.695017	0.5324139107	0.4467483161	0
45	240	0.693017	0.4900370202	0.4900370202	0
50	224	0.677017	0.4351781391	0.5186251107	0
55	208	0.661017	0.3791437752	0.5414734269	0
60	185	0.638017	0.3190085	0.55253893	0
65	158	0.611017	0.2582269424	0.5537694651	0
70	127	0.580017	0.1983774975	0.5450376948	0
75	98	0.551017	0.1426136938	0.532241551	0
80	71	0.524017	0.09099459712	0.5160560043	0
85	50	0.503017	0.04384082025	0.5011028685	0
90	31	0.484017	0	0.484017	0
95	14	0.467017	-0.04070321351	0.4652398593	0
100	2	0.455017	-0.07901287286	0.4481042694	0
105	-7	0.446017	-0.115437694	0.4308193393	0

110	-13	0.440017	-0.1504946774	0.4134807279	0
115	-17	0.436017	-0.1842687466	0.3951656024	0
120	-20	0.433017	-0.2165085	0.3750037223	0
125	-20	0.433017	-0.2483683477	0.3547067608	0
130	-20	0.433017	-0.2783379624	0.3317102666	0
135	-19	0.434017	-0.3068963639	0.3068963639	0
140	-18	0.435017	-0.3332423555	0.2796235376	0
145	-17	0.436017	-0.3571642169	0.250089077	0
150	-15	0.438017	-0.3793338493	0.2190085	0
155	-14	0.439017	-0.3978845257	0.1855366014	0
160	-12	0.441017	-0.4144204205	0.1508366975	0
165	-11	0.442017	-0.426955636	0.1144024179	0
170	-10	0.443017	-0.4362865763	0.07692909473	0
175	-9	0.444017	-0.4423273813	0.03869863143	0
180	-8	0.445017	-0.445017	0	0
185	-7	0.446017	-0.4443197707	-0.03887294291	0
190	-5	0.448017	-0.4412106151	-0.07779733561	0
195	-4	0.449017	-0.4337171167	-0.1162141512	0
200	-3	0.450017	-0.4228776541	-0.1539148788	0
205	-2	0.451017	-0.4087602192	-0.1906080206	0
210	-2	0.451017	-0.3905921795	-0.2255085	0
215	-1	0.452017	-0.3702706496	-0.2592663	0
220	-1	0.452017	-0.346265111	-0.290550927	0
225	0	0.453017	-0.3203313927	-0.3203313927	0
230	1	0.454017	-0.2918365022	-0.3477971999	0

235	1	0.454017	-0.2604134529	-0.3719089537	0
240	1	0.454017	-0.2270085	-0.3931902557	0
245	1	0.454017	-0.1918758753	-0.4114791425	0
250	1	0.454017	-0.1552829594	-0.4266364246	0
255	0	0.453017	-0.1172494274	-0.43758082	0
260	0	0.453017	-0.0786655765	-0.4461346538	0
265	-1	0.452017	-0.03939587737	-0.4502969388	0
270	-1	0.452017	0	-0.452017	0
275	-2	0.451017	0.03930872163	-0.4493007441	0
280	-3	0.450017	0.07814463197	-0.4431802306	0
285	-3	0.450017	0.1164729702	-0.4346830426	0
290	-3	0.450017	0.1539148788	-0.4228776541	0
295	-4	0.449017	0.189762784	-0.4069476036	0
300	-5	0.448017	0.2240085	-0.3879941033	0
305	-5	0.448017	0.2569719943	-0.3669940414	0
310	-5	0.448017	0.2879797765	-0.3432009333	0
315	-4	0.449017	0.3175029656	-0.3175029656	0
320	-4	0.449017	0.3439669777	-0.2886225641	0
325	-3	0.450017	0.3686323455	-0.2581191472	0
330	1	0.454017	0.3931902557	-0.2270085	0
335	8	0.461017	0.4178232971	-0.1948342032	0
340	20	0.473017	0.4444905844	-0.1617813421	0
345	33	0.486017	0.4694563723	-0.1257904558	0
350	53	0.506017	0.4983294648	-0.08786892992	0
355	75	0.528017	0.5260077359	-0.04601971382	0

360	105	0.558017	0.558017	0	0

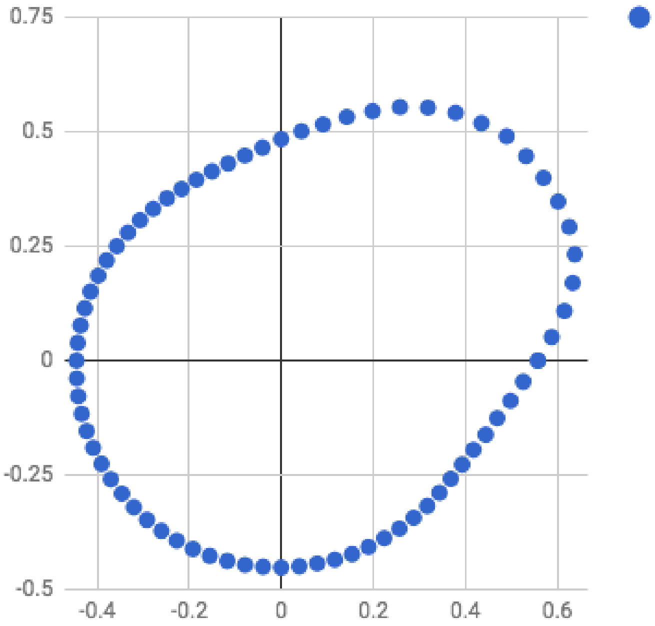


Figure 44: Exhaust Plot (Note phase relative to intake)

Source: Own Elaboration

7.1.3. Intake Design

*REF	*	D	R	X	Y	Z
0	0	0	0.433071	0.433071	0	0
5	3.333	0	0.433071	0.4323384589	0.02517832396	0
10	6.666	0	0.433071	0.4301433138	0.05027146947	0
15	9.999	2	0.435071	0.4284626124	0.07554180823	0
20	13.332	7	0.440071	0.4282111908	0.101477392	0
25	16.665	13	0.446071	0.427335061	0.1279221742	0
30	19.998	23	0.456071	0.4285719979	0.1559705089	0
35	23.331	35	0.468071	0.429797881	0.1853759491	0
40	26.664	51	0.484071	0.4325917567	0.2172305345	0
45	29.997	72	0.505071	0.4374175388	0.2525125972	0
50	33.33	97	0.530071	0.4428848048	0.291253008	0
55	36.663	127	0.560071	0.4492673411	0.3344224593	0
60	39.996	158	0.591071	0.4528131783	0.3799015038	0
65	43.329	188	0.621071	0.4517829079	0.4261706127	0
70	46.662	218	0.651071	0.4468305997	0.473535492	0
75	49.995	238	0.671071	0.4314009835	0.5140325656	0
80	53.328	255	0.688071	0.4109388824	0.5518794578	0
85	56.661	264	0.697071	0.3831043709	0.5823564373	0
90	59.994	270	0.703071	0.3515992596	0.6088405306	0
95	63.327	272	0.705071	0.3165049317	0.6300394775	0
100	66.66	271	0.704071	0.2789434975	0.6464568804	0
105	69.993	265	0.698071	0.2388344838	0.6559429932	0

110	73.326	250	0.683071	0.1959907233	0.6543497745	0
115	76.659	229	0.662071	0.1527702816	0.6442043543	0
120	79.992	197	0.630071	0.1094973179	0.6204835231	0
125	83.325	163	0.596071	0.0692857275	0.5920305102	0
130	86.658	131	0.564071	0.03288298949	0.5631117136	0
135	89.991	104	0.537071	0.00008436291506	0.5370709934	0
140	93.324	81	0.514071	-0.0298069708	0.5132061355	0
145	96.657	64	0.497071	-0.05762312374	0.4937197126	0
150	99.99	50	0.483071	-0.08380136665	0.4757466994	0
155	103.323	40	0.473071	-0.1090146599	0.4603389783	0
160	106.656	33	0.466071	-0.1335875446	0.4465160075	0
165	109.989	28	0.461071	-0.1576123857	0.4332952837	0
170	113.322	26	0.459071	-0.1817453511	0.4215623446	0
175	116.655	25	0.458071	-0.205498533	0.4093890496	0
180	119.988	24	0.457071	-0.2284525915	0.395882953	0
185	123.321	24	0.457071	-0.2510824104	0.3819313056	0
190	126.654	24	0.457071	-0.2728628159	0.366687582	0
195	129.987	24	0.457071	-0.2937201245	0.3502033517	0
200	133.32	24	0.457071	-0.3135837759	0.332534381	0
205	136.653	24	0.457071	-0.3323865712	0.3137404442	0
210	139.986	24	0.457071	-0.3500649004	0.2938851213	0
215	143.319	24	0.457071	-0.3665589577	0.273035583	0
220	146.652	24	0.457071	-0.3818129434	0.2512623634	0
225	149.985	24	0.457071	-0.3957752533	0.2286391216	0
230	153.318	24	0.457071	-0.4083986528	0.2052423919	0

235	156.651	24	0.457071	-0.4196404368	0.1811513259	0
240	159.984	24	0.457071	-0.4294625743	0.1564474236	0
245	163.317	24	0.457071	-0.4378318369	0.1312142586	0
250	166.65	24	0.457071	-0.4447199113	0.1055371949	0
255	169.983	24	0.457071	-0.4501034952	0.07950309811	0
260	173.316	24	0.457071	-0.4539643759	0.05320004178	0
265	176.649	23	0.456071	-0.4552912018	0.0266585567	0
270	179.982	22	0.455071	-0.4550709775	0.0001429647687	0
275	183.315	20	0.453071	-0.4523128818	-0.02619900739	0
280	186.648	20	0.453071	-0.4500246084	-0.05245171981	0
285	189.981	19	0.452071	-0.4452290333	-0.0783536661	0
290	193.314	18	0.451071	-0.4389473987	-0.1038760232	0
295	196.647	17	0.450071	-0.4312075795	-0.1289338142	0
300	199.98	16	0.449071	-0.4220422927	-0.1534440166	0
305	203.313	14	0.447071	-0.4105706086	-0.1769300834	0
310	206.646	13	0.446071	-0.3986957906	-0.200052502	0
315	209.979	12	0.445071	-0.3855243301	-0.2223942129	0
320	213.312	11	0.444071	-0.3711067402	-0.2438828416	0
325	216.645	10	0.443071	-0.3554975533	-0.2644492402	0
330	219.978	9	0.442071	-0.3387551168	-0.2840277097	0
335	223.311	7	0.440071	-0.3202137362	-0.3018702506	0
340	226.644	6	0.439071	-0.3014351234	-0.319249447	0
345	229.977	4	0.437071	-0.2810782044	-0.3347030057	0
350	233.31	3	0.436071	-0.2605459694	-0.3496765861	0
355	236.643	2	0.435071	-0.2392255465	-0.3633977338	0

360	239.976	0	0.433071	-0.2166925818	-0.3749597526	0
365	243.309	0	0.433071	-0.1945262526	-0.3869238014	0
370	246.642	0	0.433071	-0.1717018398	-0.3975788843	0
375	249.975	0	0.433071	-0.1482965584	-0.4068889551	0
380	253.308	0	0.433071	-0.1243895888	-0.4148225178	0
385	256.641	0	0.433071	-0.1000618083	-0.421352733	0
390	259.974	0	0.433071	-0.07539551799	-0.4264575089	0
395	263.307	0	0.433071	-0.05047416414	-0.4301195762	0
400	266.64	0	0.433071	-0.02538205585	-0.4323265459	0
405	269.973	0	0.433071	-0.0002040798933	-0.4330709519	0
410	273.306	0	0.433071	0.02497458647	-0.4323502759	0
415	276.639	0	0.433071	0.05006876364	-0.4301669559	0
420	279.972	0	0.433071	0.07499355783	-0.4265283781	0
425	283.305	0	0.433071	0.09966464829	-0.4214468518	0
430	286.638	0	0.433071	0.1239985726	-0.4149395679	0
435	289.971	0	0.433071	0.1479130088	-0.4070285406	0
440	293.304	0	0.433071	0.1713270543	-0.3977405329	0
445	296.637	0	0.433071	0.1941614992	-0.3871069662	0
450	299.97	0	0.433071	0.2163390944	-0.3751638139	0
455	303.303	0	0.433071	0.2377848129	-0.3619514799	0
460	306.636	0	0.433071	0.2584261037	-0.3475146615	0
465	309.969	0	0.433071	0.2781931373	-0.3319021986	0
470	313.302	0	0.433071	0.2970190415	-0.3151669082	0
475	316.635	0	0.433071	0.3148401283	-0.297365406	0
480	319.968	0	0.433071	0.3315961087	-0.2785579146	0

485	323.301	0	0.433071	0.3472302971	-0.2588080598	0
490	326.634	0	0.433071	0.3616898031	-0.2381826555	0
495	329.967	0	0.433071	0.3749257099	-0.2167514776	0
500	333.3	0	0.433071	0.3868932405	-0.194587028	0
505	336.633	0	0.433071	0.3975519086	-0.1717642892	0
510	339.966	0	0.433071	0.4068656557	-0.1483604705	0
515	343.299	0	0.433071	0.4148029736	-0.1244547474	0
520	346.632	0	0.433071	0.4213370101	-0.100127993	0
525	349.965	0	0.433071	0.4264456606	-0.07546250484	0
530	353.298	0	0.433071	0.4301116424	-0.05054172655	0
535	356.631	0	0.433071	0.4323225536	-0.02544996524	0
540	359.964	0	0.433071	0.4330709145	-0.0002721065165	0

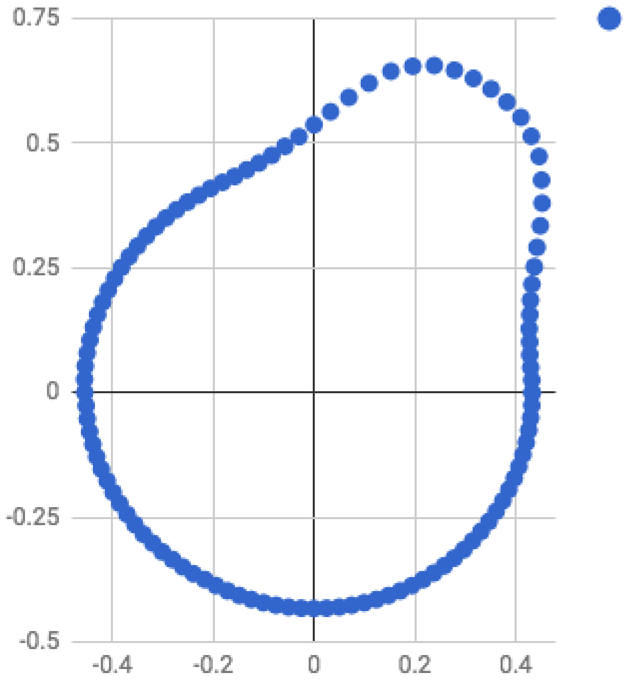


Figure 45: Intake Design Plot (Initial)

Source: Own Elaboration

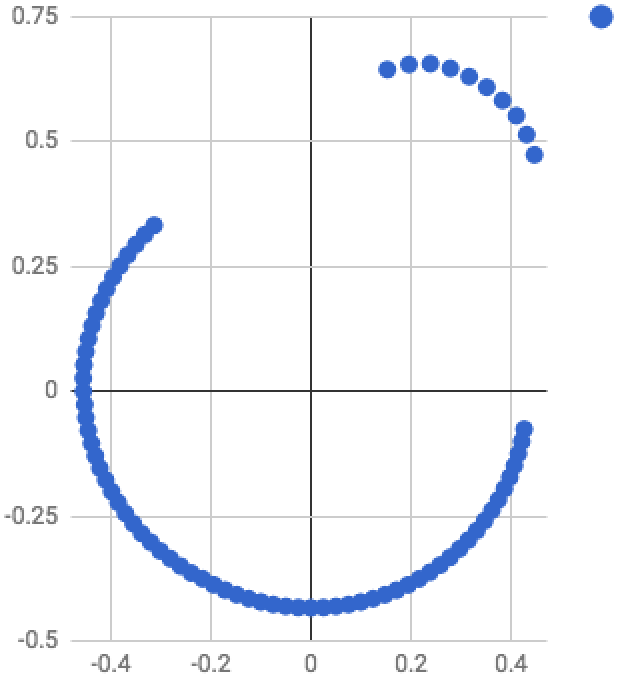


Figure 46: Intake Design Plot (Edited)

Source: Own Elaboration

7.1.4. Exhaust Design

*REF	*	D	R	X	Y	Z
0	0	-8	0.445017	0.445017	0	0
5	3.333	-7	0.446017	0.4452625607	0.02593099172	0
10	6.666	-5	0.448017	0.4449882745	0.05200642144	0
15	9.999	-4	0.449017	0.4421967836	0.07796326601	0
20	13.332	-3	0.450017	0.4378891485	0.1037708722	0
25	16.665	-2	0.451017	0.4320733184	0.1293405652	0
30	19.998	-2	0.451017	0.4238227311	0.1542421049	0
35	23.331	-1	0.452017	0.4150565807	0.1790178848	0
40	26.664	-1	0.452017	0.4039465865	0.2028460587	0
45	29.997	-1	0.452017	0.3914700382	0.225988003	0
50	33.33	-1	0.452017	0.377669144	0.2483654283	0
55	36.663	-1	0.452017	0.3625905925	0.2699026316	0
60	39.996	-1	0.452017	0.3462853945	0.2905267524	0
65	43.329	-1	0.452017	0.3288087106	0.3101680192	0
70	46.662	-1	0.452017	0.3102196645	0.3287599854	0
75	49.995	-1	0.452017	0.2905811432	0.3462397544	0
80	53.328	-1	0.452017	0.2699595838	0.3625481918	0
85	56.661	-1	0.452017	0.2484247493	0.3776301262	0
90	59.994	-1	0.452017	0.2260494922	0.3914345352	0
95	63.327	-1	0.452017	0.202909508	0.4039147185	0
100	66.66	-1	0.452017	0.1790830796	0.4150284555	0
105	69.993	-1	0.452017	0.1546508118	0.4247381484	0

110	73.326	-1	0.452017	0.1296953593	0.4330109491	0
115	76.659	-1	0.452017	0.1043011465	0.4398188708	0
120	79.992	-1	0.452017	0.0785540822	0.4451388822	0
125	83.325	-1	0.452017	0.05254126888	0.4489529857	0
130	86.658	-1	0.452017	0.02635070809	0.4512482781	0
135	89.991	-1	0.452017	0.00007100266403	0.4520169944	0
140	93.324	-1	0.452017	-0.02620894296	0.4512565341	0
145	96.657	-1	0.452017	-0.05240022355	0.4489694699	0
150	99.99	-1	0.452017	-0.07841423382	0.4451635387	0
155	103.323	-1	0.452017	-0.1041629682	0.4398516163	0
160	106.656	-1	0.452017	-0.1295593185	0.4330516728	0
165	109.989	-1	0.452017	-0.1545173688	0.4247867124	0
170	113.322	-1	0.452017	-0.1789526857	0.4150846957	0
175	116.655	-1	0.452017	-0.2027826044	0.4039784445	0
180	119.988	-1	0.452017	-0.2259265082	0.3915055315	0
185	123.321	-1	0.452017	-0.2483061011	0.3777081525	0
190	126.654	-1	0.452017	-0.2698456726	0.3626329842	0
195	129.987	-1	0.452017	-0.2904723544	0.346331026	0
200	133.32	-1	0.452017	-0.3101163662	0.3288574276	0
205	136.653	-1	0.452017	-0.3287112522	0.3102713022	0
210	139.986	-1	0.452017	-0.3461941057	0.2906355268	0
215	143.319	-1	0.452017	-0.3625057822	0.2700165294	0
220	146.652	-1	0.452017	-0.3775910991	0.2484840643	0
225	149.985	-1	0.452017	-0.3913990226	0.2261109758	0
230	153.318	-1	0.452017	-0.4038828406	0.2029729523	0

235	156.651	-1	0.452017	-0.4150003201	0.1791482699	0
240	159.984	-1	0.452017	-0.4247138506	0.1547175276	0
245	163.317	-1	0.452017	-0.4329905713	0.1297633749	0
250	166.65	-1	0.452017	-0.4398024818	0.1043702318	0
255	169.983	-1	0.452017	-0.4451265375	0.07862400349	0
260	173.316	-1	0.452017	-0.448944727	0.05261178961	0
265	176.649	-1	0.452017	-0.4512441334	0.02642158968	0
270	179.982	-1	0.452017	-0.4520169777	0.0001420053263	0
275	183.315	-2	0.451017	-0.4502623187	-0.02608023404	0
280	186.648	-3	0.450017	-0.4469911431	-0.05209816032	0
285	189.981	-3	0.450017	-0.44320612	-0.07799766355	0
290	193.314	-3	0.450017	-0.4379217275	-0.1036333001	0
295	196.647	-4	0.449017	-0.4301977548	-0.1286318702	0
300	199.98	-5	0.448017	-0.4210517309	-0.1530838731	0
305	203.313	-5	0.448017	-0.4114393739	-0.1773044666	0
310	206.646	-5	0.448017	-0.4004351147	-0.2009252379	0
315	209.979	-4	0.449017	-0.3889423893	-0.2243659602	0
320	213.312	-4	0.449017	-0.3752400746	-0.2465991742	0
325	216.645	-3	0.450017	-0.3610706691	-0.2685949966	0
330	219.978	1	0.454017	-0.3479092315	-0.2917029361	0
335	223.311	8	0.461017	-0.3354549062	-0.3162383282	0
340	226.644	20	0.473017	-0.3247400483	-0.343931655	0
345	229.977	33	0.486017	-0.3125551356	-0.3721851844	0
350	233.31	53	0.506017	-0.3023376693	-0.4057648802	0
355	236.643	75	0.528017	-0.29033228	-0.4410318803	0

360	239.976	105	0.558017	-0.2792109017	-0.4831399845	0
365	243.309	137	0.590017	-0.265023047	-0.5271459427	0
370	246.642	172	0.625017	-0.2478036368	-0.5737940466	0
375	249.975	203	0.656017	-0.2246399859	-0.616356375	0
380	253.308	226	0.679017	-0.1950318663	-0.6504049949	0
385	256.641	238	0.691017	-0.1596606805	-0.6723190919	0
390	259.974	242	0.695017	-0.1209990203	-0.6844032929	0
395	263.307	243	0.696017	-0.08112036203	-0.6912735719	0
400	266.64	242	0.695017	-0.0407345685	-0.6938222577	0
405	269.973	240	0.693017	-0.0003265765553	-0.6930169231	0
410	273.306	224	0.677017	0.03904260412	-0.6758902968	0
415	276.639	208	0.661017	0.07642235091	-0.6565844185	0
420	279.972	185	0.638017	0.1104834191	-0.6283781556	0
425	283.305	158	0.611017	0.1406161909	-0.5946165665	0
430	286.638	127	0.580017	0.1660727226	-0.5557333633	0
435	289.971	98	0.551017	0.1881968138	-0.5178819301	0
440	293.304	71	0.524017	0.2073061669	-0.4812670459	0
445	296.637	50	0.503017	0.225520838	-0.4496292405	0
450	299.97	31	0.484017	0.2417889894	-0.4192976758	0
455	303.303	14	0.467017	0.256423427	-0.3903228207	0
460	306.636	2	0.455017	0.2715219224	-0.3651250689	0
465	309.969	-7	0.446017	0.2865092987	-0.3418239109	0
470	313.302	-13	0.440017	0.3017829122	-0.3202218515	0
475	316.635	-17	0.436017	0.3169818533	-0.2993882579	0
480	319.968	-20	0.433017	0.3315547617	-0.2785231809	0

485	323.301	-20	0.433017	0.3471870007	-0.2587757888	0
490	326.634	-20	0.433017	0.3616447037	-0.2381529563	0
495	329.967	-19	0.434017	0.3757446974	-0.2172249494	0
500	333.3	-18	0.435017	0.3886317412	-0.1954614028	0
505	336.633	-17	0.436017	0.4002562871	-0.1729327295	0
510	339.966	-15	0.438017	0.4115123708	-0.1500548599	0
515	343.299	-14	0.439017	0.4204981563	-0.1261634924	0
520	346.632	-12	0.441017	0.4290677145	-0.1019651445	0
525	349.965	-11	0.442017	0.4352548001	-0.07702134293	0
530	353.298	-10	0.443017	0.4399896772	-0.05170247851	0
535	356.631	-9	0.444017	0.4432496363	-0.02609322077	0
540	359.964	-8	0.445017	0.4450169122	-0.0002796124092	0

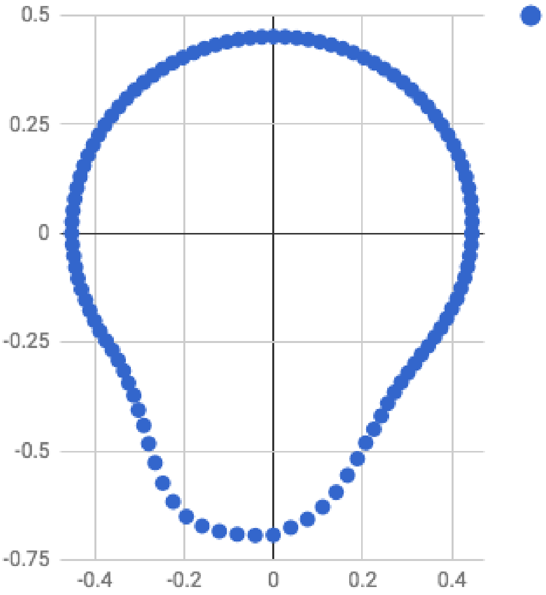


Figure 47: Exhaust Design Plot (Initial)

Source: Own Elaboration

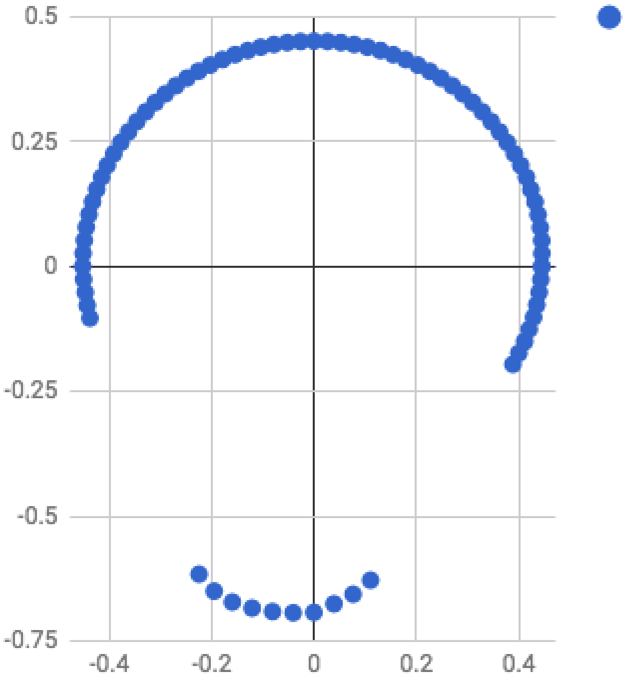


Figure 48: Exhaust Design Plot (Edited)

Source: Own Elaboration

7.1.5 Steam Exhaust Design

*REF	*	D	R	X	Y	Z
0	0	105	0.558017	0.558017	0	0
5	3.333	137	0.590017	0.5890189842	0.03430301075	0
10	6.666	172	0.625017	0.6207917029	0.07255282167	0
15	9.999	203	0.656017	0.6460526158	0.1139048808	0
20	13.332	226	0.679017	0.6607176528	0.1565767211	0
25	16.665	238	0.691017	0.6619928035	0.198166653	0
30	19.998	242	0.695017	0.6531106435	0.2376870162	0
35	23.331	243	0.696017	0.6391052463	0.2756522236	0
40	26.664	242	0.695017	0.6211043937	0.3118941527	0
45	29.997	240	0.693017	0.6001884696	0.3464770747	0
50	33.33	224	0.677017	0.5656610943	0.3719940116	0
55	36.663	208	0.661017	0.5302423265	0.3946980485	0
60	39.996	185	0.638017	0.4887780073	0.4100753002	0
65	43.329	158	0.611017	0.4444693715	0.4192716924	0
70	46.662	127	0.580017	0.3980661771	0.4218566569	0
75	49.995	98	0.551017	0.3542237345	0.4220726007	0
80	53.328	71	0.524017	0.3129603781	0.4202970592	0
85	56.661	50	0.503017	0.2764539213	0.4202372326	0
90	59.994	31	0.484017	0.2420523942	0.4191456725	0
95	63.327	14	0.467017	0.2096429774	0.4173184639	0
100	66.66	2	0.455017	0.1802716394	0.4177829656	0
105	69.993	-7	0.446017	0.1525980022	0.4191002434	0

110	73.326	-13	0.440017	0.1262522492	0.4215155156	0
115	76.659	-17	0.436017	0.1006092094	0.4242506468	0
120	79.992	-20	0.433017	0.07525215426	0.4264279958	0
125	83.325	-20	0.433017	0.05033275879	0.4300817779	0
130	86.658	-20	0.433017	0.02524308724	0.4322805904	0
135	89.991	-19	0.434017	0.00006817523066	0.4340169946	0
140	93.324	-18	0.435017	-0.02522324546	0.4342851346	0
145	96.657	-17	0.436017	-0.05054541814	0.433077343	0
150	99.99	-15	0.438017	-0.07598556571	0.4313758061	0
155	103.323	-14	0.439017	-0.1011672433	0.4272014925	0
160	106.656	-12	0.441017	-0.1264064448	0.422513201	0
165	109.989	-11	0.442017	-0.1510989715	0.4153891297	0
170	113.322	-10	0.443017	-0.1753896025	0.4068200457	0
175	116.655	-9	0.444017	-0.1991936668	0.3968286524	0
180	119.988	-8	0.445017	-0.222427778	0.3854426207	0
185	123.321	-7	0.446017	-0.2450101263	0.372694516	0
190	126.654	-5	0.448017	-0.2674577476	0.3594239635	0
195	129.987	-4	0.449017	-0.2885445131	0.3440324552	0
200	133.32	-3	0.450017	-0.3087442215	0.327402361	0
205	136.653	-2	0.451017	-0.3279840423	0.3095848871	0
210	139.986	-2	0.451017	-0.3454282184	0.2899925521	0
215	143.319	-1	0.452017	-0.3625057822	0.2700165294	0
220	146.652	-1	0.452017	-0.3775910991	0.2484840643	0
225	149.985	-1	0.452017	-0.3913990226	0.2261109758	0
230	153.318	-1	0.452017	-0.4038828406	0.2029729523	0

235	156.651	-1	0.452017	-0.4150003201	0.1791482699	0
240	159.984	-1	0.452017	-0.4247138506	0.1547175276	0
245	163.317	-1	0.452017	-0.4329905713	0.1297633749	0
250	166.65	-1	0.452017	-0.4398024818	0.1043702318	0
255	169.983	-1	0.452017	-0.4451265375	0.07862400349	0
260	173.316	-1	0.452017	-0.448944727	0.05261178961	0
265	176.649	-1	0.452017	-0.4512441334	0.02642158968	0
270	179.982	-1	0.452017	-0.4520169777	0.0001420053263	0
275	183.315	-1	0.452017	-0.4512606455	-0.02613805943	0
280	186.648	-1	0.452017	-0.4489776953	-0.05232969895	0
285	189.981	-1	0.452017	-0.4451758505	-0.07834430673	0
290	193.314	-1	0.452017	-0.4398679727	-0.1040938752	0
295	196.647	-1	0.452017	-0.4330720185	-0.1294912933	0
300	199.98	-1	0.452017	-0.4248109787	-0.1544506415	0
305	203.313	-1	0.452017	-0.4151128004	-0.1788874821	0
310	206.646	-1	0.452017	-0.4040102925	-0.2027191452	0
315	209.979	-1	0.452017	-0.3915410151	-0.2258650079	0
320	213.312	-1	0.452017	-0.3777471517	-0.2482467677	0
325	216.645	-1	0.452017	-0.362675367	-0.2697887071	0
330	219.978	-1	0.452017	-0.3463766491	-0.2904179493	0
335	223.311	-1	0.452017	-0.3289061365	-0.3100647056	0
340	226.644	-1	0.452017	-0.3103229322	-0.3286625108	0
345	229.977	-1	0.452017	-0.2906899033	-0.3461484485	0
350	233.31	-1	0.452017	-0.2700734684	-0.3624633636	0
355	236.643	-1	0.452017	-0.2485433731	-0.3775520626	0

360	239.976	-1	0.452017	-0.2261724538	-0.3913635004	0
365	243.309	-1	0.452017	-0.2030363915	-0.4038509527	0
370	246.642	-1	0.452017	-0.1792134558	-0.4149721744	0
375	249.975	-1	0.452017	-0.1547842396	-0.4246895424	0
380	253.308	-1	0.452017	-0.1298313873	-0.4329701828	0
385	256.641	-1	0.452017	-0.1044393145	-0.4397860819	0
390	259.974	-1	0.452017	-0.07869392283	-0.4451141818	0
395	263.307	-1	0.452017	-0.05268230903	-0.4489364572	0
400	266.64	-1	0.452017	-0.02649247061	-0.4512399775	0
405	269.973	-1	0.452017	-0.0002130079851	-0.4520169498	0
410	273.306	-1	0.452017	0.02606717525	-0.4512647456	0
415	276.639	-1	0.452017	0.05225917305	-0.4489859097	0
420	279.972	-1	0.452017	0.07827437771	-0.4451881513	0
425	283.305	-1	0.452017	0.1040247796	-0.4398843183	0
430	286.638	-1	0.452017	0.1294232649	-0.4330923536	0
435	289.971	-1	0.452017	0.1543839105	-0.4248352345	0
440	293.304	-1	0.452017	0.1788222742	-0.4151408948	0
445	296.637	-1	0.452017	0.2026556809	-0.4040421306	0
450	299.97	-1	0.452017	0.225803502	-0.3915764891	0
455	303.303	-2	0.451017	0.2476383617	-0.3769503629	0
460	306.636	-3	0.450017	0.2685382764	-0.3611128554	0
465	309.969	-3	0.450017	0.2890787909	-0.3448894793	0
470	313.302	-3	0.450017	0.3086413498	-0.3274993397	0
475	316.635	-4	0.449017	0.3264327786	-0.3083146239	0
480	319.968	-5	0.448017	0.3430400415	-0.2881714112	0

485	323.301	-5	0.448017	0.3592137918	-0.267739956	0	
490	326.634	-5	0.448017	0.3741723194	-0.2464027348	0	
495	329.967	-4	0.449017	0.3887307566	-0.2247324301	0	
500	333.3	-4	0.449017	0.4011389407	-0.2017518688	0	
505	336.633	-3	0.450017	0.4131080521	-0.1784853988	0	
510	339.966	1	0.454017	0.4265442027	-0.1555361032	0	
515	343.299	8	0.461017	0.4415701409	-0.1324857917	0	
520	346.632	20	0.473017	0.4602006796	-0.1093636906	0	
525	349.965	33	0.486017	0.4785816658	-0.08468833105	0	
530	353.298	53	0.506017	0.5025591715	-0.05905491904	0	
535	356.631	75	0.528017	0.527104465	-0.03102958705	0	
540	359.964	105	0.558017	0.5580168899	-0.0003506123985	0	

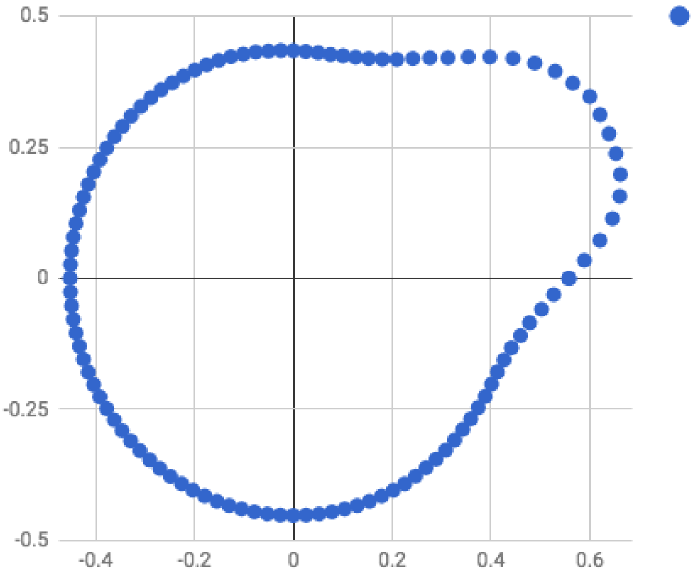


Figure 49: Steam Exhaust Design Plot (Initial)

Source: Own Elaboration

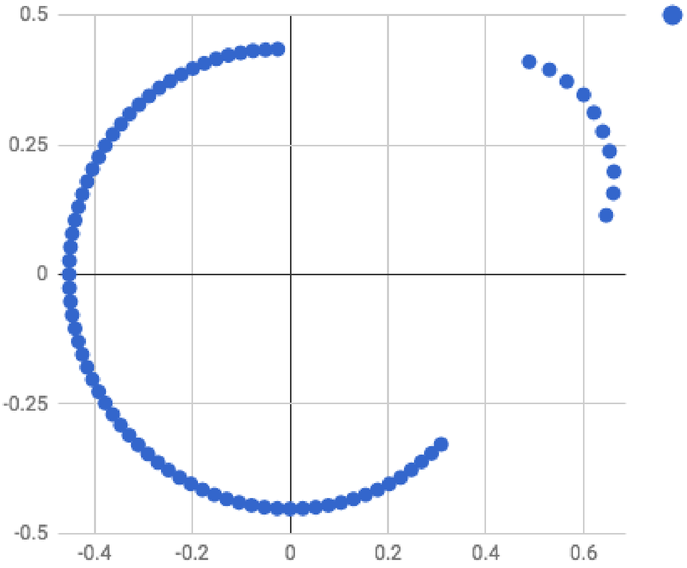


Figure 50: Steam Exhaust Design Plot (Edited)

Source: Own Elaboration

7.2 CAD Production Drawings

The following section contains the CAD production drawings for the whole camshaft piece (shaft, cam lobes and assembly) and the timing gear. All four Drawings came from CAD designed in SolidWorks®. Such drawings are drawn to scale, but scale is not shown, as the size of each drawing in not defined. However, all dimensions are numerically shown. Note that the drawings do not match the final pieces, they were initially drawn to serve as a starting point and they do not take into account final modifications such as the change in the number of teeth (from 57 to 30). Moreover, the lobes are also indicative for timing and not cam lobe geometry.

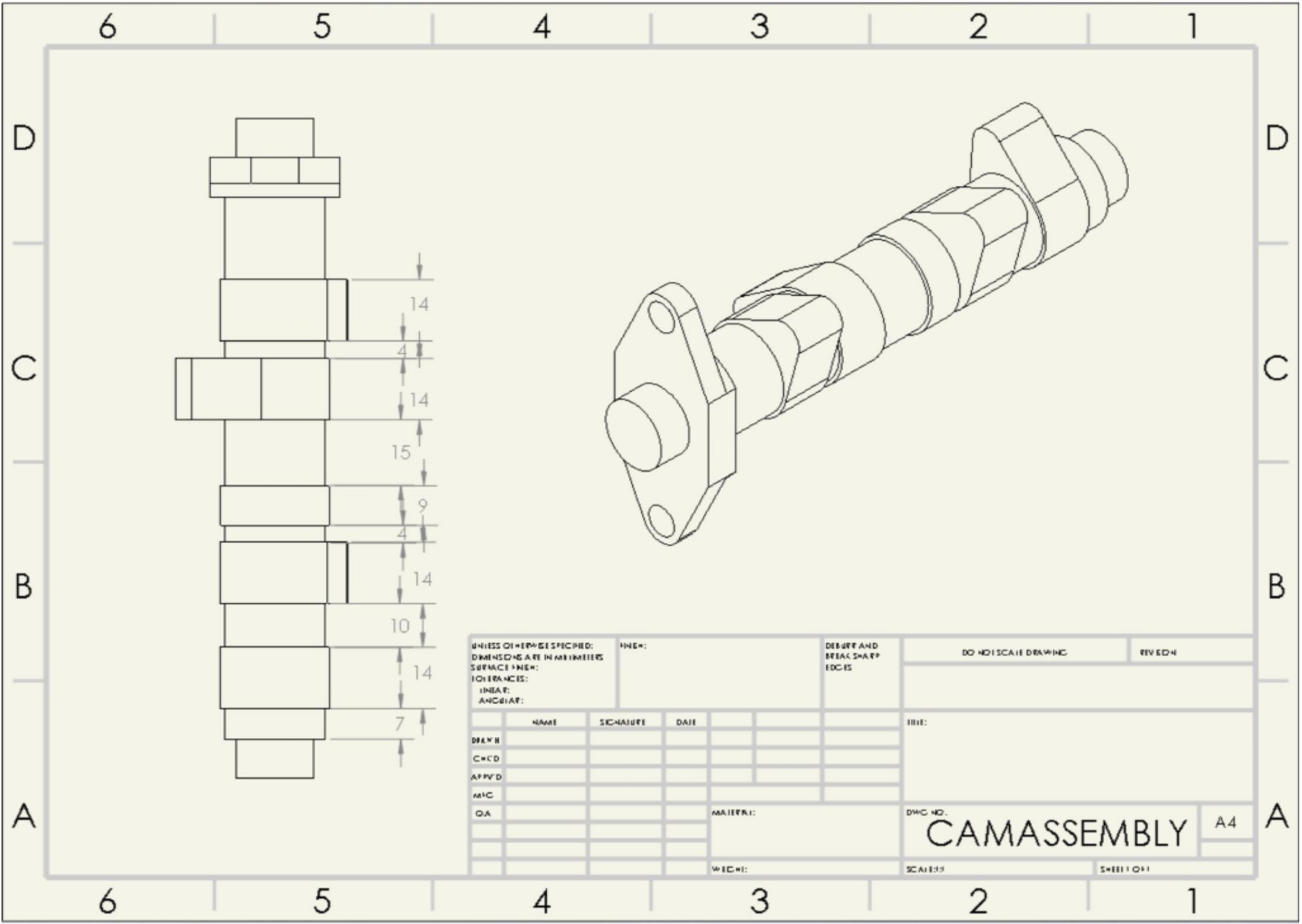
7.2.1.a. Cam Assembly

7.2.1.b. Cam Base (lobes)

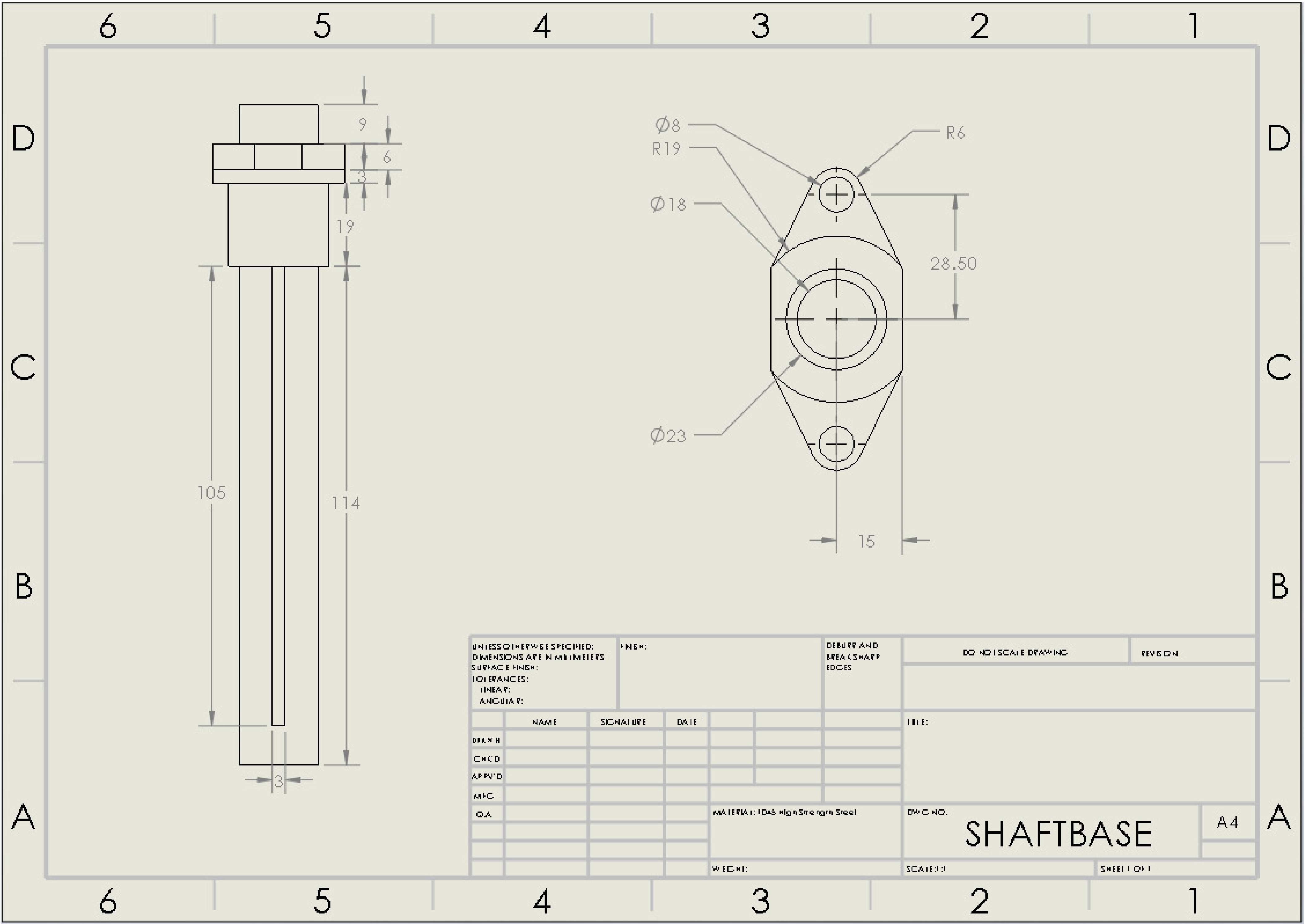
7.2.1.c. Shaft Base

7.2.2 Timing Gear

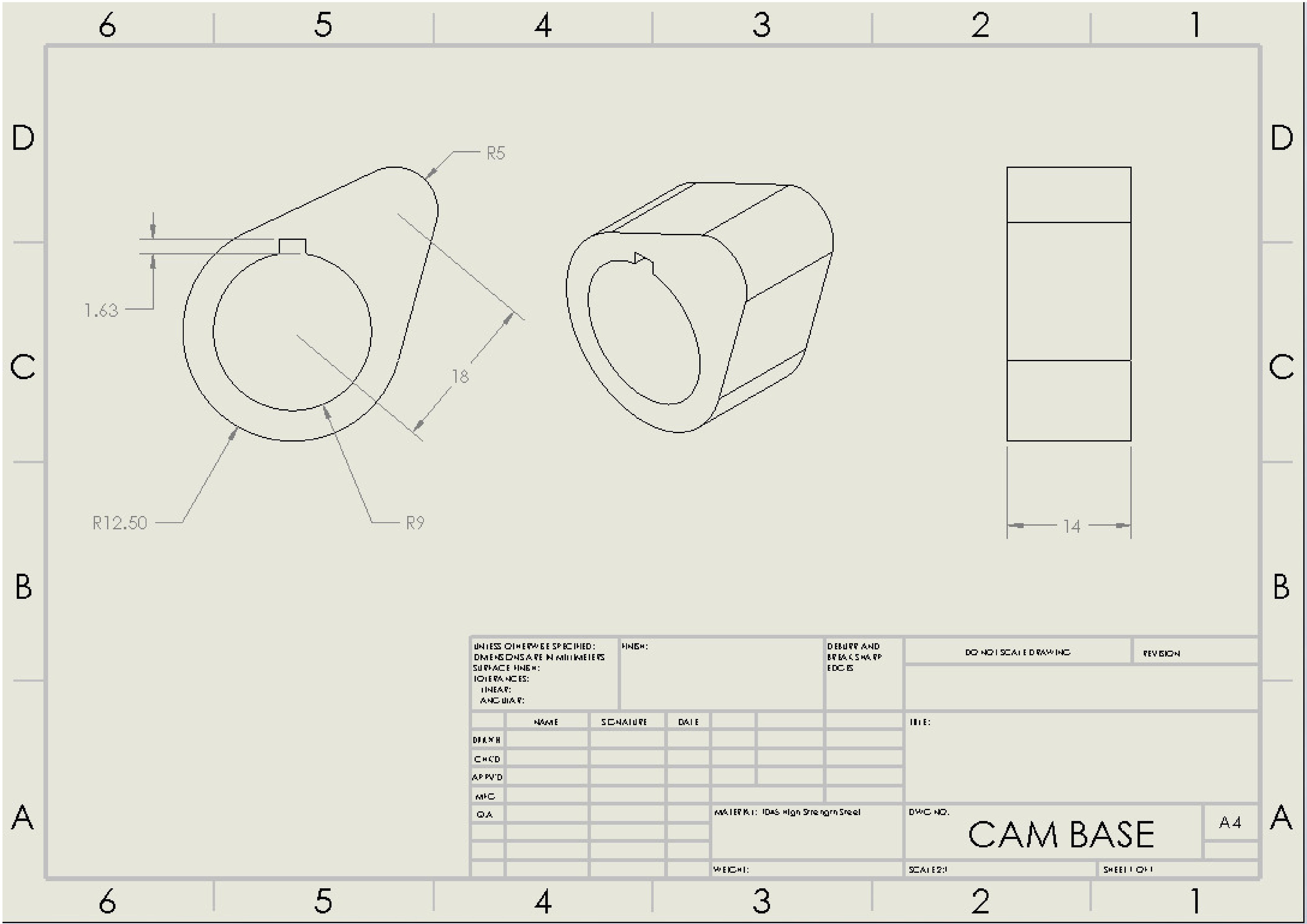
5.3.1.a.


6
5
4
3
2
1
D
C
B
A
14
4
14
15
9
4
14
10
14
7
UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN MILLIMETERS
SURFACE FINISH:
TOLERANCES:
LINEAR:
ANGULAR:
FINISH:
DEBURR AND BREAK SHARP EDGES
DO NOT SCALE DRAWING
REVISION
NAME
SIGNATURE
DATE
DRAWN
CHK'D
APPV'D
MFG
Q.A
TITLE:
MATERIAL:
DWG NO.
CAMASSEMBLY
A4
WEIGHT:
SCALE:1:1
SHEET 1 OF 1

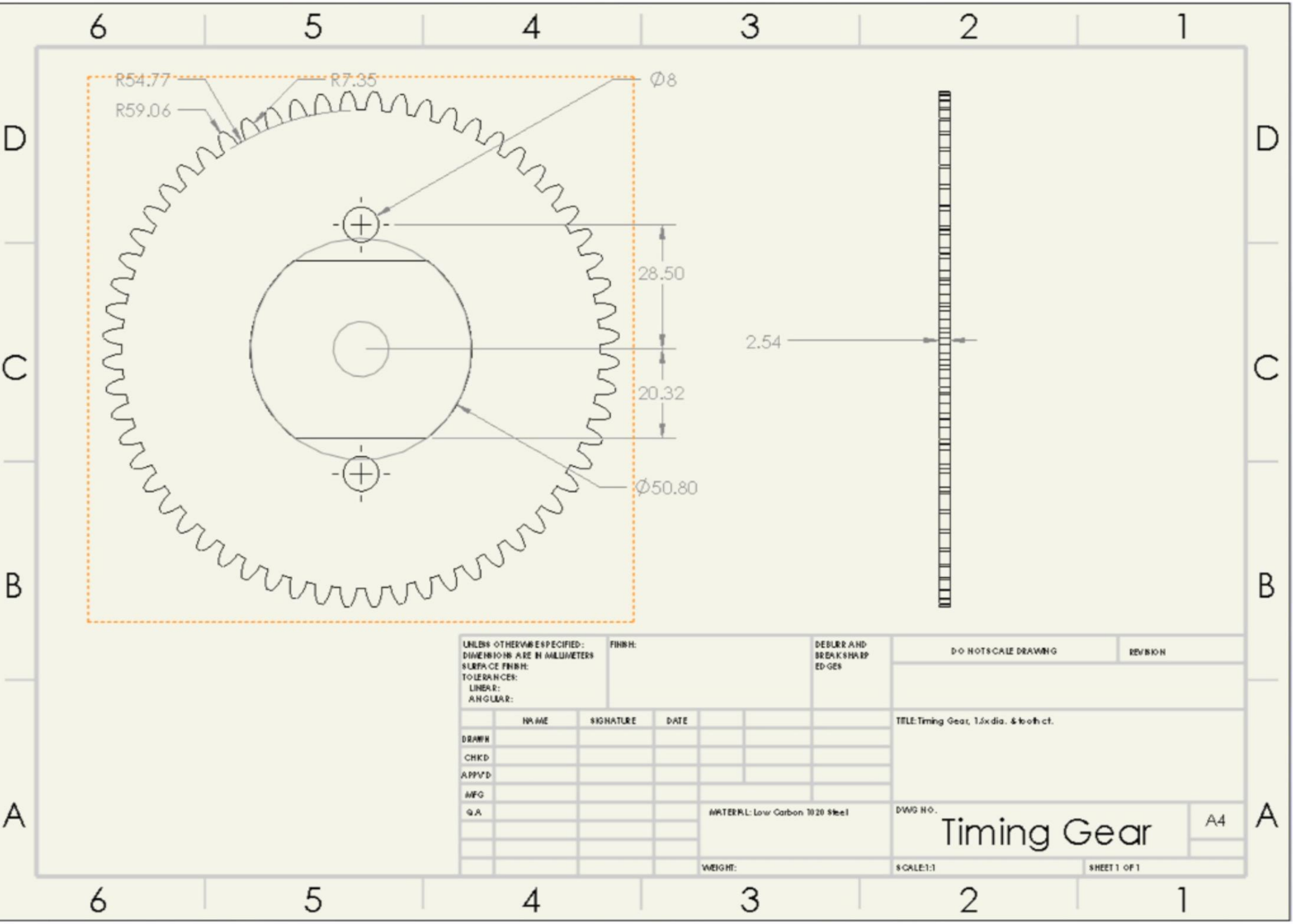
5.3.1.b.


9
6
3
19
105
114
3
Ø8
R19
Ø18
Ø23
R6
28.50
15
UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN MILLIMETERS
SURFACE FINISH:
TOLERANCES:
LINEAR:
ANGULAR:
FINISH:
DEBURR AND BREAK SHARP EDGES
DO NOT SCALE DRAWING
REVISION
NAME
SIGNATURE
DATE
DRAWN
CHK'D
APPV'D
MFG
Q.A
TITLE:
MATERIAL: IDAS High Strength Steel
DWG NO.
SHAFTBASE
A4
WEIGHT:
SCALE:1:1
SHEET 1 OF 1
1
2
3
4
5
6
A
B
C
D

5.3.1.c.


R5
1.63
18
R12.50
R9
14
UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN MILLIMETERS
SURFACE FINISH:
TOLERANCES:
LINEAR:
ANGULAR:
FINISH:
DEBURR AND BREAK SHARP EDGES
DO NOT SCALE DRAWING
REVISION
NAME
SIGNATURE
DATE
DRAWN
CHK'D
APPV'D
MFG
Q.A
TITLE:
MATERIAL: 1045 High Strength Steel
WEIGHT:
DWG NO.
CAM BASE
A4
SCALE:2:1
SHEET 1 OF 1
A
B
C
D
1
2
3
4
5
6

5.3.2


R54.77
R59.06
R7.35
Ø8
28.50
20.32
Ø50.80
2.54
UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN MILLIMETERS
SURFACE FINISH:
TOLERANCES:
LINEAR:
ANGULAR:
FINISH:
DEBURR AND BREAK SHARP EDGES
DO NOT SCALE DRAWING
REVISION
NAME
SIGNATURE
DATE
DRAWN
CHK'D
APPV'D
MFG
Q.A
TITLE: Timing Gear, 1.5x dia. & tooth ct.
MATERIAL: Low Carbon 1020 Steel
DWG NO.
Timing Gear
A4
WEIGHT:
SCALE:1:1
SHEET 1 OF 1
6
5
4
3
2
1
D
C
B
A