DEVELOPMENT OF COMPRESSED AIR POWERED ENGINE SYSTEM BASED ON SUBARU EA71 MODEL

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A project report submitted in partial fulfillment of the requirements
for the award of the degree of
Bachelor of Mechanical Engineering with Automotive Engineering

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FACULTY OF MECHANICAL ENGINEERING

I certify that the project entitled DEVELOPMENT OF COMPRESSED AIR POWERED ENGINE SYSTEM BASED ON SUBARU EA71 MODEL is written by CHEN RUI. I have examined the final copy of this report, and in my opinion, it is fully adequate in terms of language standard, and report formatting requirement for the award of the degree of Bachelor of Engineering. I herewith recommend that it be accepted in partial fulfillment of the requirements for the degree of Bachelor of Mechanical Engineering with Automotive Engineering.

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I hereby declare that the work in this project is my own except for quotations and summaries which have been duly acknowledged. The project has not been accepted for any degree and is not concurrently submitted for award of other degree.

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Dedicated to my dear parents

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ABSTRACT

This thesis deals with development of compressed air powered engine system based on Subaru EA71 model. The objective of this thesis is to make a reverse engineering and design of the engine model, and make the computational analysis of the compressed air powered engine working model by using GT-Power. The thesis describes the compressed air technology that addresses the problems of exhaust gas pollution from vehicles, as well as utilization of fossil fuel. The development of the compressed air powered engine model starts with dismantling the original engine, cleaning the engine with petrol, and drawing all the components into Solidworks. Then develop the engine into two working stages that working with gasoline for four cylinders in the first stage and working with compressed air for two cylinders in the second stage. In this thesis, the research focuses on the second stage. Some components such as cylinder heads and cam profile are modified based on the new design. After this, a simulation by GT-Power is run, and computational analysis the performance of new compressed air powered engine. The results indicated the engine performance predictions and key cylinder predictions. The project achieves the objective of reducing the emission of carbon dioxide. However the new model lacks the power output so that continuous research is needed to fully prove the viability of the technology of the compressed air powered engine.

ABSTRAK

Thsis ini membincangkan tentang pembangunan udara termampat sistem enjin kuasa pada model Subaru EA71. Objektif project ini telah melakukan terbalik dari reka bentuk model enjin, dan pengiraan udara berkuasa model termampat enjin bekerja dengan menggunakan GT- Power telah dianalisis. Tesis ini menerangkan teknologi udara termampat untuk menangani masalah pencemaran gas ekzos dari kenderaan serta kegunaan bahan api fosil. Pelajar telah membuatkan udara termampat berkuasa model enjin bermula dengan pembongkaran enjin asal, membersihkan enjin dengan petrol, dan lukiskan komponen dalam Solidworks. Selepas itu, beliau membahagikan enjin kepada dua peringkat kerja ia itu yang bekerja dengan petrol empat silinder dalam peringkat pertama dan bekerja dengan udara termampat untuk dua slinder pada peringkat kedua. Dalam tesis ini, kajian ini telah member tumpuan pada peringkat kedua. Sesetengah komponen seperti kepala silinder dan profil cam diubah suai berdasarkan reka bentuk baru. Selepas itu, simulasi telah dibuat pada GT-Power. Analisis ini telah dijalankan dan pengiraan prestasi baru tentang udara termampat enjin berkuasa. Keputusan telah menunjukkan ramalan prestasi enjin dan ramalan utama slinder. Projek ini telan mencapai matlamat bahawa enjin ini telah megurangkan pelepasan karbon dioksida. Walau bagaimanapun, kekurangan keluaran kuasa teantang model baru dilakaukan supaya kajian diperlukan benar-benar membuktikan teknologi daripada udara termampat enjin berkuasa.

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LIST OF SYMBOLS

A	Cross-section area of piston
B	Bore
BP	Brake power
BMEP	Brake mean efficiency pressure
CR	Cylinder compression ratio
CTA	Cam timing angle
EVO	Exhaust valve open angle
$h_{clearance}$	Clearance height
IVO	Intake valve open angle
IMEP	Indicated mean efficiency pressure
K	Number of strokes
L	Stroke length of piston
m	Mass of gas
m	Slope of P-V curve after TDC
n	Amount of substance of gas
η_v	Volumetric efficiency
η_{map}	Volumetric efficiency from the table
N	Engine speed, rpm
N	Crankshaft rotational speed
P	Pressure of gas
P	Power
P	Instantaneous cylinder pressure between TDC and the transition point
P_b	Brake power
P_{comb}	Pressure rise due to combustion
P_i	Indicated power
P_i	Pressure in upstream volume
$P_{i,map}$	Intake pressure from the table
P_{max}	Maximum cylinder pressure (pressure at TDC)
P_{IVC}	Cylinder pressure at IVC

PR	Pressure ratio (exh/int) across the cylinder
PR_{map}	Pressure ratio (exh/int) from the table
R	Gas constant for a particular gas
R	Ratio of the connecting rod length to crank offset
S	Stroke
t	Off-load time in minutes
T	On-load time in minutes
T	Temperature of gas
T	Torque
T_i	Temperature in upstream
$T_{i,map}$	Intake temperature from the table
$\overline{U}_p$	Mean piston speed
U_p	Indicated piston speed
v	Specific volume
V	Volume of gas
V	Engine displacement
V	Instantaneous cylinder volume between TDC and the transition point
$V_{pistoncup}$	Piston cup volume
$V_{headregion}$	Head region volume
V_{TDC}	Cylinder volume at TDC
W_i	Indicated work
ω	Shaft angular velocity
γ	Ratio of specific heat values for the intake air
γ	Specific heat ratio
η	Mechanical efficiency
η_R	Number of crank revolutions per cycle

CHAPTER 1

INTRODUCTION

1.1 BACKGTOUND STUDY

Nowadays environment pollution becomes a much serious issue in the world. Vehicles' exhaust product is one of the source of environmental problems. Their combustion products are causing the greenhouse effect, ozone layer depletion, acid rains and some other pollution (Mohammad, 2006). On the other hand, a current study researched on fossil fuel in the year 2004, predicts that if the oil is consumed at the current rates, 80% of the entire available resource will be consumed by 2020 (Singh and Onkar, 2004). So now manufacturers begin to get some alternative energy to replace fossil fuel.

There is some alternative energy, such as battery, wind mill, photocells, hydrogen fuel cell, bio-diesel or compressed air can be chose. Among them, compressed air is abundantly available as well as free from pollution, and also can be compressed to higher pressures at an extremely low cost. Researchers started to work on compressed air engine at 1979. By now, 52 patents have been registered (Singh & Onkar, 2004).

The compressed air engine can become one of the prime options because it can be produced as almost zero emission. At the same time, compressed air method wastes only about 40% energy on leakage (Robin, 2010) when the conventional internal combustion engine wastes 86% on heat (Jaume, 2002). On the other hand, the cost is also 3 times cheaper (Mohammad, 2006).

1.2 PROBLEM STATEMENT

Both the hybrid system and hybrid engine can be powered by more than one power source. For hybrid system, generally it employs an IC engine together with one more hybrid motor generator, such as an electric motor or air motor (Xiaoyong, 2008.) However, for hybrid engine, all the power processes can be done inside the engine and an external hybrid motor would no longer be in use.

Petrol or diesel is extracted from fossil oil, which is a non-renewable resource, and their combustion products such as CO_x, $NO_{x,}$ and hydrocarbon are harmful for both environment and human health. So use of hybrid engine can leave more resources to the future generations and also reduce the exhaust pollution.

The researches on compressed air engine have already been going for thousands of years since the end of 19th century (Thipse, 2008). Nevertheless until now, the compressed air engine is still not in mass production. This is because the engine simply powered by compressed air requires a large air tank, at the same time it is also lack in mileage and not so powerful compared to conventional IC engine.

So to eliminate the drawback, a hybrid air engine is required to be developed. The hybrid air engine can be powered either by compressed air or gasoline. The car with this type of engine can move further with less pollution than the car with general automotive engine.

1.3 OBJECTIVE

The objectives for this project are as following

a. Reverse engineering and design of a four cylinder Subaru EA71 flat-four engine using compressed air powered concept,
b. Computational analysis of compressed air powered engine working model.

1.4 SCOPES

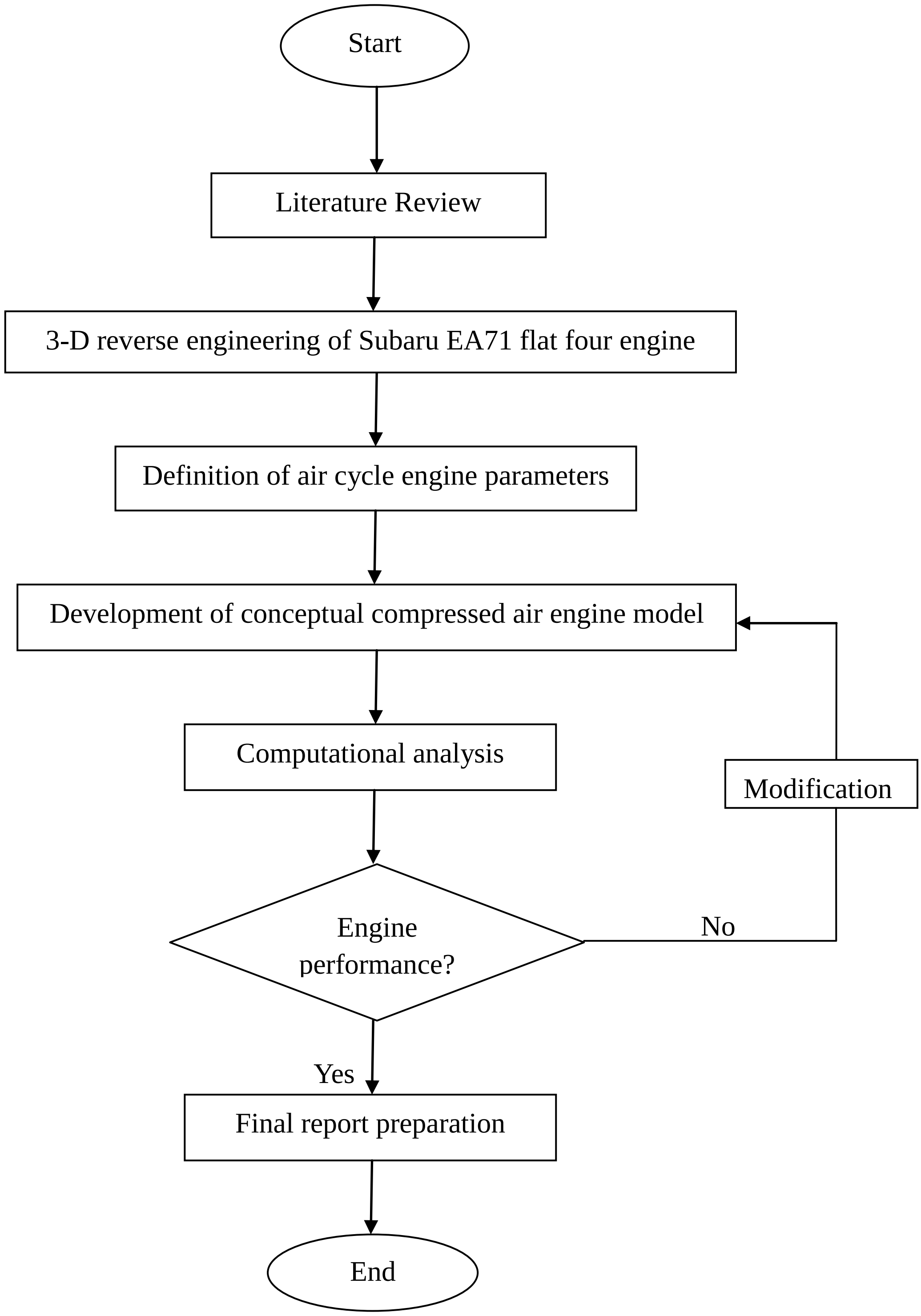
The scopes for this project are as following

a. 3D reverse engineering of Subaru EA71 engine model,
b. Theoretical analysis on air cycle concept,
c. Design of compressed air powered engine model,
d. Computational analysis on fabrication model,
e. Final report preparation

1.5 HYPOTHESIS

Subaru EA71 flat-four engine serves as a potential and economic modification platform for hybrid engine development, which consists of internal combustion, air compression and innovated air powered cylinders integration. By the end of the development, prototype model could further eliminate the drawback of normal air engine while maintain its uniqueness as utilizing recyclable air, high thermal efficiency, fewer components and less emission.

1.6 FLOW CHART



CHAPTER 2

LITERATURE REVIEW

2.1 CONVENTIONAL INTERNAL COMBUSTION ENGINE

Internal combustion engine is used extensively in the daily life, not only in vehicles but also in lawnmowers, snow blowers, chain saws, and generators, and pumps. The first internal combustion was invented by Reverend W. Cecil from England in 1820 (Christian, 2006). An internal combustion engine is the engine which burns fuel inside cylinders. It converts chemical energy of fuel into thermal energy to perform work as mechanical energy.

2.1.1 Engine systems

An IC engine consists of some accessory systems. Fuel system is used to store and control the fuel which supply at various load and speed. Ignition system ignites the fuel and air mixture in the combustion chamber and initiates combustion reaction. Air intake and exhaust system are used to intake fresh air from the atmosphere to mix with fuel and exhaust the product of combustion from engine. Cooling system is the system for cooling the engine parts which withstand high temperature, removing the excess heat. Lubrication system provides lubrication oil in moving parts so that can prevent metal to metal attrition and cooling the moving parts, as well. Furthermore, a starting system is used to start the engine by using electric-drive motor and gear arrangement

2.1.2 Working process of 4-stroke engine & 2-stroke engine

Most of the small IC engines are four-stroke engines in which the piston finishes one cycle with moving two revolutions. The cycle starts with both valves close and the piston up. When the first intake stroke starts, intake valve open, the piston moves from TDC to BDC and intake air from outside. At the second compression stroke, intake valve close, piston reaches BDC and move to TDC. In the third expansion stroke, spark plug ignites and piston moves downward to BDC with both valves closed. In the last exhaust stroke, exhaust valve open and push out all the exhaust gas during the piston moving from BDC to TDC.

Another type of engine is called two-stroke engine in which the piston moves one revolution in every cycle. The independent intake and exhaust stroke are combined as downward stroke. In the downward stroke, when piston at TDC, the spark plug ignites and the piston be pushed down. During this process, the burnt gases exhaust from the exhaust port and new mixture gas come in through the intake port. In the second upward stroke, piston moves from BDC to TDC. In this process, piston compress the mixture gas in the upper cylinder, and suck new mixture gas through the inlet port in the lower cylinder.

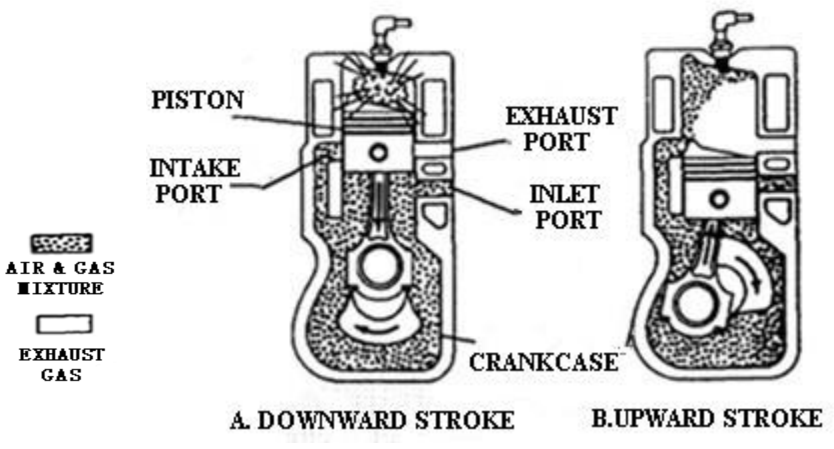


Figure 2.1: 2-Stroke Engine Working Process

Source: Christian (2006)

2.1.3 Flat four engine

A flat-four engine also can be called as horizontal opposed four engine. It arranges two banks of two cylinders horizontally opposite each other on a single crankshaft. The pistons are assembled on the crankshaft and opposing pistons will move in the opposite direction at the same time. The flat four engine has a low centre of gravity, extremely short engine length and inherent proper balance of reciprocating parts. However, the flat-four engine requires high manufacturing cost. Figure 2.2 shows a basic concept of flat-four engine.

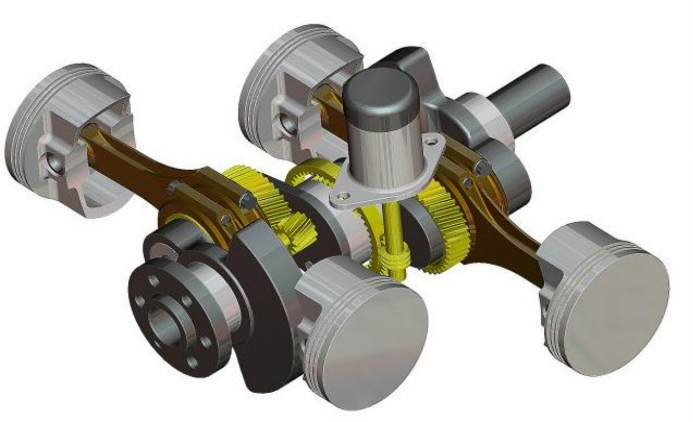


Figure 2.2: Flat-Four Engine Piston Position

2.2 FUNDAMENTAL OF COMPRESSED AIR ENGINE

As the conventional IC engines bring the amount of pollution and also hard pressure of fossil resource, a new type of engine called compressed air engine is developed. The compressed air engine doesn’t need any fuel to provide power. It can be powered just by compressed air, which is stored in a tank only. The piston is driven by compressed air expansion. As the power source is just compressed air, the exhaust gas is clean, making it as a zero pollution engine. At the same time, it doesn’t require a cooling system since there is no combustion happens. So it can reduce volume, weight as well as cost of the engine.

2.3 DEVELOPMENT OF COMPRESSED AIR ENGINE

The research on the compressed air engine started long times ago since the end of 19^{th} century. In 1872, the single-stage engine named Mekarski air engine was used for street transit. In 1879, the first regular line to manufacture locomotive with this kind of engine was opened in Nantes. . In the eastern U.S, hundreds of these locomotives are sold to coal-mining companies by H. K. Porter Company in Pittsburgh. In 1892, Robert Hardie introduced a new method of heating to increase the range of the engine travel distance. Its main feature was regenerative braking, which can collect air and heat into a tank during deceleration (Thipse, 2008).

In 1898, a two-stage engine is introduced by Hoadley and Knight (Thipse, 2008). The two-stage engine principle is based on the longer time air is kept in the engine, more heat it can absorb so that it can have a larger range.

In 1912, one more expansion stage was added by Europeans which the three-stage engine came into the world (Thipse, 2008). After that more and more people continued doing research on compressed air engine, they even started to convert a gasoline engine into compressed air engine. Until now, many new technologies have been developed and patented.

2.4 COMPRESSED AIR TECHNOLOGY (CAT)

Compressed air technology is developed by a French engineer named Guy Nègre. After 12 years of research, he developed a compressed air engine with low consumption and low pollution. Guy Nègre is the head of research at Moteur Development International (MDI) cars. In MDI, a crucial step for zero emission vehicles is CAT. There are only around 22KW needed to refill tanks, and has a top speed of 110 km/h, a range of 200 km (Thipse, 2008). CAT vehicles have significant technological advantage in economic and environment. Cooperation with the bio-energy which means together use compressed air and fuel, the CAT vehicles driving range can be increased to almost 2000km with zero emission urban and low pollution outside the city. The Table 2.1 lists the technical specification of the CAT vehicle.

Table 2.1: Technical Specification of CAT Vehicle

		Mono-energy	Dual-energy 2	Dual-energy 4
Length	m	2.65	2.65	2.65
Width	m	1.62	1.62	1.62
Height	m	1.66	1.66	1.66
Number of seats	-	3	3	3
Luggage compartment volume	Dm3	500/700	500/700	500/700
Weight	Kg	550	520	540
Engine	-	41P03	41P01	41P01/4
Power	cv	25	25	50
Max. speed	Km/h	110	125	140
Urban range (zero pollution)	Km	140/150	50	50
CO2 emission in urban use	g/Km	0	0	0
Non-urban range	Km	80	1650	1500
Non-urban consumption (pertol)	litres	-	1.8	2
CO1 emission in non-urban use	g/Km	0	35	40
Price (from) taxes included	9200			

Source: Thipse (2008)

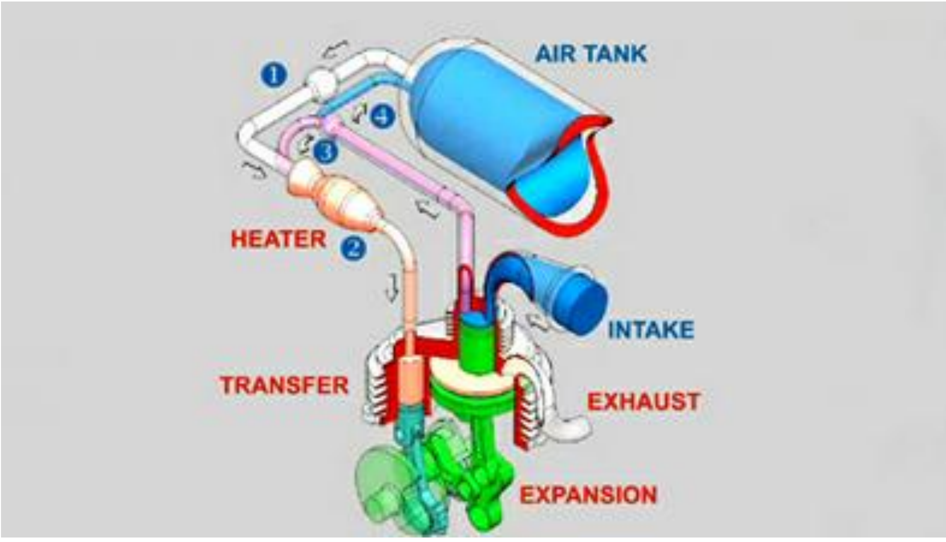


Figure 2.3: MDI Designed Air Engine

Source: Kaho (2008)

The Figure 2.3 shows an air engine which wasdesigned by MDI. The engine uses one large and one small air-driven pistons to turn the crankshaft. First the small piston turns the crankshaft with conventional connecting rod, and the large piston uses an innovate rocker arm connected with the connecting rod. With this kind of design, the large piston can pause at TDC for 70 degree of crankshaft rotation (Kaho, 2008) when metered air pressure builds in a pre chamber, at the same time, the small piston keeps turning the crankshaft during its power stroke. Then the large piston rotates the crankshaft with larger power as over 270 degrees of crankshaft rotation is powered (Kaho, 2008).

2.5 CONSTRUCTION OF COMPRESSED AIR ENGINE

A compressed air engine has 6 main components: pneumatic cylinder, pneumatic solenoid valve, light chaser circuit, compressor, bearing, and crank shaft (Yadav & Bharat, 2011). Table 2.2 shows the description of each component.

Table 2.2: Components of Compressed Air Engine

Component	Description
Pneumatic cylinder	Pneumatic cylinder is powered by compressed air and produce force. There is no external energy input, the inner piston move because of the high pressure of air as well as air expansion. During the whole process, the potential energy of air is converted into kinetic energy and provides force.
Pneumatic solenoid valve	The pneumatic solenoid, which is controlled by the use of pneumatics, can be described as a transducer mechanism. It is used to convert energy into motion. The solenoid controls solenoid valves and solenoid valves control the flow of air.
Light chaser circuit	In the compressed air engine, light chaser consists of several lighting circuits, usually 3 or 4, strung together. Light chaser circuit is used to create lighting animation sequences.
Compressor	As the name, compressor is used to compress the air. It decreases the volume of gas so that its pressure will increase. A compressed air piston can produce working pressure at 1.5 bar to 414 bar, and a compressed air vane can produce work pressure at 7 bar to 8 bar and 10 bar.
Bearing	A ball bearing is used to maintain the separation between the moving parts of the bearing by balls rotation. The ball bearing can reduce rotational friction, support radial and axial loads, as well. Commonly at

	least two races, which on held fixed and one free, are used to contain the balls and transmit the loads through the balls.
Crank shaft	Crank shaft is used to convert the reciprocating linear piston motion into rotation. It normally connects to a flywheel to reduce pulsation. Sometimes it connects to a vibration damper at the opposite end to reduce the torsion vibration.

2.6 WORKING PORCESS OF COMPRESSED AIR ENGINE

The compressed air engine working principle is similar to the internal combustion engine. However, it stores compressed air in the tank instead of energy. The air engine surely uses compressed air to drive. The compressed air is stored in tanks which will probably hold about 3,200 cubic feet (Yadav & Bharat, 2011) of compressed air. Then compressed air can be released into a pipe via valve and go into the engine, where the pressure of the air's expansion will push against the pistons as well as turn the crankshaft. The limited speed for this process is about 35 miles per hour (Yadav & Bharat, 2011). When that speed is surpassed, a motor will start to operate the in-car air compressor so that it can compress more air and have the ability to provide extra power for the engine.

In one research, researchers modify a single, horizontal cylinder, low speed prototype engine to run with compressed air. In this modification, they used a dwelling connecting rod which consists of a reciprocated link, an oscillate link and a rotate instead of a conventional connecting rod. With this kind of connecting, a practical volume can be obtained constant when the piston stays any angle at TDC.

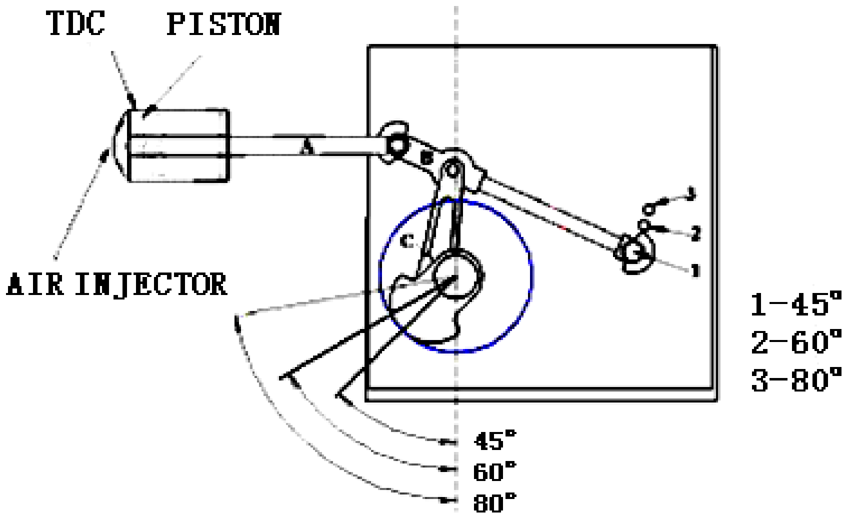


Figure 2.4: Dwelling Connecting Rod

Source: Mohammad (2006)

This engine works like a diesel engine. However, the dwelling connecting rod provides a constant volume cycle instead of constant pressure cycle. At the end of the compression stroke, the air at room temperature with high pressure is injected into a compression chamber. At that moment, the pressure is not high enough to push the piston down. When the piston pause, as the inner cylinder is hot, and inject compressed air is colder, the mixture will attain an equilibrium temperature. As the temperature of mixture drops, the air inside cylinder starts to expand. During the whole process, no combustion takes place. The engine runs because of the expansive forces.

2.7 AIR ENGINE CYCLE

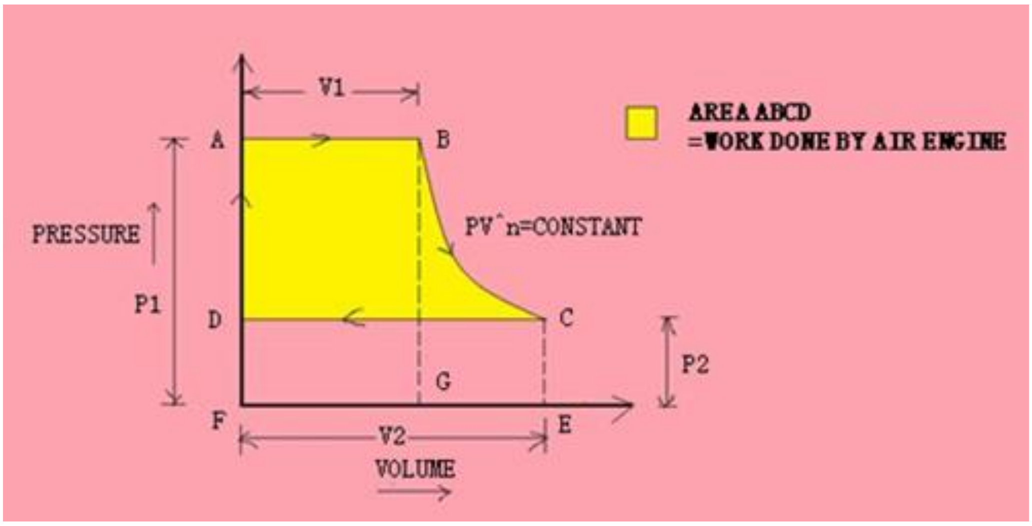


Figure 2.5: Air Engine P-V Diagram – 1

Source: Narasimhan (2010)

The Figure 2.5 shows the relationship between pressure and volume for a single cylinder reciprocating air engine. P_1 and V_1 represent the pressure and volume of compressed air enters into the cylinder. P_2 and V_2 represent the pressure and volume of compressed air delivery from the cylinder. Letter n is polytropic index and R is the universal gas constant.

Process A-B: Isobaric air injection.

At point A, compressed air enters into the cylinder. Piston starts to move downward, with constant pressure P_1 until it reaches point B

Process B-C: Isentropic air expansion.

Air supply is cut-off at point B. The compressed air start to expand in the cylinder and push the piston move downward until it reaches point C. During this process, no heat transfer between inside the cylinder and outside atmosphere.

Process C-D: Isobaric air rejection.

At point C, exhaust valve opens and compressed air is delivered from cylinder to the atmosphere with constant pressure P_2 until piston reaches point D.

Process D-A: Isochoric air injection.

Inject air starts at point D. In a very short moment, the pressure increases rapidly with constant volume. When the pressure reaches P_2 at point B, piston will start to move again.

In the Figure 2.5, area of yellow region shows the work done by the air engine (Narasimhan, 2010). Therefore in each cycle, the work is expressed in Equation 2.1 and Equation 2.2.

$$W = \text{Area ABCD}$$

$$= \text{Area ABGF} + \text{Area BCEG} - \text{Area DCEF}$$

$$= P_1V_1 + \frac{P1V1 - P2V2}{(n-1) - P2V2}$$

$$= \frac{n}{n-1} P_1V_1 \left(1 - \frac{P2}{P1}\right)^{\frac{n-1}{n}} \tag{2.1}$$

Since PV = mRT

$$W = \frac{n}{n-1} mRT_1 \left(1 - \frac{P2}{P1}\right)^{\frac{n-1}{n}} \tag{2.2}$$

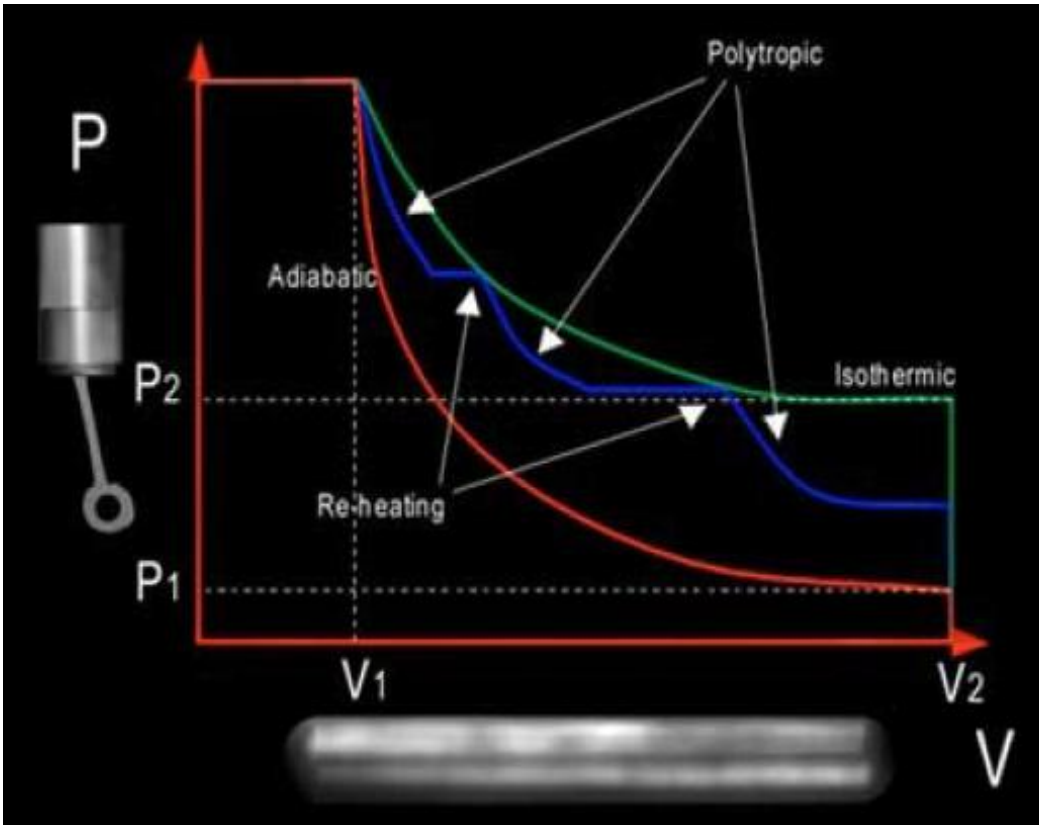


Figure 2.6: P-V Diagram of Air Engine - 2

Source: Hatwar (2004)

The Figure 2.6 shows another relationship between pressure and volume during the air engine working process. The green line is isothermic line. It represents the isothermal compression process which the ideal transformation of the compressed air. The air temperature contains stable, and the power reaches maximum. The blue line is a polytropic curve. It represents polytropic compression process which the transformation and the individual stages outlined above can be seen. The red line is adiabatic line. It represents the adiabatic compression process which the power reaches minimum and air leave the system at a low temperature. Following will show some formula about the diagram (Hatwar, 2004).

The polytropic expansions work:

$$W = \frac{P1V1 - P0V0}{n-1} \tag{2.3}$$

The volume after expansion:

$$V = V_0 \left(\frac{P0}{P1}\right)^{1/n} \tag{2.4}$$

The work of isothermal transformation:

$$W = P_1V_1 \ln \left(\frac{V1}{V0}\right) \tag{2.5}$$

2.8 GOVERNING PARAMETERS & EQUATIONS

Following Table 2.3 and Equation 2.6 to Equation 2.9 are listing some parameters of air engine.

Table 2.3: Compressed Air Powered Compact CAFS (Truck Carried)

Compressed Air Powered Compact CAFS (Truck carried)			
Make and Model	Intelagard, Inc.	Innovative Foam Systems Truck CAFS	Stanley Mfg Tri-max 3-GHR
Engine Horse Power	None(compressed air powered)	None(compressed air powered)	None(compressed air powered)
Pump Type	Air actuated	Positive displacement diaphragm pump	Compressed air
Max Pressure	125 psi	125 psi	
Water Flow	135 gpm @ 100 psi	35 gpm	
Air Flow		40 cfm	
Air Compressor	None (air cylinders)	None (from the cylinder)	6 cuft 3,000 PSI Scuba air tank
Proportioner	Premix (automatic - optional)	None, premix	
Width	48 inches	24 inches	9 1/2 inches
Length	86 inches	60 inches	
Height	24 inches	24 inches	26 inches
Weight	480 lb empty, 2600 lb charged	575 lb (with water)	36 lb
Integral Water Supply	200 gallons	75 gallons	3 gallons

Source: Dan & Mike (2001)

Estimating leak load: in a compressed air engine, most of the energy is lost because of leakage. As the compressor use start and stop control, it is easy to estimate the amount if leakage in the system (Yadav & Bharat, 2011). So the total leakage can be calculated as:

$$\text{Leakage\%} = \frac{T \times 100}{T + t} \tag{2.6}$$

Some other governing equations are shown as follow:

$$P_i = \frac{PimLANK}{60{,}000} \text{ kW} \tag{2.7}$$

$$P_b = \frac{2\pi NT}{60{,}000} \text{ kW} \tag{2.8}$$

$$\eta = \frac{\text{Braking Power}}{\text{Indicated Power}} \tag{2.9}$$

2.9 ADVANTAGES & SHORTAGES

The potential advantages of the compressed air powered engine are:

a. Can reduce the vehicle exhaust pollution and protect the environment,
b. Can reduce usage of fossil fuel so that leave more resource to descendants,
c. CAT reduces the cost of vehicle production about 20% because the cooling system, fuel tank, ignition system, or silencers are not required,
d. Air is non-flammable so that more safety than gasoline or diesel,
e. Can provide high torque for minimum volume,
f. The mechanical design of the engine is simple,
g. Low manufacture and maintain cost is required,
h. Compare to battery, air tank can be disposed of or recycled with less pollution,
i. The air tank can be refilled faster,
j. Reduce the weight of the vehicle so that waste less energy to move the body,
k. The price for fueling air is cheap.

Although the compressed air engine has so many advantages, it still not be mass produced. There are still some shortages occur.

a. It may take 4 hours to refill the compressed air tank by using home or low-end conventional air compressor even though it may only need 3 minutes to refill by specialized equipment (Shahu, 2010),
b. Air tanks may get extremely hot if filled rapidly,
c. Limited storage capacity of air tank, which only range of 7.22km in the published test(Shahu, 2010).

CHAPTER 3

METHODOLOGY

3.1 3D REVERSE ENGINEERING

The first step in this project is to do the 3D reverse engineering of the Subaru EA71 model. Reverse engineering is taking apart an object to see how it works in order to duplicate or enhance the object. By doing the 3D reverse engineering, it eases further modification, and the period of the design cycle can be shorter. In this case, it means to the reverse process of how to build an engine. So the first step is to overhaul the engine, clean them with petrol, and then draw all the components in 3D by Solidworks. After finishing the 3D reverse engineering, the engine can be modified in a proper method.

3.1.1 Engine overhaul and cleaning

Dismantle the engine part by part. After moving every component, put it in a plastic bag or box and record its name and position. This step is necessary because there are some same components taken from different cylinders, such as piston, connecting rod and valves. So when reassembly the engine, every component must put back at the same position. Following are the some of the engine component

After dismantle all the components, following is cleaning process. Every component should be cleaned by petrol. First is because fatlute and carbon deposit can dissolve in the petrol. Second is because the Subaru EA71 is a petrol engine. If the components are cleaned by diesel or other fluid, it will affect performance when any residue left. After cleaning, dimensions can be measured more accurate in 3D drawing process.

3.1.2 3D drawing process

After cleaning all the components, they should be drawn in Solidworks. Every dimension need to be measured by caliper, and then drawn the components in Solidworks. As many components are complex, when drawing they can be divided into several small parts and then assemble them together. After this, the model can be modified easily, and computational analysis model using a software.

During the drawing process, it is a little harder to measure the cam profile. The cam profiles are irregular and has different angles with each other, and they can't be measured by caliper or ruler directly. So a special process to measure the cam profiles is necessary. The process of measuring the cam profiles is as follow:

a. Paste a 360^o protractor with a piece of paper, and fixed them together with camshaft pulley,

b. Mark a line on the cams at 0^o on protractor,

c. Put the camshaft on the cylinder block and adjust the dial gauges touch the first and third cam, set them to zero. Make sure the dial gauge needle touches the centre of mark line on every cam.

d. Start from 0^o, rotate the camshaft and record the every one degree reading in the dial gauges until 360^o,

e. Repeat step c and step d to measure the cam profile for second and fourth cams. Make sure it also starts at 0^o,

f. Repeat step c to step e, record the reading one more time,

g. Input all the data in Excel and get the average data as the result,

h. Transfer the result into graph,

i. Draw the cam profiles in Solidworks based on the data and graph.

The Figure 3.1 shows the equipment arrangement during the process of measuring the cam profiles. Figure 3.11 is measuring the second and last cams.

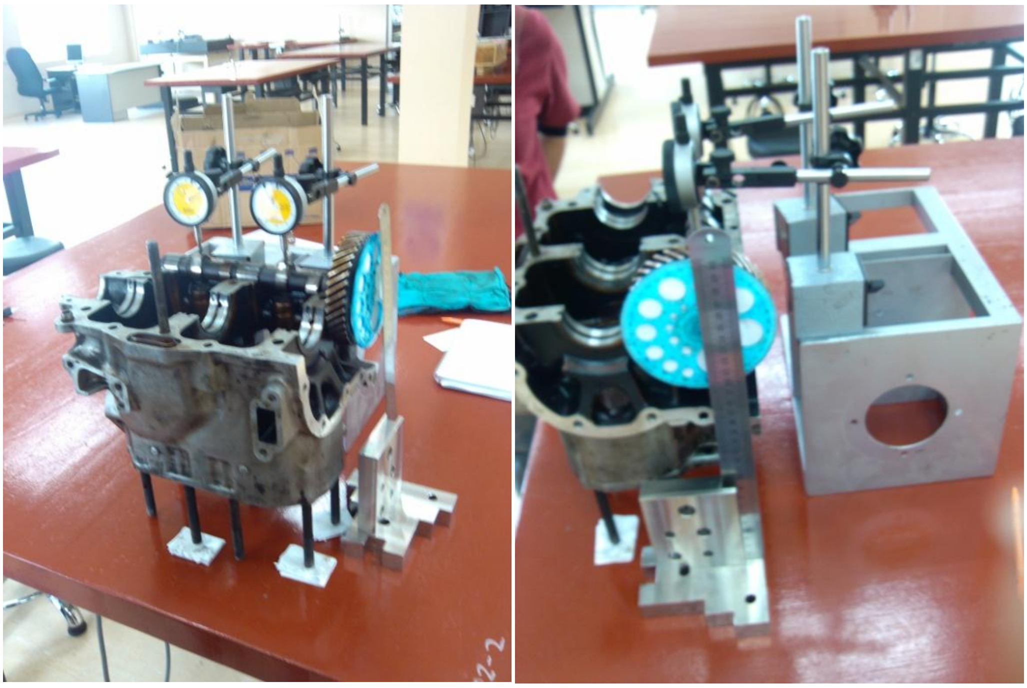


Figure 3.1: Cam Profile Measuring

During the drawing process, some errors may occur especially in taking caliper reading. When some components need to be assembled, they may not match. In this case, the work should be redone.

3.2 DEFINITION OF AIR CYCLE

The Subaru EA71 is a 4-stroke SI engine. The engine cycle performs based on the Otto cycle. In this project, an air powered cylinder will be innovated. In this cylinder, piston only performs 2 strokes without ignition process. The compressed air will be injected into the cylinder via air injector, and provides force which due to high pressure to work on piston. To analysis the piston working process much clearer and easier, an air cycle pressure-volume diagram require to be developed.

3.2.1 Theoretical air cycle

In theory, Carnot cycle is the one with highest thermal efficiency. In this project, an ideal air cycle is designed to perform with high thermal efficiency, meaning that it is better if the air cycle is more approximate to the Carnot cycle. So an air cycle P-V diagram is built in Figure 3.2.

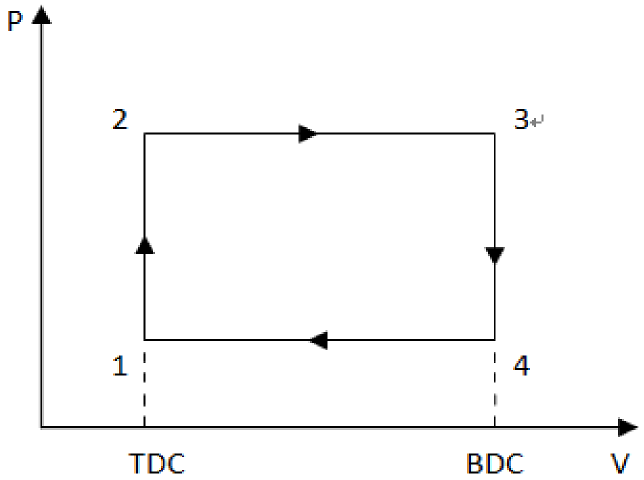


Figure 3.2: Theoretical Air Cycle P-V Diagram

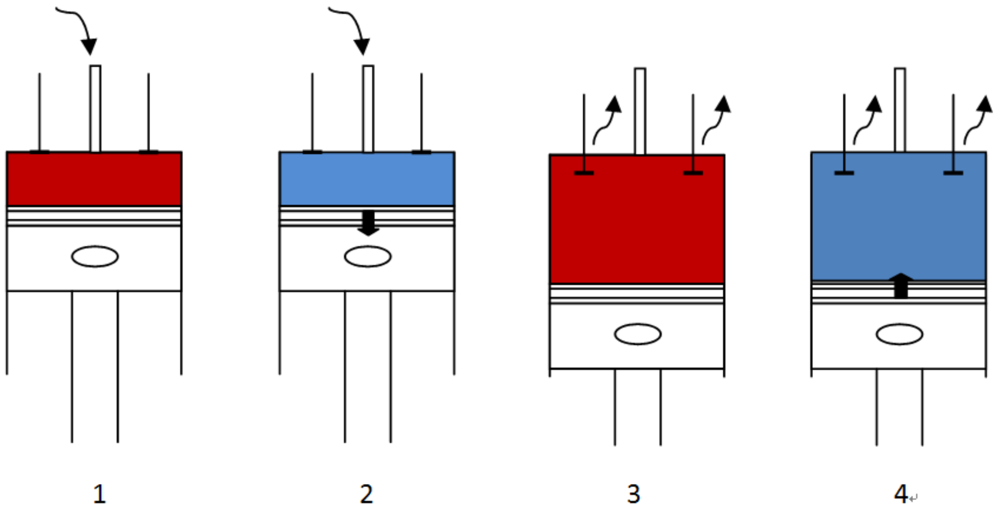


Figure 3.3: Air Powered Cylinder Theoretical Working Process

Process 1-2: Isochoric air injection

At point 1, the piston reaches TDC and air valves close. Air injector starts to inject compressed air into the cylinder. At this moment, the pressure will increase rapidly, but the force is not enough to push the piston move downward. During this process, the volume keeps stable with high pressure.

Process 2-3: Isobaric air injection

Then air injector continues injecting compressed air. At point 2 where the force is enough to push the piston, the piston will move from TDC to BDC. During this process, pressure keeps stable, and piston moves because of expansion force.

Process 3-4: Isochoric air rejection

At point 3, piston reaches BDC. Air injection stop and air valves open. Similar as process 1-2, compressed air will exhaust rapidly in a moment with constant volume and low pressure.

Process 4-1: Isobaric air rejection

At point 4, the piston starts to move upward from BDC to TDC and deliver the compressed air into the atmosphere. During this process, the pressure keeps stable.

3.2.2 Prediction of air cycle

In actual, the air injection may not just start at TDC and stops at BDC properly. So in the design, the air injection will start several degrees after TDC and stop several degrees before BDC. So the P-V diagram is developed as shown in Figure 3.4.

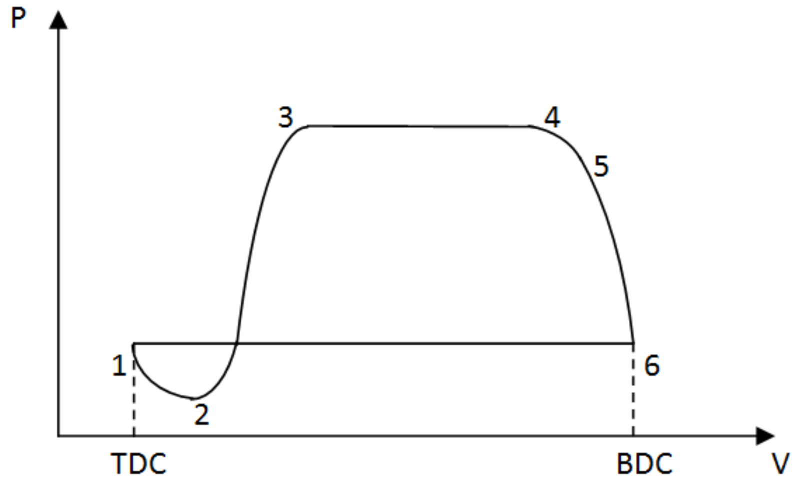


Figure 3.4: Prediction Air Cycle P-V Diagram

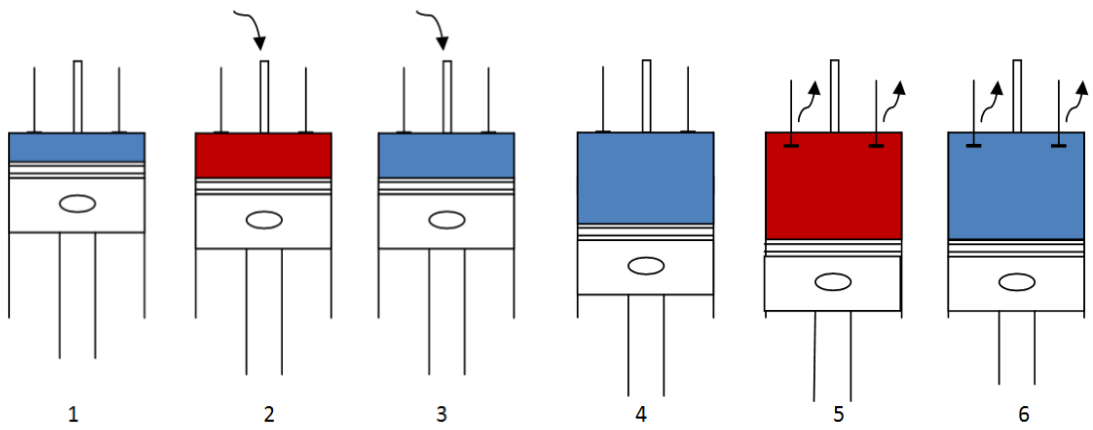


Figure 3.5: Air Powered Cylinder Prediction Working Process

Process 1-2: Isentropic expansion

At point 1, the piston just finishes isobaric air rejection. At this time, air valves close and air injection haven’t started. Heat energy converts to mechanical energy, piston moves downward. This process is similar as the isentropic expansion process in Otto cycle.

Process 2-3: Air injection

When it reaches the certain level at point 2, air injection starts with air valves keep close. In theoretical, it should be an isochoric process as mention in 3.21 process 1-2. In fact, the piston may be move a little bit downward. So the line is not straight and vertical anymore.

Process 3-4: Isobaric air injection

At point 3, the force is enough to push the piston to move. With continuous injecting air from air injector, piston moves from TDC to BDC with constant pressure.

Process 4-5: Isentropic expansion

When it reaches the certain level at point 4, air injection stop and air valves still close. So the piston will do the isentropic expansion same as the process in 1-2 again.

Process 5-6: Air rejection

When it reaches BDC, air valves open. Same as the explanation before, the piston may be move a little bit during the theoretical isochoric air rejection process.

Process 6-1: Isobaric air rejection

At point 6, piston starts to move upward and delivers all the air outside cylinder. During this process piston moves from BDC to TDC with constant pressure.

3.3 DESIGN OF COMPRESSED AIR POWERED ENGINE MODEL

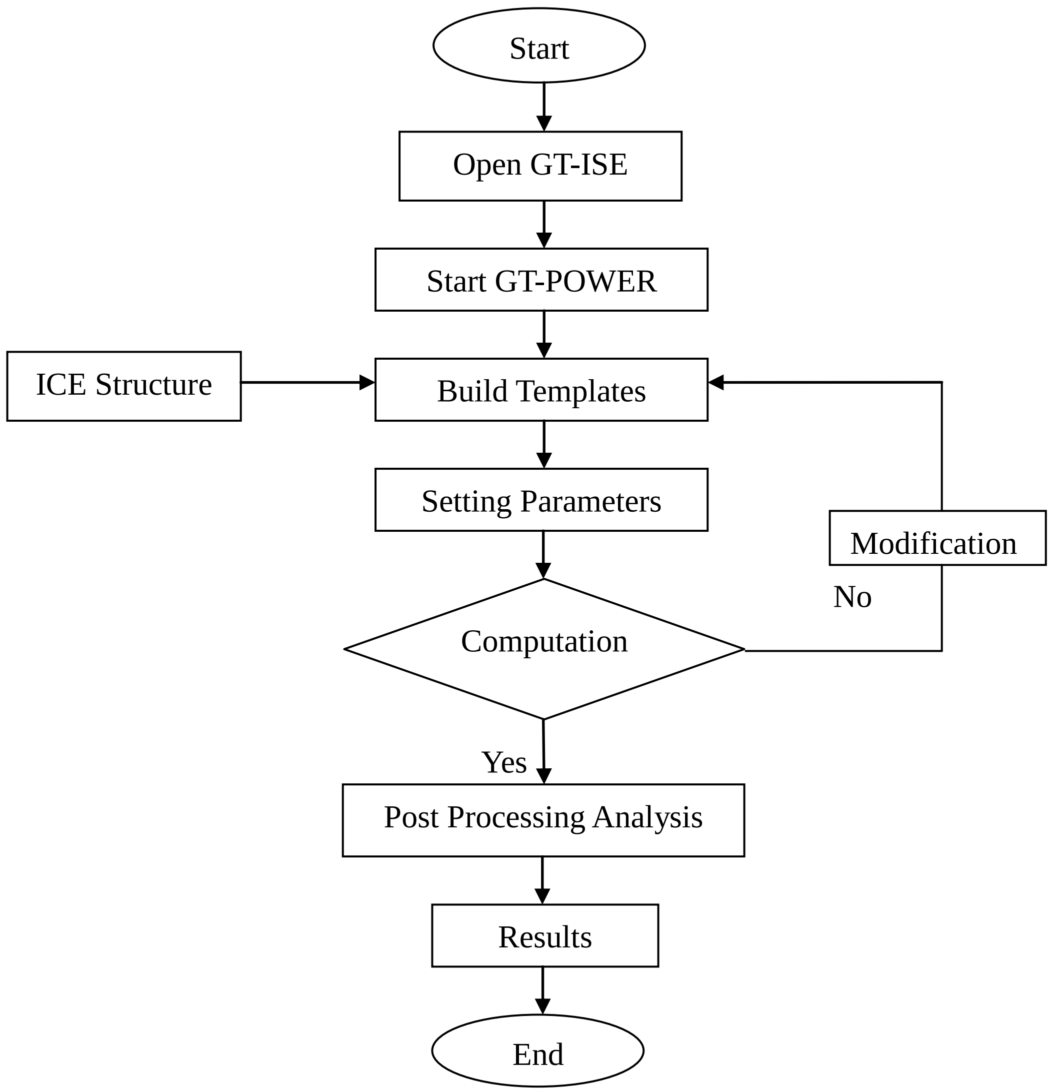
From 3.1.2 3D drawing process, every component has already been drawn in Solidworks. Based on the concept of compressed air powered engine there are a few of components need to be designed and modified. First the cylinder 3 and cylinder 4 will be modified as two-stroke work cylinders, and the intake valve and exhaust valve open, and close once within 360 degree, so that the camshaft should be modified.

Second the intake compressed air is from compressed air reservoir which means the intake system should be modified. The intake port of cylinder head should be divided into 2, and the intake manifold also needs to be designed based on the new concept. At the same time, exhaust system also need to make some changes.

3.4 SOFTWARE COMPUTATION ANALYSIS

Analysis and simulation are extremely crucial parts in the project. The analysis result can testify whether the design concept is correct. It is also can be seen how the model performs clearly. In this process, GT-POWER, which is the most famous software in GT SUITE series, will be used to analysis the model. GT SUITE is software that produced by GAMMA TECHNOLOGIES and used to simulate the vehicle, internal combustion engine and its components. It includes 6 aspects: vehicle, internal combustion engine, cooling system, fuel supply system, crankshaft connecting system and valve mechanism.

To use the GT-POWER, first is to open the GT-ISE and then choose the GT-POWER. After this build the GT-POWER templates based on the structure and process of internal combustion engine. In this research, templates for cylinder 3 and cylinder 4, with 2-stroke work will be built. Next step is setting the parameters of every template and then start computation. After computation, some post processing is analyzed by GT-POST and gets the results.



The results get are based on some formulas. Following are listing some governing equations which are used for producing calculation in the simulation.

Mean and Instantaneous Piston Speeds:

$$s = a\cos\theta + \left(l^2 - a^2\sin^2\theta\right)^{1/2} \tag{3.1}$$

$$\overline{U}_p = 2LN \tag{3.2}$$

$$U_p = \frac{ds}{dt} \tag{3.3}$$

$$\frac{U_p}{\overline{U}_p} = \frac{\pi}{2}\sin\theta\left[1 + \frac{\cos\theta}{(R^2 - \sin^2\theta)^{\frac{1}{2}}}\right] \tag{3.4}$$

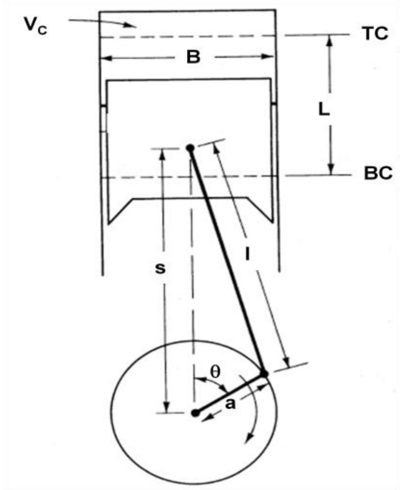


Figure 3.6: Piston and Cylinder Geometry of Reciprocating Engin**e**

Piston Speed vs Crank Angle:

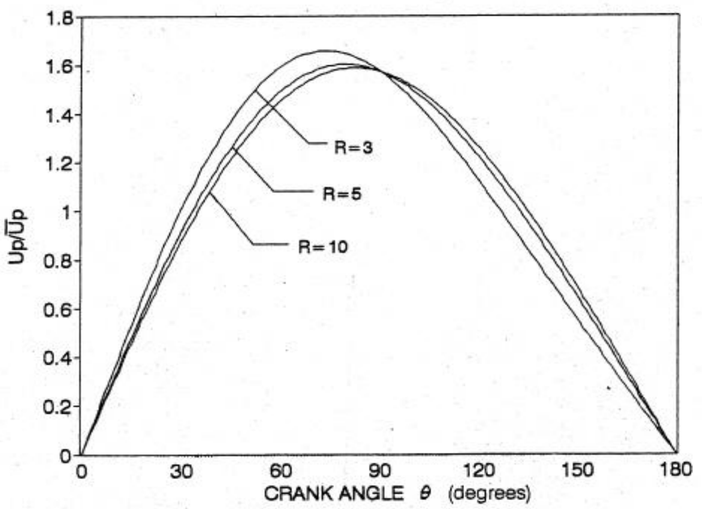


Figure 3.7 Instantaneous Piston Speed Relative to Average Piston Speed as a Function of Crank Angle for Various R Values

Figure 3.7 shows the relationship between piston speed and crank angle. The piston speed for y axle is calculated by Equation 3.4.

Engine Torque and Power:

$$T = F*b \tag{3.5}$$

$$P = \omega*T = (2\pi N)\,T \tag{3.6}$$

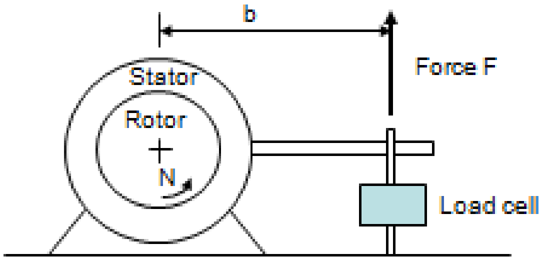


Figure 3.8: Force Position

Indicated Work:

$$W_i = \oint Pdv \tag{3.7}$$

Indicated Power:

$$P_i = W_i\,N/\,\eta_R \tag{3.8}$$

Brake Mean Efficiency Pressure:

$$BMEP = \frac{2\pi T\eta_R}{V} \tag{3.9}$$

Volumetric Efficiency:

$$\eta_v = \eta_{map}\left[\left(\frac{T_{i,map}}{T_i}\right)\left(\frac{P_i}{P_{i,map}}\right)\left(\frac{1+\gamma\,(CR-1)-PR}{1+\gamma\,(CR-1)-PR_{map}}\right)\right] \tag{3.10}$$

P-V Diagram:

$$P = P_{max}\left(\frac{V_{TDC}}{V}\right)^{m} \tag{3.11}$$

$$P_{max} = P_{IVC}CR^{\gamma} + P_{comb} \tag{3.12}$$

Clearance Volume:

$$V_{TDC} = \frac{\left(\frac{\pi}{4}\right)B^2S}{CR-1} = V_{pistoncup} + V_{headregion} + \left(\frac{\pi}{4}\right)B^2h_{clearance} \tag{3.13}$$

CHAPTER 4

RESULT AND DISCUSSION

4.1 3D REVERSE ENGINEERING

The first step is dismantling the engine and cleaning all the components by petrol and sandpaper. The photos of some engine components after the cleaning process are shown in Appendix B.

The next step is drawing all the components in 3D model. During this process, Solidworks is used. After the drawing of all the components complete, they should be assembled as an integrated engine. Later on, the drawings should be modified based on the design so that the drawing must be accurate. The figures of some components, which are drawn in the Solidworks, are shown in Appendix C.

4.2 AIR POWERED ENGINE DESIGN

As the working process of air engine is just only the power and exhaust, which can be considered as 2-stroke engine. Some components of cylinder 3 and cylinder 4 should be modified to achieve the goal.

First, since cylinder 3 and cylinder 4 will work as 2-stroke, which means camshaft rotates one cycle while crankshaft rotates 360 degree. But as the cylinder 1 and cylinder2 still works as 4-stroke, the rotate speed ratio between the camshaft and crankshaft won't change. To achieve the scope, one lobe is added on the cam profile for both cylinder 3, and cylinder 4, that means for each cam (cam 1 and cam 2) has two lobes so that both the intake and exhaust valves can open and close once within 360 °

The design of the camshaft is shown in Figure 4.1.

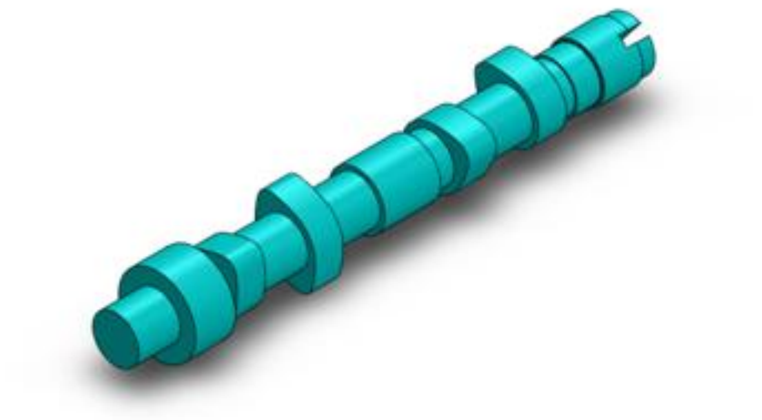


Figure 4.1: New Design of Camshaft

On the other hand, the intake compressed air is no longer from the atmosphere but from a compressed air reservoir. At the same time, there is also another working stage in the engine working process. Cylinder 3 and cylinder 4 hve different usage in that stage and requires separate inlet and outlet. To achieve this scope, the design of cylinder head is shown in Figure 4.2 and Figure 4.3.

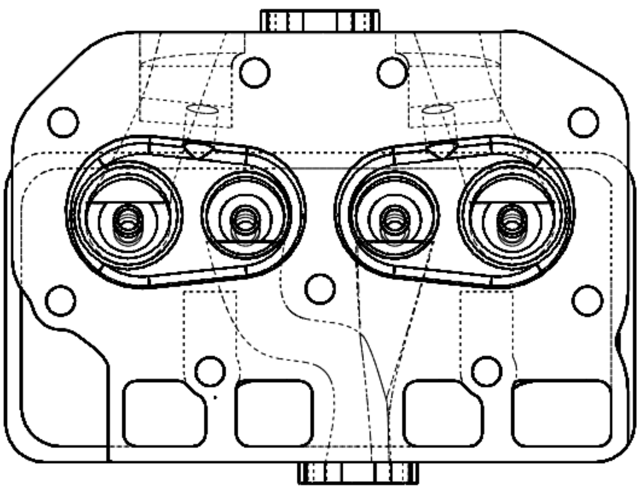


Figure 4.2: New Design of Cylinder Head

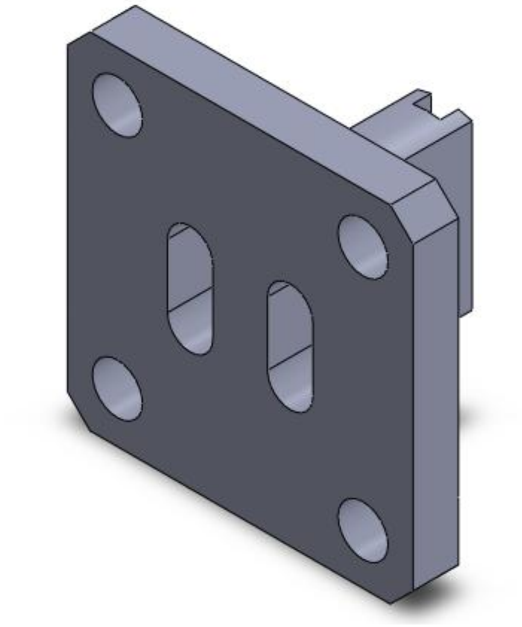


Figure 4.3 Design of Separation Port

From the Figure 4.18, it can be seen that the intake port of cylinder head will be casted, and two separate holes are built to connect intake manifold for cylinder 3 and cylinder 4. There is no enough space for making two holes in the cylinder head at the exhaust port side. A separation port, which shows in Figure 4.19, will be installed into the exhaust port so that the exhaust gas from cylinder 3 and cylinder 4 can be separated.

4.3 GT POWER COMPUTATION ANALYSIS

Hence the design of some engine components are changed, before fabricate the new components, some simulation must be done to analysis the performance of the new engine model. In this research, GT Power is used to do the simulation and computation analysis. And after run the simulation, results are produced in GT Post.

First of all, templates for the process of engine working should be built in the GT Power. In GT Power template library, there are 7 aspects of models and templates for this air engine are chosen from flow and mechanical models only. Based on the real engine model, as well as the new design, amount of data are keyed into templates. Then use create links button to link the related components together. The Figure 4.4 shows the templates which are built for air engine.

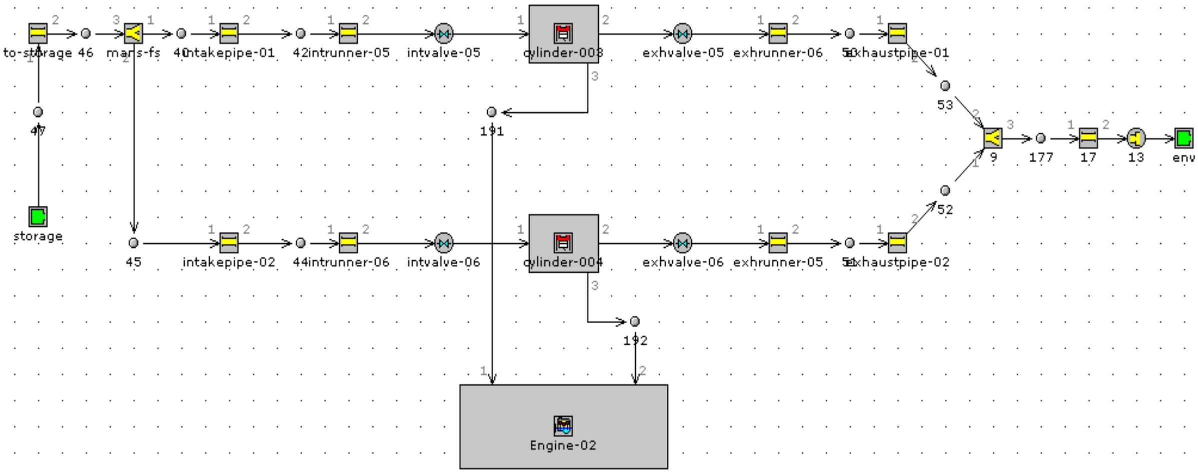


Figure 4.4: Templates for Air Engine in GT Power

Secondly, the cam profile of cam 1 and cam 2, that control intake valve and exhaust valve open and close for cylinder 3 and cylinder 4, are modified. So to decide what is the best valve timing is necessary. During the simulation process, different cam timing angle for both intake valve and exhaust valve are keyed into ValveCamConn template, which shown in Figure 4.21. The cam timing angle is added to theta array to give the timing of the lift relative to the cam and crank angle. The value is simply the angle between TDC firing and the 0.0 value of the theta array. The cam timing angles for the intake valve and exhaust valve are controlled by intake valve opening angle as well as the overlap. For a 2-stroke engine, the rotational speed for camshaft and crankshaft are same. The relationship between intake and exhaust cam timing angle is shown as Equation 4.1, Equation 4.2 and Equation 4.3:

$$\text{Intake CAT} = \text{IVO} + \text{Theta Angle} \tag{4.1}$$

$$\text{Exhaust CAT} = \text{EVO} + \text{Theta Angle} \tag{4.2}$$

$$\text{EVO} = \text{Valve Lift Duration} - \text{Valve Overlap} \tag{4.3}$$

Theta Angle refers the Figure 4.6 which is the duration of theta array which correspond lift array start from the number larger than valve lash to the peak value.

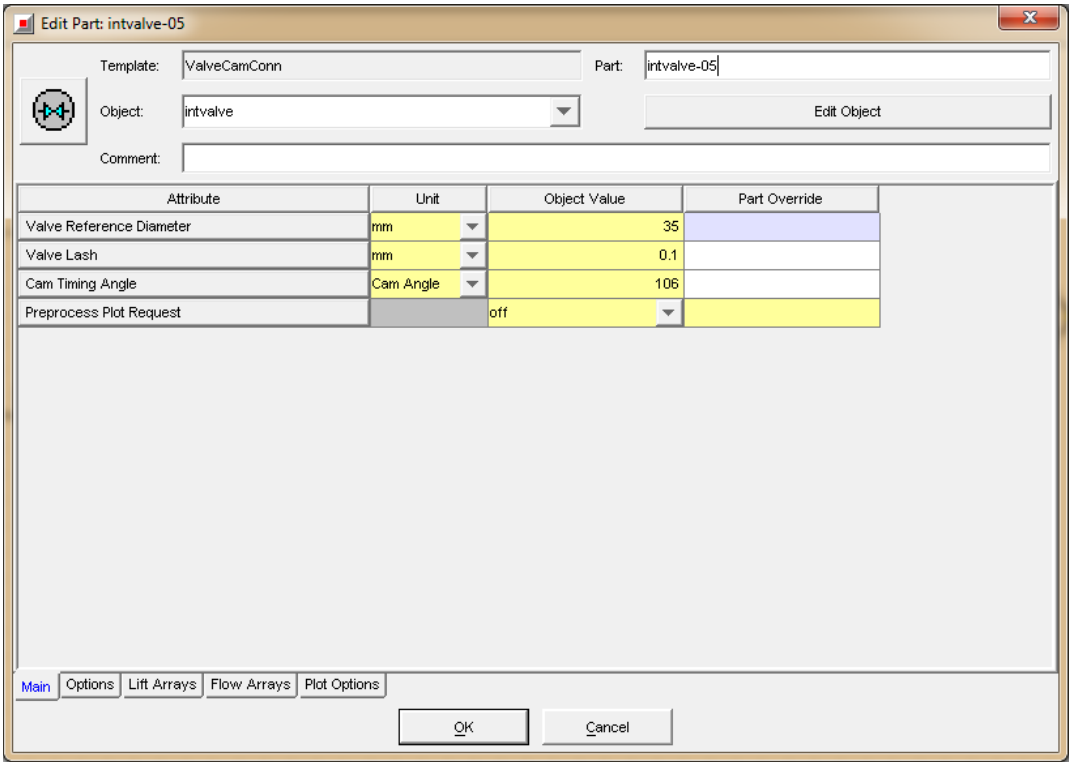


Figure 4.5: Setting of Intake Valve

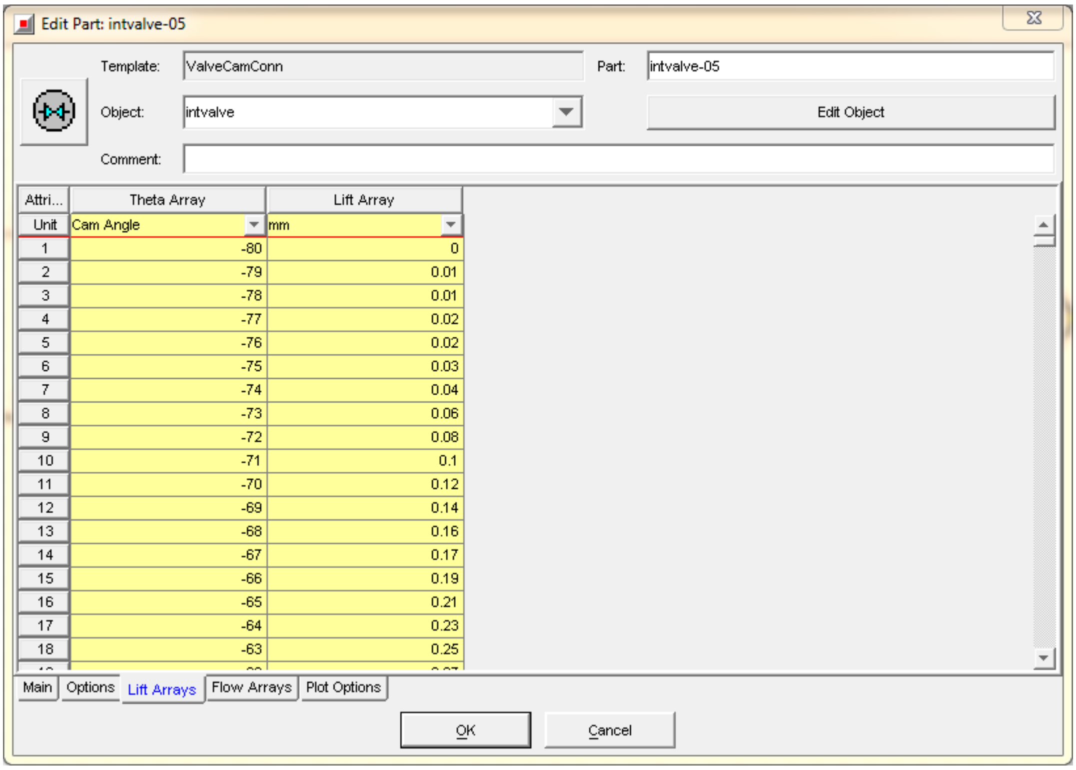


Figure 4.6 Theta Array and Lift Array

After running the simulation and getting the results from GT Post, contrast the results based on Indicated Power, Indicated Torque and Indicated Mean Efficiency Pressure, the Figure 4.33 can be obtained. This figure shows the relationship between Intake Valve Open Angle and Indicated Power, Indicated Torque as well as Indicated Mean Efficiency Pressure. From this figure, the best intake valve open angle can be got that is 33 degree. At this point, indicated power, indicated torque and IMEP all reach the peak values which are 1.5 kW, 5.6 Nm and 0.4 bar.

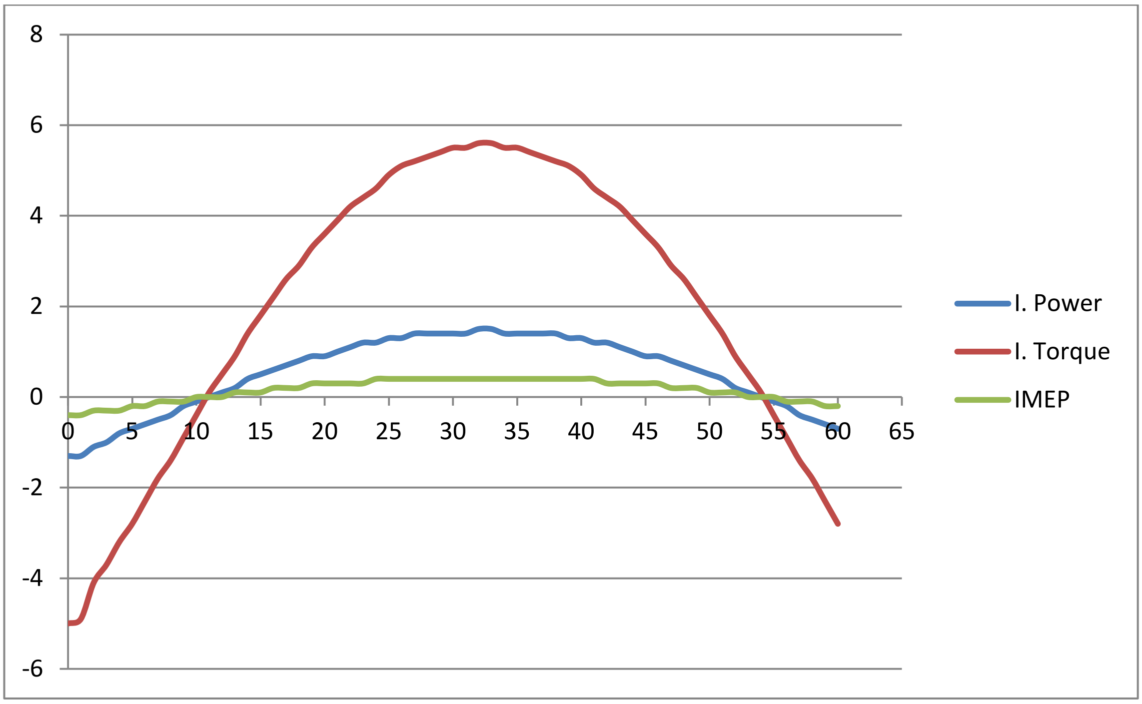


Figure 4.7: Indicated Power, Indicated Torque and IMEP Change Curve with Different Intake Valve Open Angle

The calculation equations of these items are shown as follow.

Indicated Power:

$$P_i = W_i N / \eta_R \tag{4.4}$$

Indicated Work:

$$W_i = \oint Pdv \tag{4.5}$$

Indicated Torque:

$$T_i = W_i / 2\pi \tag{4.6}$$

Indicated Mean Efficiency Pressure:

$$\mathrm{IMEP} = \mathrm{W_i}/\mathrm{V_d} \tag{4.7}$$

Hence the intake valve open angle already been decided, a result of IVC, EVO and EVC can be obtained from GT Post and a valve timing graph can be drawn.

Table 4.1: Engine Geometry

Bore [mm]	92.0
Stroke [mm]	60.0
Connecting Rod Length [mm]	110.0
Piston Pin Offset [mm]	2.50
Displacement/Cylinder [liter]	0.399
Total Displacement [liter]	0.798
Number of Cylinders	2
Compression Ratio	9.00
Bore/Stroke	1.533
IVC [VA]	175
EVO [CA]	143
IVO [CA]	33
EVC [CA]	-75

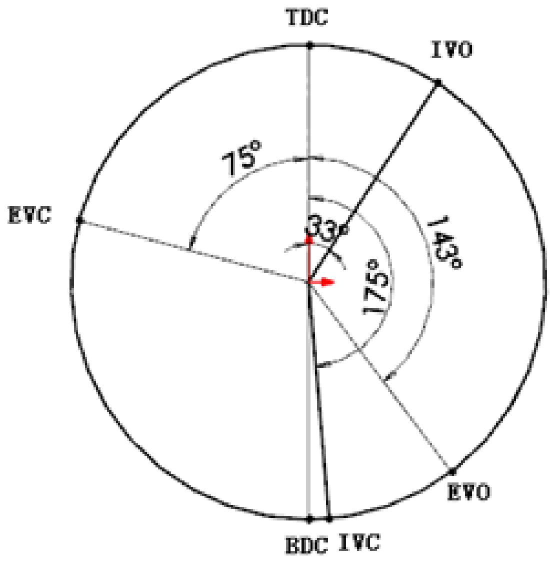


Figure 4.8: Valve Timing Graph

The Figure 4.8 shows the valve timing graph which drawn based on the computational results in Table 4.1. The results are calculated based on the Equation 4.1, Equation 4.2 and Equation 4.3.

The Table 4.2 to Table 4.6 shows the results that read from GT Post.

Table 4.2: Engine MEP, Torque and Power

	Indicated	Crankshaft	Friction	Attachments	Brake
MEP [bar]	0.4	0.4	-0.3	0.0	0.1
Torque [N-m]	5.6	5.6	-3.8	0.0	1.4
Power [kW]	1.5	1.5	-1.0	0.0	0.4

Table 4.3: Engine Operation Condition

Rpm	2500
Injection Start [CA]	N/A
Vol. Eff. Ref. Pressure [bar]	1.000
Vol. Eff. Ref. Temperature [K]	300
Mean Piston Velocity [m/s]	5.0

Table 4.4 Engine Performance Predictions

Brake Power [kW]	0.4
Brake Power [HP]	0.5
Brake Torque [N-m]	1.4
IMEP [bar]	0.44
FMEP [bar]	0.30
PMEP [bar]	0
Air Flow Rate [kg/hr]	302.6
BSAC [g/kW-h]	833465
Fuel Flow Rate [kg/hr]	0.0
BSFC [g/kW-h]	0.0
Volumetric Efficiency [%]	218.2
Trapping Ratio	1.00
A/F Ratio	0.0

Table 4.5: Key Cylinder Predictions

Cylinder	1	2
Part Name	Cylinder-03	Cylinder-04
Volumetric Efficiency [%]	218.3	218.3
Trapping Ratio	1.00	1.00
F/A Ratio	0.0	0.0
IMEP [bar]	0.45	0.45
Maximum Pressure [bar]	73.99	73.89
CA at Max. Pressure [deg]	0.0	0.0
dPmx/DCA [bar/deg]	1.617	1.614
Maximum Temperature [K]	768	769
Intake Pressure [bar]	9.730	9.730
Intake Temperature [K]	405	405
Exhaust Pressure [bar]	1.510	1.516
Exhaust Temperature [K]	389	388

Table 4.6 Gas-Structure Heat Transfer

	Piston 1	Piston 2	Head 1	Head 2	Cylinder 1	Cylinder 2
Area [mm^2]	3192	2460	4607	2932	2932	5924
Hg_eff [W/m^2-K]	652	652	652	652	489	317
Tg_eff [K]	543	543	543	543	482	415
T_wall [K]	590	590	550	550	450	450
Q_conv [W]	-98	-76	-22	-14	47	-57
Q_rad [W]	0	0	0	0	0	0
Q_total [W]	-98	-76	-22	-14	47	-57
Q_flux [kW/m^2]	-31	-31	-5	-5	16	-11

Figure 4.9 to Figure 4.11 show the maximum pressure, maximum temperature, heat transfer rate and p-v diagram for the working model. The plots are all analyzed by GT-Post. Other plots are shown in Appendix D.

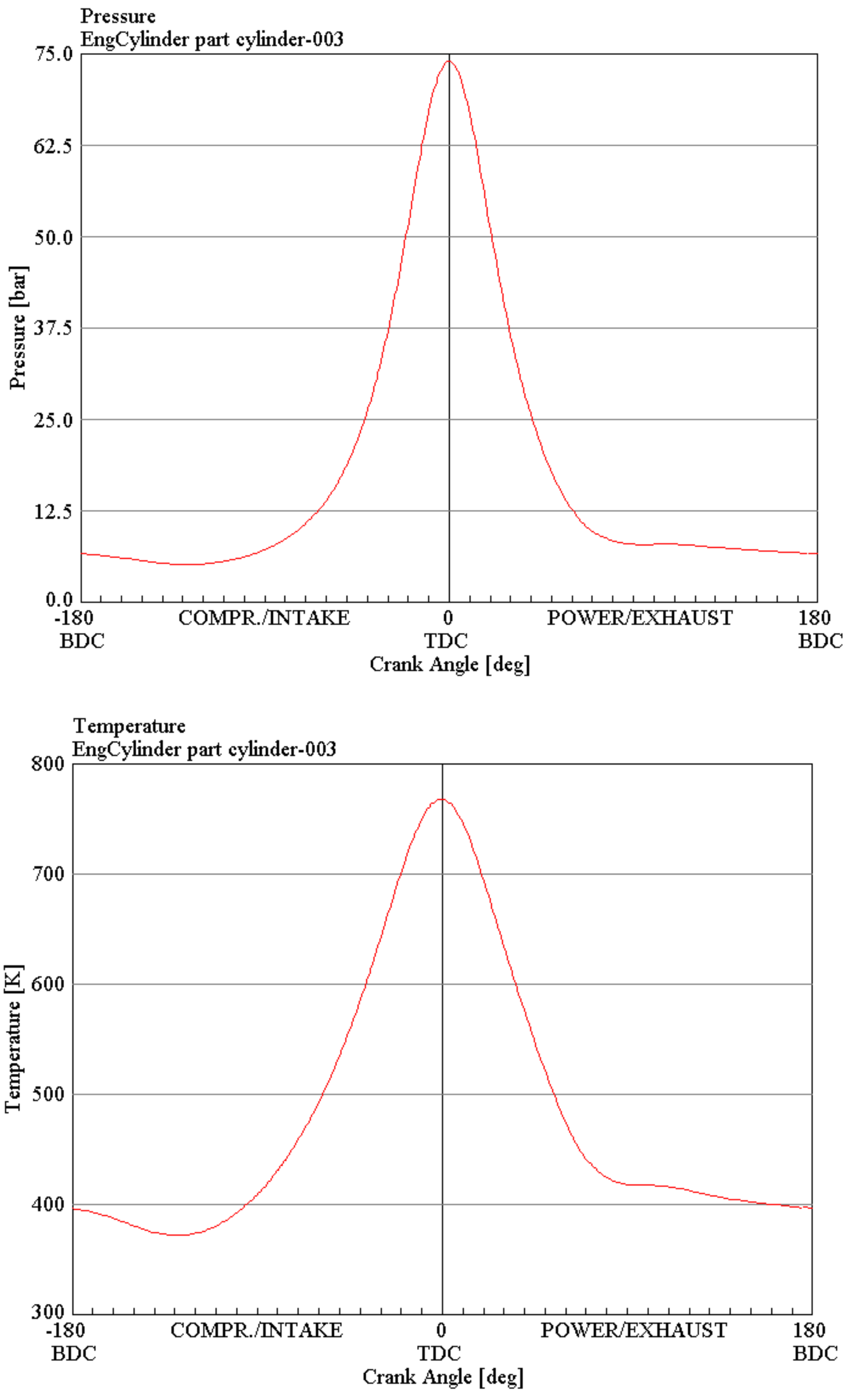


Figure 4.9: Pressure and Temperature Curve in the Cylinder

Figure 4.9 and Figure 4.10 show the pressure and temperature changing curve for a typical 2- stroke engine. In the design, the pressure and temperature set for storage is 10 bar and 600 K. From Table 4.5, it shows the pressure of intake compressed air to both cylinders is 9.73 bar while the temperature is 405 K. After power process, almost 74 bar pressure is produced in the engine cylinder while the temperature is around 770 K.

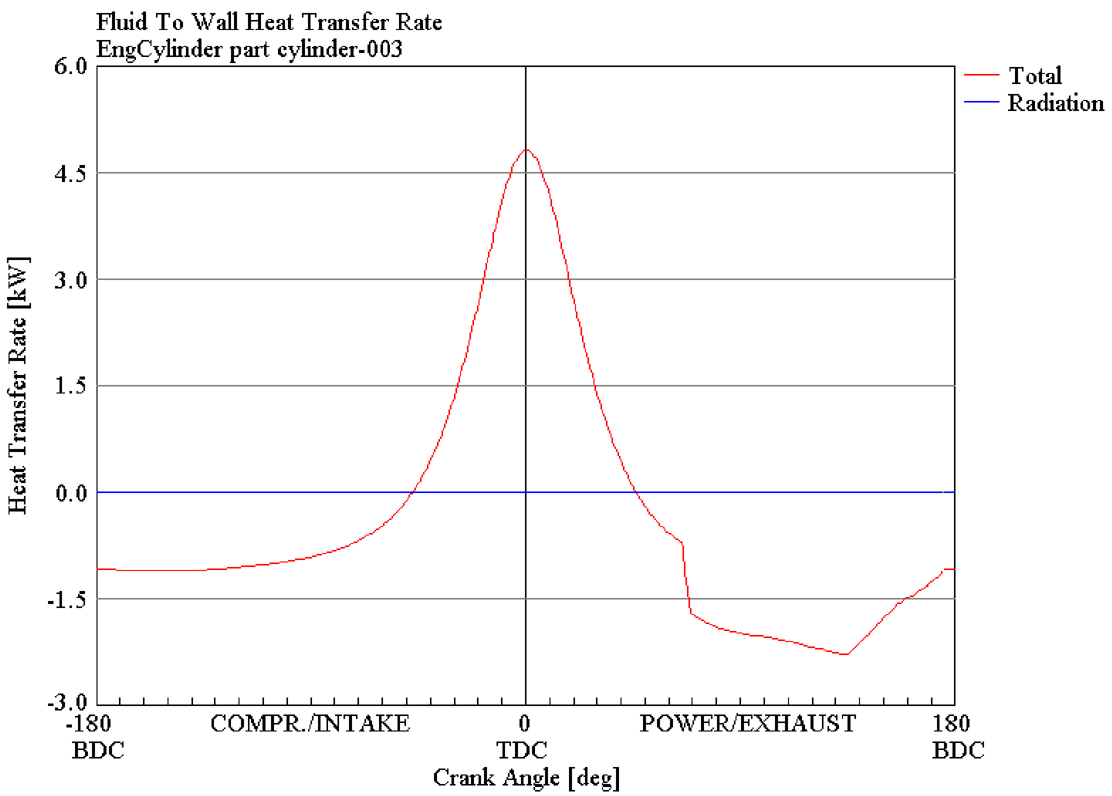


Figure 4.10: Fluid to Wall Heat Transfer Rate

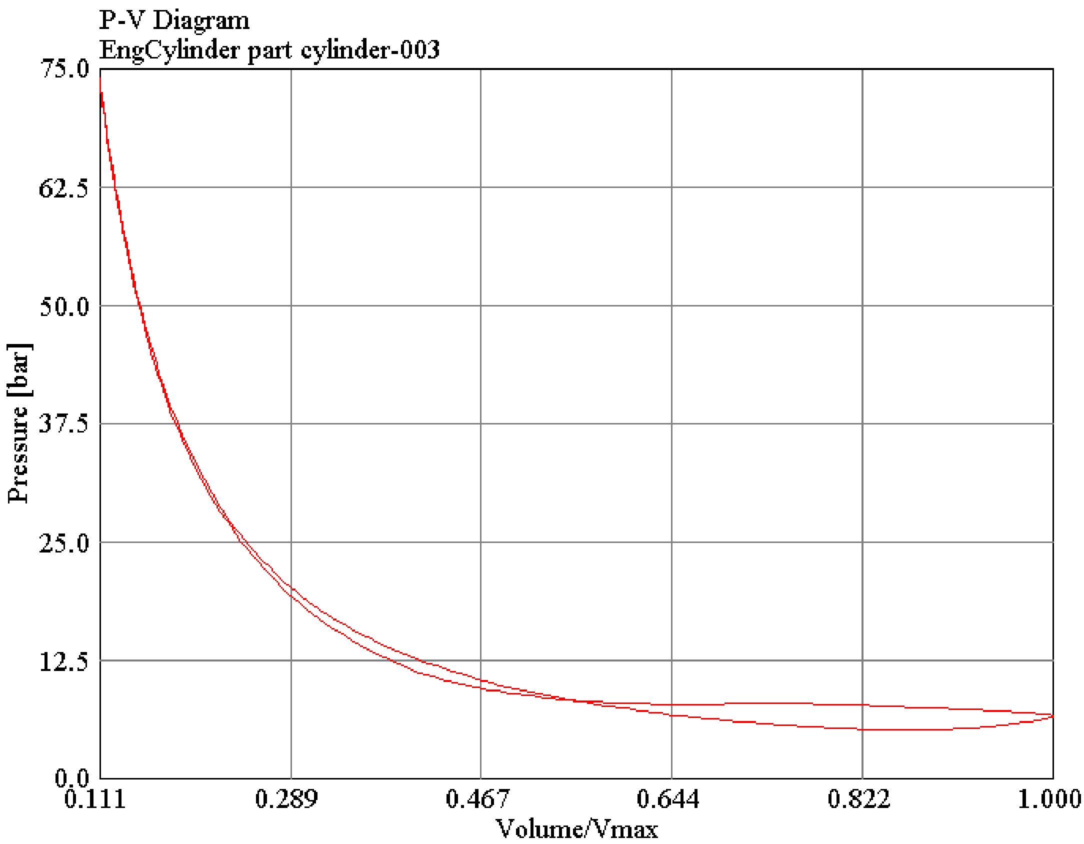


Figure 4.11: P-V Diagram

Figure 4.11 shows the P-V diagram of the air engine working cycle. This diagram is produced based on the Eq. (4.8) and Eq. (4.9).

$$P = P_{max} \left(\frac{V_{TDC}}{V}\right)^{m} \tag{4.8}$$

$$P_{max} = P_{IVC} R_c{}^{\gamma} + P_{comb} \tag{4.9}$$

From the P-V diagram, the engine working process can be analysed. First, from TDC to 33 degree after TDC, both valves close, and the piston move downward because of momentum. During this period, it works similar as isentropic expansion process. After crankshaft rotates 33 degree, intake valve open, then intake compressed air. The exhaust valve opens after 143 degree from TDC. When the crankshaft rotates 175 degree, the intake valve close and piston continue moving downward until it reaches

BDC. Then the next process starts. The piston starts to move upward smoothly until it reaches 75 degree before TDC where the exhaust valve closes. In these two processes, the pressure theoretically should be constant. But the heat lost, and friction lost also in consider so that the line of these two processes is not horizontal. Next the period from exhaust closes until the piston reaches TDC, it does the similar isentropic compression process.

This graph is different from the design P-V diagram which mention in Chapter 3. There are some causes. First, the previous P-V diagram is theoretically design which doesn’t consider about heat lost, friction lost, and some other effect factors such as the fluid to wall heat transfer, which is shown in Figure 4.10 during all the process. Second, when doing the theoretically design, the valve timing are neglected so that the timing of valve open and close is not so appropriate which influence the tendency of pressure grievously.

From the computational analysis, the best intake valve open angle can be found as 33 degree after TDC. Then the simulation runs depend on this valve timing. The Figure 4.11 indicates that the work produced in the cylinder is quite small so that the indicated power and brake power, which are shown in Table 4.2, are also much lower than the expected values. The results illustrate some setting parameters may not be accurate, or the design working stage is irrational.

CHAPTER 5

CONCLUSION

5.1 CONCLUSION

This paper reports the research of a compressed air powered engine development from an original Subaru EA71 model. Actually this kind of technology is not new. It has already been researched for hundreds of years although still, not in mass production. It is a revolutionary engine design which not only reduce exhaust gas pollution, but also economic. The project achieves the objective of reduce the emission of carbon dioxide, however, the new model lack of power output.

In this research, the two cylinders are powered only by compressed air, which stored in reservoir. As the pressure and temperature set in the air reservoir is 10 bar and 600 K, the intake compressed air pressure and temperature to cylinder are 9.73 bar and 4.05 K. After the power process of piston, the pressure achieves around 74 bar while the temperature is around 770 K. But the power output from the engine is quite low which is only 1.5 kW is. According to conjecture, it may because the setting engine speed is low which only 2500 rpm and the engine displacement for two cylinders are only 0.798 liters.

5.2 RECOMMENDATION

In fact, the result get in this paper is not perfect and complete. To address the problems, there are some recommendations. First, try to change some setting data and parameters in the template. Second, run the simulation with higher engine speed. Third use higher pressure compressed air. On the other hand, the duration of the engine can work is still not decided. Therefore, more research is needed to prove the technology of this engine design perfectly.

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APPENDIX A
GANTT CHART

	SCOPES	Week 1	Week 2	Week 3	Week 4	Week 5	Week 6	Week 7	Week 8	Week 9	Week 10	Week 11	Week 12	Week 13	Week 14
FYP 1	3D Reverse Engineering														
	Air Cycle Engine Definition														
	Working Conceptual Design														
	PSM1 Report Preparation														
FYP 2	Engine Component Design														
	Computational Analysis														
	Final Report Preparation														

APPENDIX B

LIST OF ENGINE COMPONENTS AFTER DISMANTLING AND CLEANING

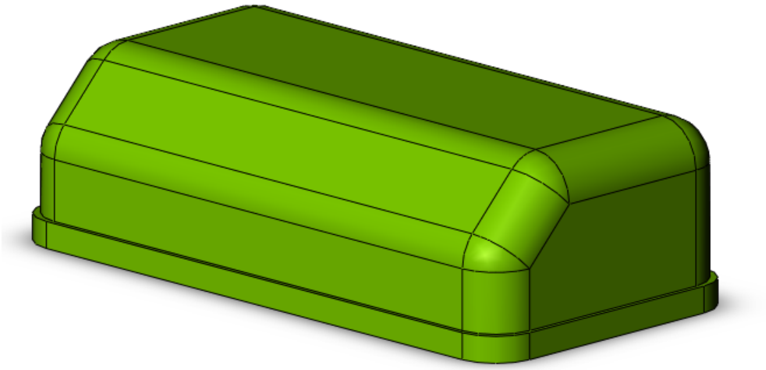
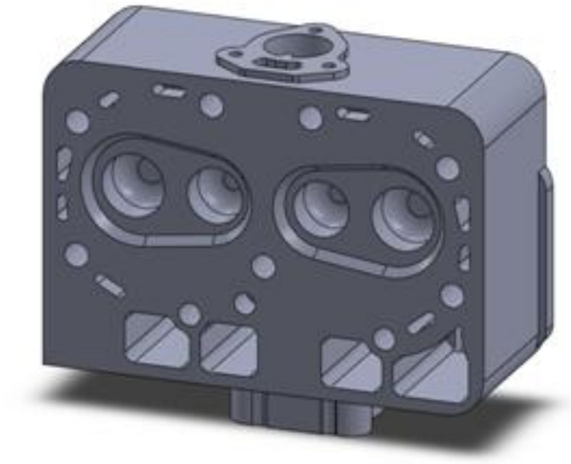
Carburetor	
Cylinder Head	

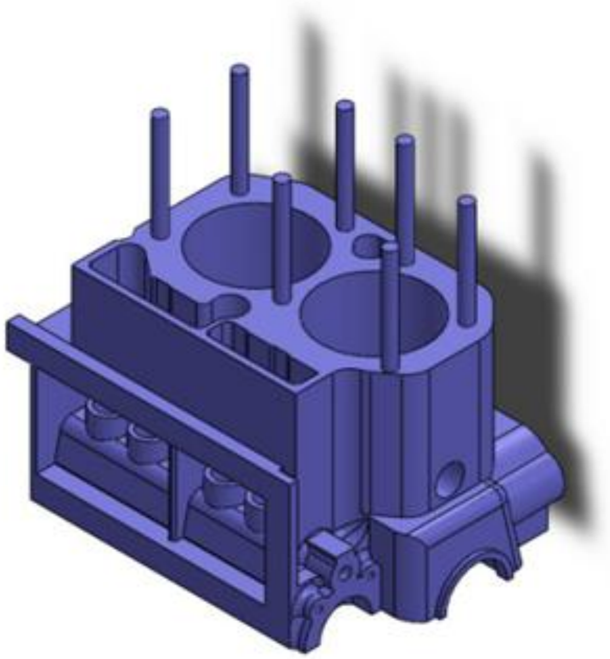
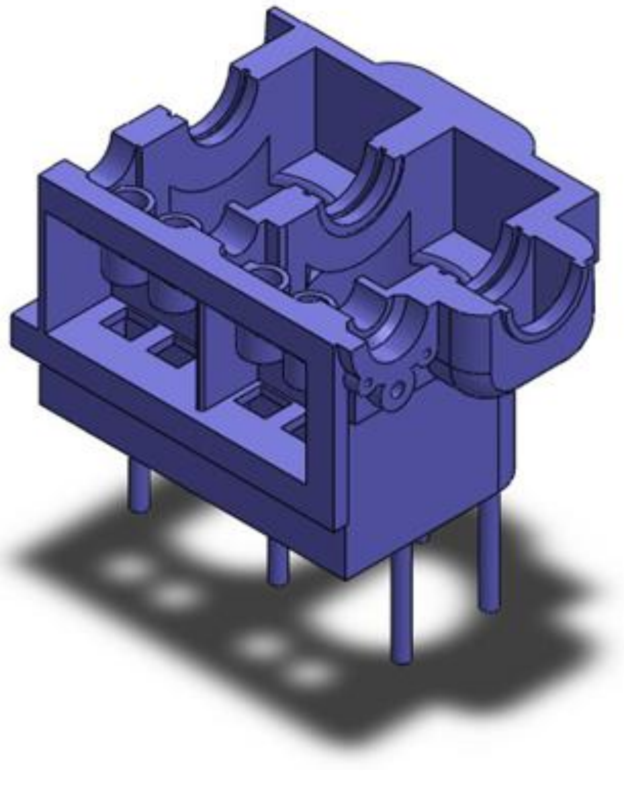
Cylinder Block	
Exhaust Valve and Components	

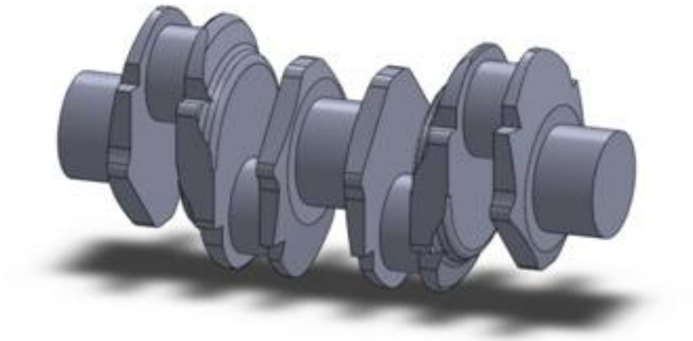
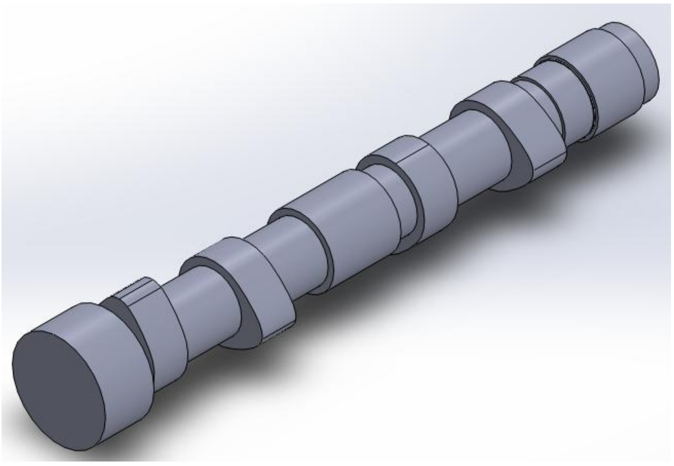
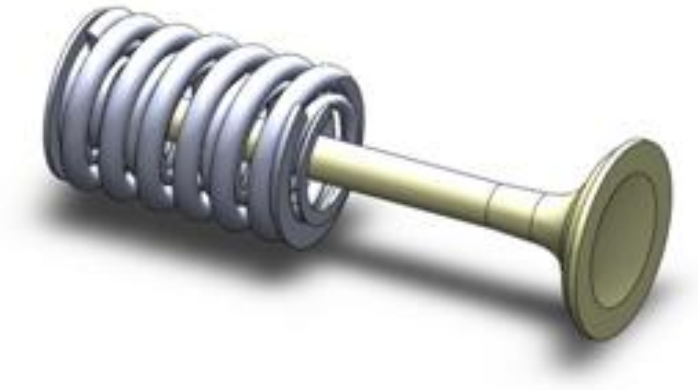
Camshaft and Pulley	
Crankshaft	
Connecting Rod and Piston	 

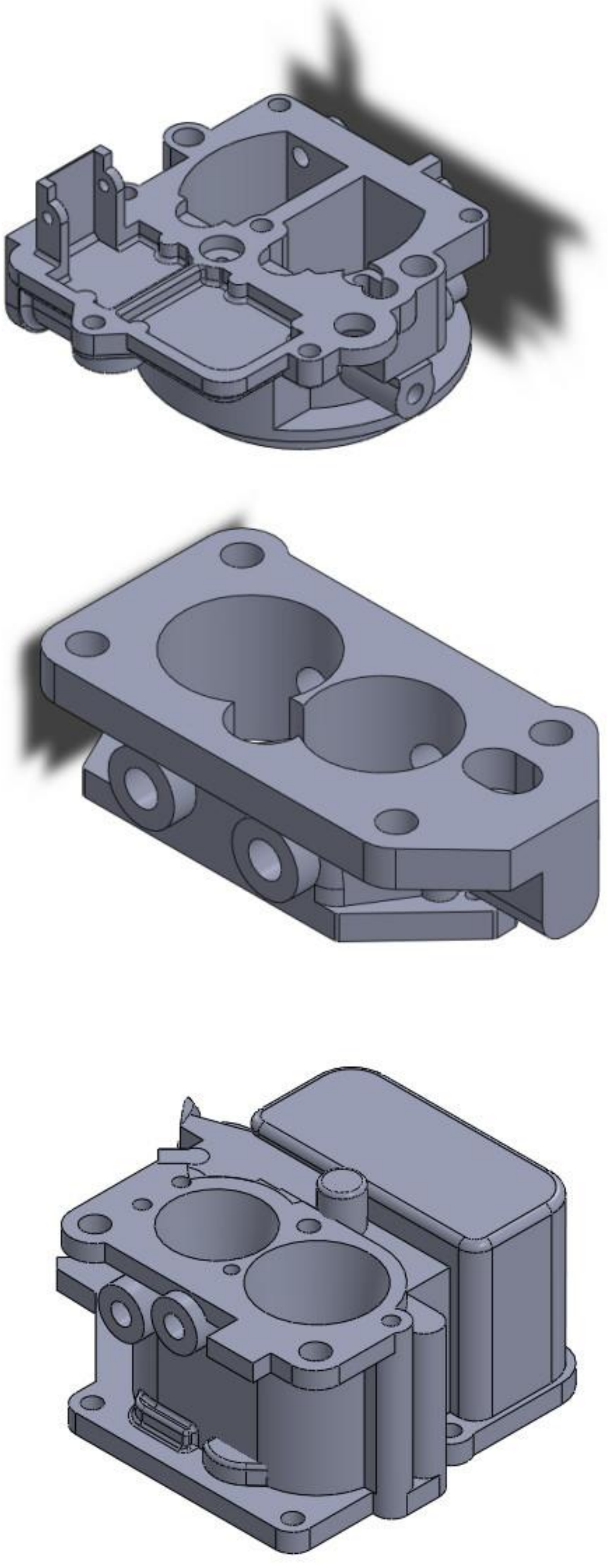
APPENDIX C

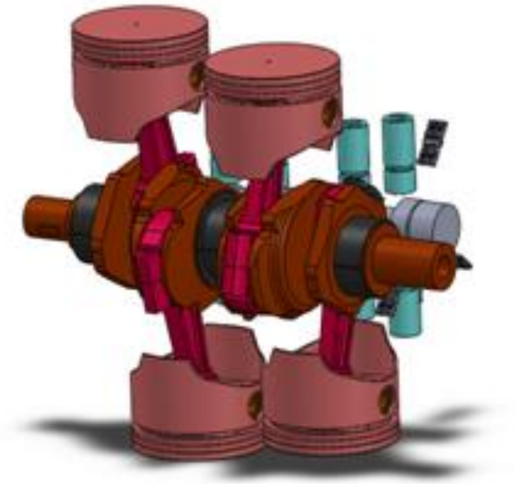
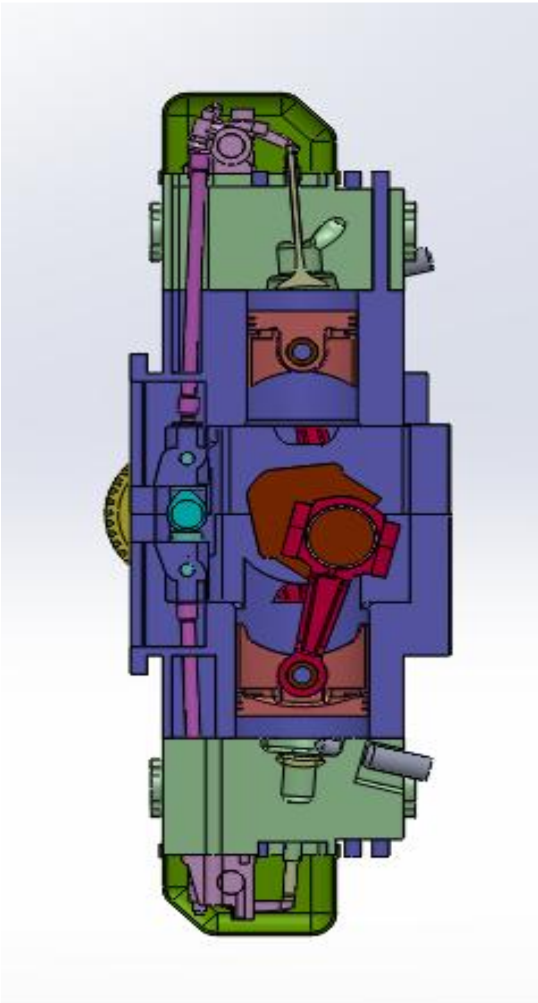
LIST OF ENGINE COMPONENTS DRAWING IN SOLIDWORKS

Cylinder Head Cover	
Cylinder Head	

Cylinder Block	 

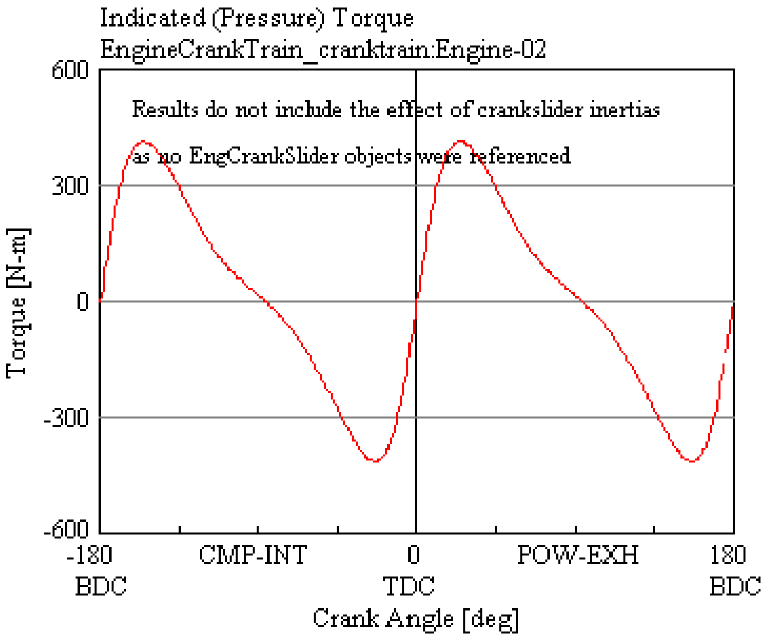
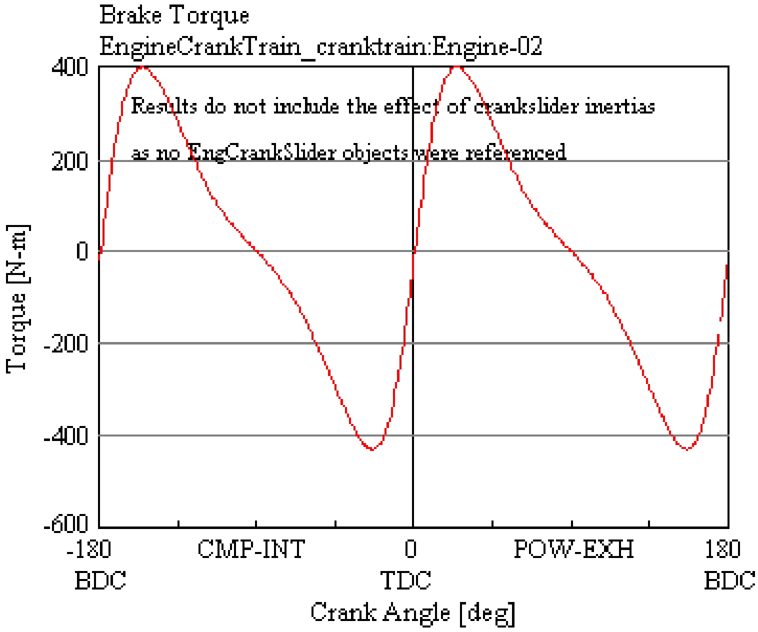
Crankshaft	
Camshaft	
Valve	

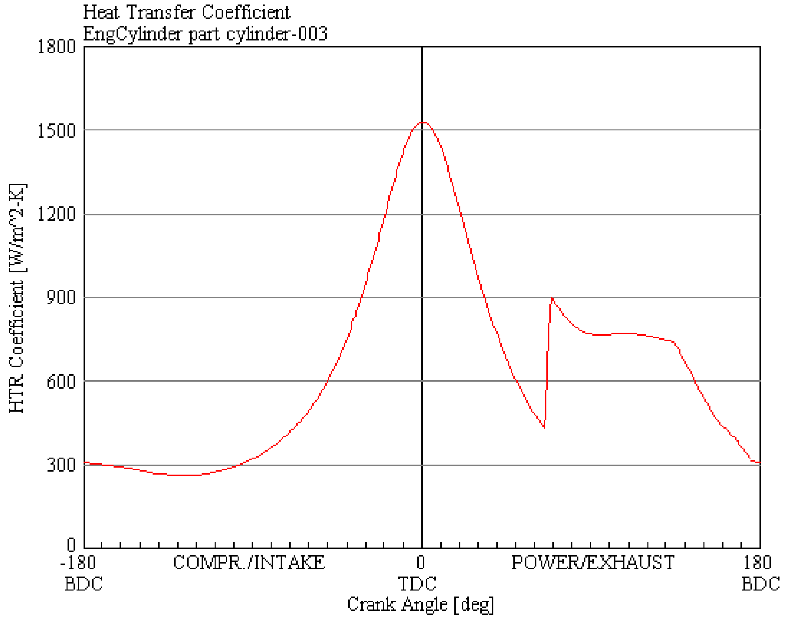
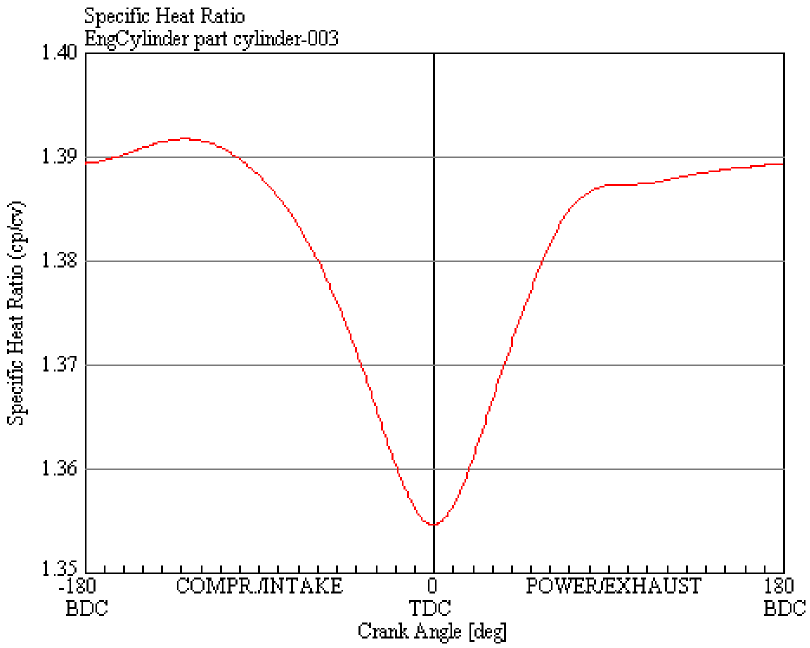
Three Parts of Carburetor	

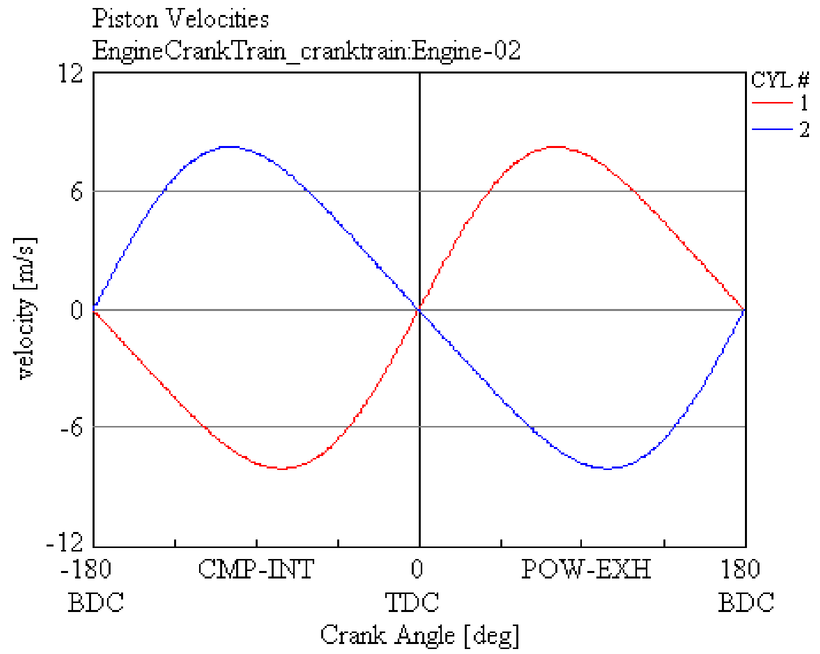
Pistons and Crankshaft Assembly	
Integrated Engine Assembly	

APPENDIX D

LIST OF PLOTS IN GT-POST

Indicated Torque	
Brake Torque	

Heat Transfer Coefficient	
Specific Heat Ratio	

Piston Velocities	
Piston Accelerations