SIX STROKE INTERNAL COMBUSTION ENGINE HEAT RECOVERY

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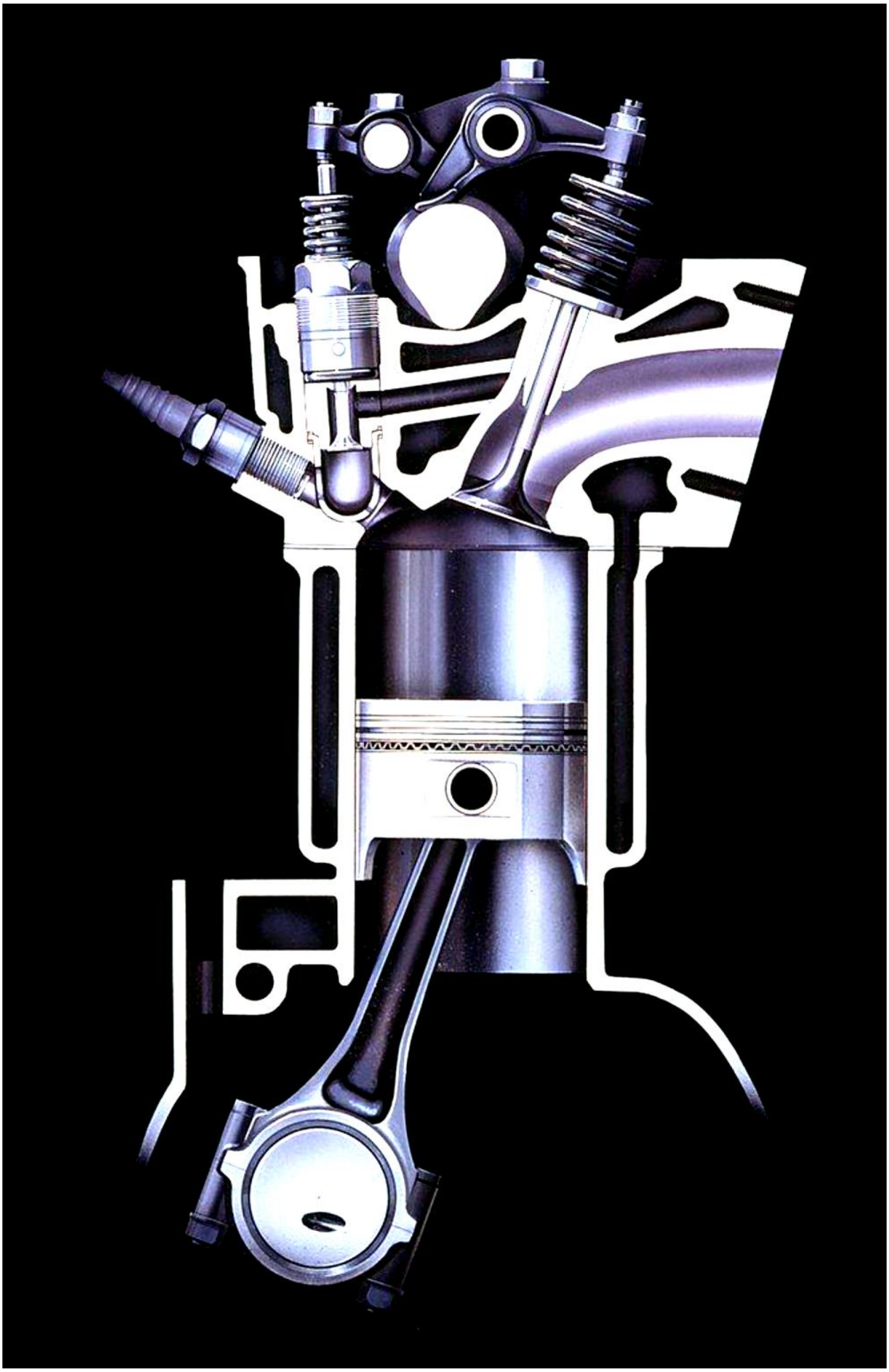

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Abstract

In thermal design of the internal combustion engines most researchers use air-standard power cycle models to perform their thermodynamic analyses. The concept adding two more strokes to the ideal Otto cycle to increase fuel power and efficiency is studied and presented here. It can be thought of as a four stroke Otto cycle followed by a two-stroke heat recovery steam cycle or also known as six stroke engine.

In this project, thermodynamic analysis was performed for a single cylinder six stroke gasoline internal combustion engine to identify the effect of added the amount of water injected for the second power stroke and to identify the cylinder pressure, a computer simulation by using Engineering Equation Solver (EES) was developed based on the Otto cycle which basically six stroke is the adding of two stroke into four stroke engine. Then, performance results can be obtained.

Wide range of engine thermal properties was computed, such as cylinder pressure and temperatures, density of air, entropy, enthalpy and specific volume of air in each cycle at all degrees of crank shaft from 0 to 1080 CA$^{\circ}$.

From the results, at constant engine speed (3000 RPM) due to one cycle the P-V and P-α diagrams were plotted and analysis. Thus, power , thermal efficiency improved by 3%, 30% respectively and decreased in fuel consumption about 29.5%.

الملخص

في التصميم الحراري لمحركات الاحتراق الداخلي ، يستخدم معظم الباحثين نماذج دورة الطاقة المعيارية للهواء لإجراء تحليلاتهم في الديناميكا الحرارية. حيث تمت في هذا البحث دراسة وفهم عملية اضافة شوطين حركيين الى دورة أوتو المثالية لزيادة قدرة الوقود وكفاءته. وذلك باعتبار دورة أوتو لمحركات الاشواط الأربع متبوعة بدورة بخار لاسترداد الحرارة الضائعة خلال شوطين اضافيين أو ما يعرف أيضًا بمحرك الستة أشواط.

في هذا المشروع ، تم إجراء تحليل ديناميكي حراري لمحرك احتراق داخلي يعمل على ستة أشواط ؛ لتحديد تأثير إضافة كمية من المياه التي تم حقنها خلال شوق القدرة الثاني أو ما يعرف بشوط قدرة البخار؛ لتحديد قيمة الضغط الذي يمكن اي يصله البخار داخل غرفة الاحتراق خلال هذا الشوط ،هنا تم تطوير محاكاة الكمبيوتر باستخدام برنامج EES بناءً على دورة أوتو لمحرك الستة أشواط . ثم ، يمكن الحصول على نتائج التحليل.

الكثر من الخصائص الحرارية تمت دراستها في هذا البحث ، مثل ضغط الاسطوانة ودرجات الحرارة ، كثافة الهواء ، عشوائية النظام ، المحتوى الحراري والهواء المحدد في كل دورة في جميع درجات عمود الكرنك من 0 إلى 1080 درجة.

وقد رُصدت النتائج عند سرعة ثابتة للمحرك (3000 دورة في الدقيقة) خلال دورة واحدة. حيث تم رسم مخططات P-V و P-α وتحليلها. وهكذا تحسنت الطاقة و الكفاءة الحرارية بنسبة 3 ٪ و 30 ٪ على التوالي ، وانخفاض حاد في استهلاك الوقود بحوالي 29.5 ٪.

شكر وإهداء

مع عبق الورد وترانيم الأمل المشرق ومع بزوغ شمعة إضاءة المستقبل وعبر زعفران ارض فلسطين، من هنا، من قلعة البوليتكنك كانت سحابة الإهداء تمطر مطر البسمات والكلمات والتحايا، وتبث جذورها إلى منبع المهد وإلى حاضنة الأجيال وإلى مقر الرجال، إلى أرض الإيمان إلى بيت الحكمة والآمال، إلى تلك المعشوقة المظللة بسجايا الدفء والافتعال، إلى حاضنة الآباء والأمهات، إلى تلك المزهرية التي رشت المهنيين والتقنيين في أرضها وأضحت على الأفق تعاليم العلم والمعلمين ورسمت وسطرت في قلبها وقلمها كل أنفاس التحايا والإهداء، إلى طيور التخرج في البوليتكنك، إلى كل الأصحاب والأحباب، إلى كل الكوادر التي ربت هذه الأجيال، إلى كل من اعتلى الهمة وزرع النبتة وجعل من هذا البلد بلد الصنعة، إلى كل أب وإلى كل أم وإلى كل من عمرها ورسم سمائها.. فلسطيننا السعيد.

يسرنا ونحن في نهاية دراستنا العلمية في قسم هندسة السيارات والتي دامت خمس سنين متواصلة من الدراسة والتحصيل العلمي أن نزف أسمى آيات الشكر والتقدير لمشرف المشروع - - د. زهدي سلهب - ولكوادر الهندسة الميكانيكية لما بذلوه معنا من جهودٍ وإرشاداتٍ خلال هذا الصرح العلمي، وكما نهيب لهم على ما قدموه وما بذلوه في سبيل توصيل المعلومات في مجال العلم والمعرفة في مضمار الميكانيك وسعيهم المتواصل لتسهيل المصاعب لطلاب القسم خلال هذه الفترة وهذا إن دل على شيء فإنما يدل على عطائهم المستمر في هذا المضمار والذي يجعلهم مثالاً مشرقاً لنا، ولن نستطيع بكلمة شكر أن نفي بحقهم ونتمنى لهم مزيداً من العطاء والتقدم العلمي . كما نتقدم بالشكر إلى كل الإخوة والأخوات العاملين في هذا الصرح العلمي من المدرسين والإداريين والعاملين لما بذلوه من تعاون كبير سواء في المجال العلمي أو المجال المعنوي الذي يرفع من مستوى هذا البلد ليكون الطريق الأول لتقدم الأجيال والشكر للجميع.

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CHAPTER ONE

1. Introduction

Since the industrial revolution, cars have been invented. The general objectives were to increase engine capacity. After that, the objectives were varied to include the efficiency of the engine and finally the fuel consumption. After increasing the environmental pollutants, the goals of the engines included reducing harmful emissions to the environment as much as possible.

1.1. Importance of the study

One of the most difficult challenges in engine technology today is the urgent need to increase engine thermal efficiency. If the efficiency is higher, then there will be less fuel consumption and lower atmospheric emissions per unit of work produced by the engine in addition to that noise and pollution are reduced [1].

In order to improve the efficiency of internal combustion engines, the six stroke engine was introduced by makes several modifications to the current four stroke cycle engine.

The six stroke engine is a type of internal combustion engine with an advance feature of more power generation some complexity intended to make it more efficient and utilize the fuel. Two more additional strokes are the fifth stroke, which called water injection stroke while the other sixth stroke is called re-exhaust stroke [2].

The vaporization of water from water injection stroke converts waste heat energy into usable power. This steam will force the piston down. As well as extracting power, the additional stroke cools the engine by water which is used for steam generation and removes the need for a cooling system which is used in four stroke Otto cycle and makes the engine lighter and gives 40% increased efficiency over the normal Otto cycle efficiency [3].

Six stroke engine is an effective way of recovery of heat lost through the exhaust gases by adding additional steam stroke to a partial exhaust stroke [4]. Figure (1.1) shows energy losses in combustion engines.

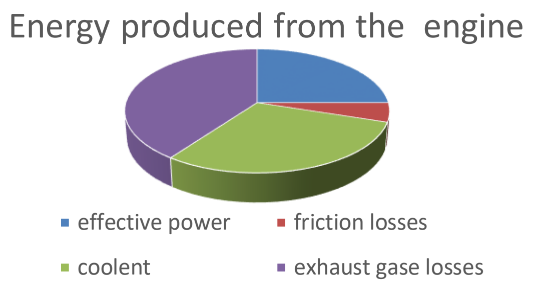


Figure 1.1: Energy produced from the four stroke engine

The automotive industry may soon be revolutionized by a new six stroke design which adds a second power stroke, resulting in much more efficiency with less amount of pollution [1].

1.2. Study objectives

In the present project the effect of adding two additional strokes to the four stroke engine on thermal efficiency, power, fuel consumption. This will be accomplished by injecting water in the combustion chamber at the additional two strokes.

1.3. Motivation of study

- Four stroke engines have negative impacts on the human and the environments:
  - ☒ On environments: engine produces a lot of pollution. The combustion creates a lot of emissions which leads to air pollution.
  - ☒ On human: some emissions produce unpleasantly smell and some people may be sensitive and some has negative effect on respiratory system like CO.

- The increase of automotive number mean increase demand on fossil fuel so the economy and efficiency are increased.

1.4. Scope of project

- Literature review crankshaft and camshaft gear ratio and modification part of the six stroke engine.
- Calculate engine thermal efficiency for six stroke internal combustion engine.
- Calculate engine power and fuel consumption.

1.5. Project time table

The time table for this project illustrated as shown in table 1.1.

Table 1.1: Time table for the project

Number of weeks task	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**	**14**	**15**	**16**
System design	🟦	🟦	🟦	🟦												
EES code written					🟦	🟦	🟦	🟦								
Analysis and result									🟦	🟦	🟦	🟦				
Writing report													🟦	🟦		
Make presentation															🟦	🟦

CHAPTER TWO

2. Literature review

In order to gain a better perspective of the development process of this project, research was conducted to obtain the best requirement that suitable for this system design. The literature review was conducted using variety of methods including library books, journal and articles.

2.1. Introduction

In this chapter, a brief explanation will focus on history of four and six stroke engines included the basic of internal combustion engines.

2.2. Internal combustion engine

An internal combustion engine (ICE) is a heat engine where the combustion of a fuel occurs with an oxidizer (usually air) in a combustion chamber that is an integral part of the working fluid flow circuit. In an internal combustion engine, the expansion of the high-temperature and high-pressure gases produced by combustion applies direct force to some component of the engine. The force is applied typically to pistons, turbine blades, rotor or a nozzle. This force moves the component over a distance, transforming chemical energy into useful mechanical energy.

The first commercially successful internal combustion engine was created by Etienne Lenoir around 1859 and the first modern internal combustion engine was created in 1876 by Nikolaus Otto.

2.2.1. Four stroke engine

The four stroke engine is probably the most common engine type nowadays. It powers almost all cars and trucks. Figure (2.1) shows four stroke engine cylinder structure.

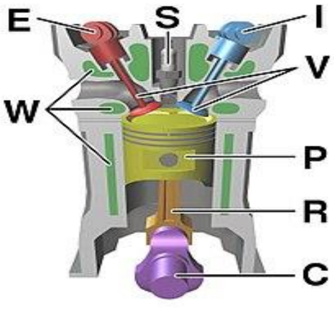


Figure 2.1: Four stroke engine cylinder structure [6]

C – Crankshaft.
E – Exhaust camshaft.
I – Inlet camshaft.
P – Piston.
R – Connecting rod.
S – Spark plug.
V – Valves. Red: exhaust, blue: intake.
W – Cooling water jacket.

It consists of four stroke, one cycle operation is completed in four movement stroke of the piston. That is one cycle complete in every two revolutions of the crankshaft. Each stroke consists of 180^{0}of crankshaft rotation and hence a cycle consists of 720^0 of crankshaft rotation.

A four stroke internal combustion engine has to do four things to complete one cycle as discussed below:

First stroke (intake stroke)

From Figure (2.2) piston moves from Top Dead Center (TDC) to Bottom Dead Center (BDC) and creates vacuum pressure in the cylinder. Due to the vacuum pressure air fuel is sucked into the cylinder via the inlet port.

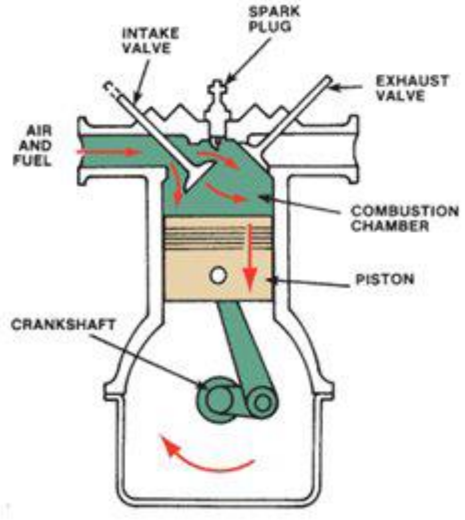


Figure 2.2: Intake stroke [5]

Second stroke (compression stroke)

From Figure (2.3) piston moves from BDC to TDC and compresses the mixture. During this stroke, both the intake and exhaust valve are closed.

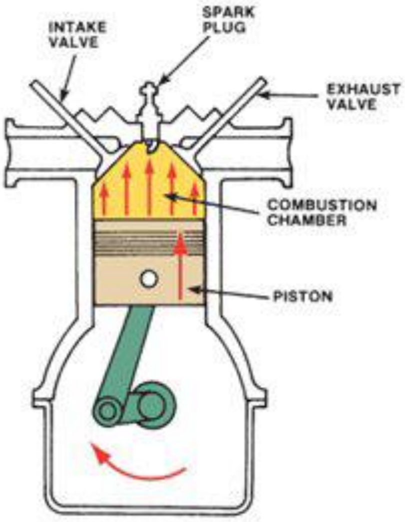


Figure 2.3: Compression stroke [5]

Third stroke (power stroke)

In Figure (2.4) at the end of the compression stroke the fuel is ignited and burnt. The pressure and temperature in the cylinder increases rapidly. The increased pressure pushes the piston downward.

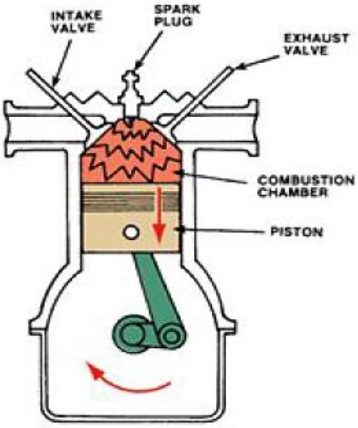


Figure 2.4: Power stroke [5]

Fourth stroke (exhaust stroke)

In Figure (2.5), the burnt product is pushed out from the exhaust valve by scavenging.

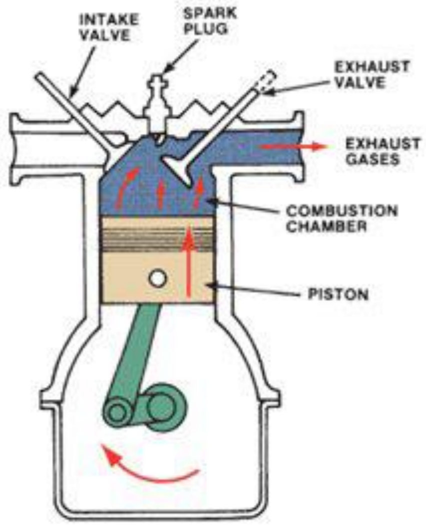


Figure 2.5: Exhaust stroke [5]

2.2.2. Six stroke engine

The six stroke engine is a radical hybridization of two and four stroke engine that the top portion of two stroke engines and the bottom rather the middle section of a four stroke engine [7].

But in six stroke engine the exhausted gases which are left after combustion is further used. Then water is injected in superheated cylinder. Through hot gases the water changes its phase into steam as the temperature of the hot gases is high. This steam will works as a working fluid which will forces the piston down. This movement will give additional two strokes for the same cycle.

Fifth stroke (second power stroke)

- Figure (2.6) shows the 5th stroke. At the end of the exhaust stroke the cylinder wall temperature becomes around (900-1100) C.
- At this stage atomized water expansion is injected into the cylinder.
- The water turns into vapor increasing its volume around 1700 times. This causes the piston to move from TDC to BDC. Thereby rotating the crankshaft for another half cycle.

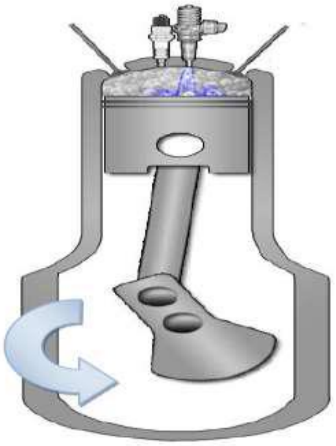


Figure 2.6: Fifth stroke (second power stroke) [8]

Here the fuel is injected once in every 3 complete cycles of the crankshaft which is anytime better than a four stroke ICE where fuel is injected once in 2 complete cycles of the crankshaft. It should be noted that efficiency of the six stroke ICE is more than the existing four stroke ICE. Two major type of secondary fuels used in the 5th stroke are air and water.

Sixth stroke (second exhaust stroke)

The piston will move upward direction with steam exhaust valve open as shown in Figure (2.7). The expanded steam is exhausted through the valve and out passageway. This exhaust may be directed to a conventional condenser, to a muffler system in which combines with and cools the hot exhaust, or directly to the atmosphere.

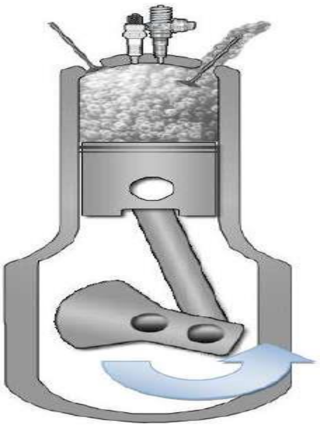


Figure 2.7: Sixth stroke (second exhaust stroke)[8]

2.3. History of six stroke engine

The term six stroke engine developed since the 1990s, to improve its efficiency and reduce emissions.

2.3.1. Griffin six stroke engine

As shown in Figure (2.8) Griffin engine was the first six stroke engine developed in the world. It is developed by the engineer Samuel Griffin in 1883. He used this engine mainly for electric power generation [9].

Figure 2.8: Griffin six stroke engine [9]

2.3.2. Bajulaz six stroke engine

The Bajulaz six stroke engine was invented in 1989 by the Bajulaz S. A. Company, based in Geneva, Switzerland**.** The Bajulaz six stroke engine is similar to a regular combustion engine in design. There was however modifications to the cylinder head, with two supplementary fixed capacity chambers, a combustion chamber and an air preheating chamber above each cylinder. Figure (2.9) shows Bajulaz six stroke engine. The advantages of the engine include reduction in fuel consumption by 40%, multi- fuel usage capability, and a dramatic reduction in pollution [2].

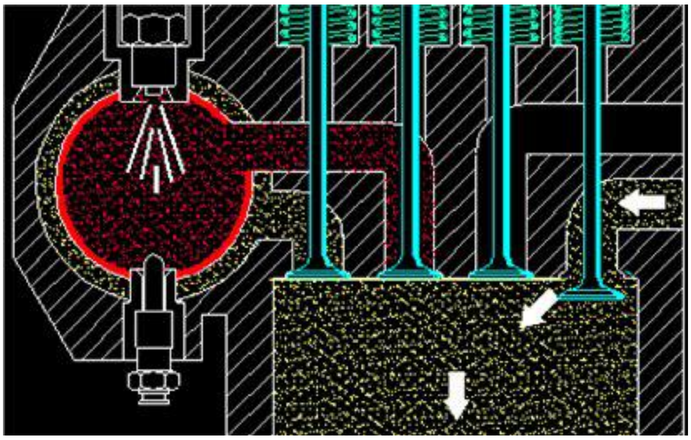


Figure 2.9: Bajulaz six stroke engine [5]

2.3.3. Beare head six stroke engine

Malcolm Beare Australian wheat farmer is the inventor of this six stroke engine in 2001 as shown in Figure (2.10). Malcolm Beare claims his engine is 35% more economical at low revs/throttle openings than an equivalent conventional engine and 13% less thirsty at high rpm/full throttle [10].

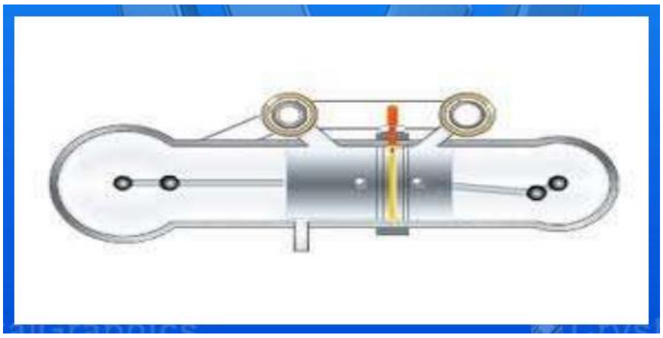


Figure 2.10: Beare head engine [10]

2.3.4. Crower six stroke engine

This engine is invented by Bruce Crower of California in USA in the year 2004 Figure (2.11). In Crower six stroke engine water is injected into the cylinder after the exhaust stroke and is instantly turned to steam, which expands and forces the piston down for an additional power stroke [11].

Crower's six stroke engine features:

- Reduce fuel consumption by 40 %.
- No cooling system required.
- Improves a typical engine’s fuel consumption.
- Requires a supply of distilled water to act as the medium for the second power stroke.

Figure 2.11: Crower’s six stroke engine [11]

2.4. Additional strokes

To summarize in graphical form on Figure (2.12) there were representative valve lifts and resultant representative combustion chamber pressure traces are superimposed versus crank angle where the proposed exhaust recompression and water injection are explicitly shown.

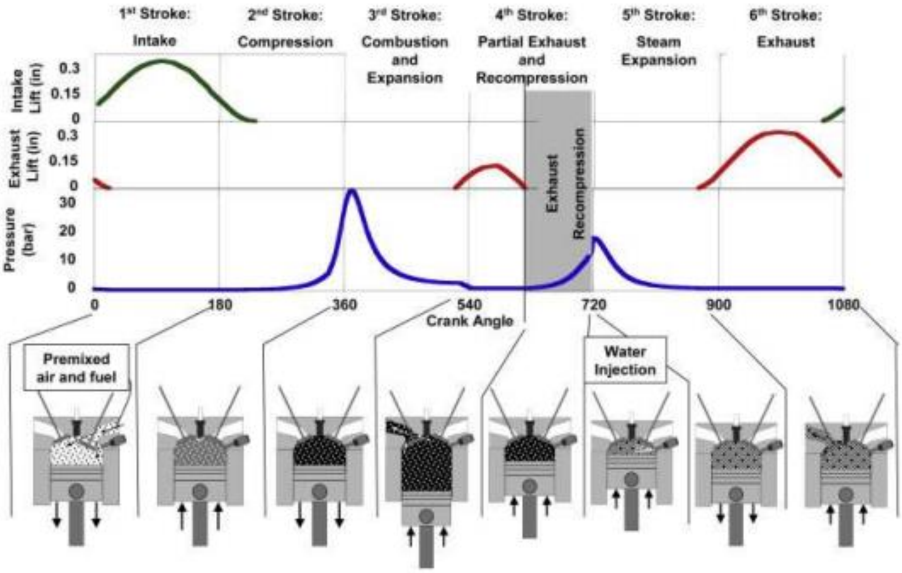


Figure 2.12: Exhaust valve events and cylinder pressure for the six stroke cycle [4]

2.4.1. Recompression

As shown in Figure (2.13). An additional assumption that the recompression process is isentropic from state 1 to state 2 yields the additional state property required by the state postulate of thermodynamics for a simple compressible system to determine completely the thermodynamic properties at state 2. The work required by the recompression process is thus known for a given crank angle closing.

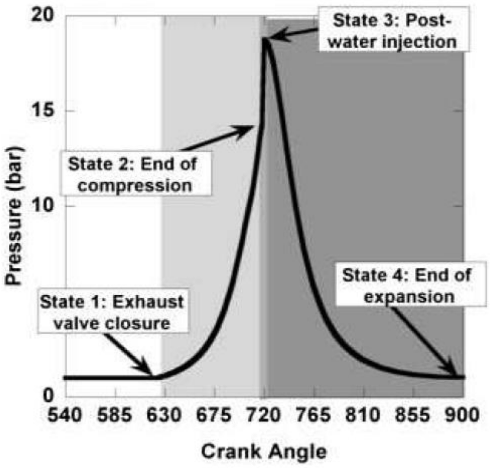


Figure 2.13: Ideal in-cylinder pressure of present six stroke engine [3]

2.4.2. Water injection

From Figure (2.13).The identity of mass conservation was employed to equate the mass at state 3 to the mass at state 2 and the mass of the injected water. Now that the two properties of internal energy and specific volume are known at state point 3, the thermodynamic state is uniquely determined. Thus the temperature and pressure at the start of the additional power stroke are known.

2.4.3. Additional power stroke expansion

From Figure (2.13).Because there is no mass flow across the combustion chamber control volume during the expansion process and assuming that the recompression process is adiabatic. An additional assumption that the expansion process is isentropic from state 3 to state 4 yields the additional state property required by the state postulate to determine completely the thermodynamic properties at state 4. The work output from the expansion process can be calculated.

2.4.4. Effect of the additional two strokes

The network is the expansion work less the recompression work. The net mean effective pressure (MEP) of the early exhaust valve closure and water injection (the fourth and fifth strokes) is then determined by dividing the expansion work of the fifth stroke less the compression work of the fourth stroke by the displacement volume. Although having the units of pressure, the MEP is a measure of the performance of any engine irrespective of size or volumetric displacement. Condensation during an expansion is generally undesirable because of potential equipment damage due to droplet erosion and also because of the resultant decrease in specific volume. An increase in specific volume results in desirable expansion work.

The modified sequence of six strokes is illustrated in Figure (2.14) and the corresponding pressure-volume trace is shown in Figure (2.15).

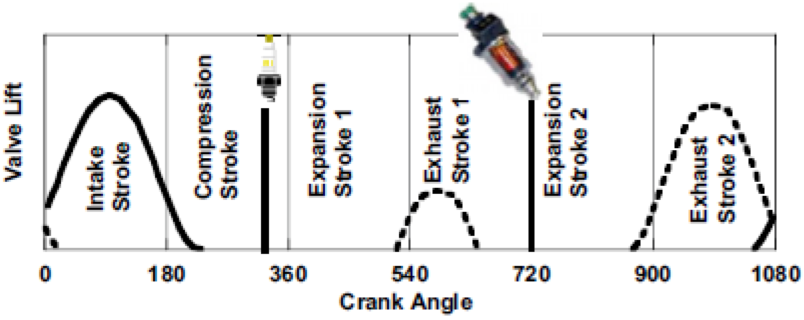


Figure 2.14: Schematic of typical intake and exhaust valve events for the six stroke[4]

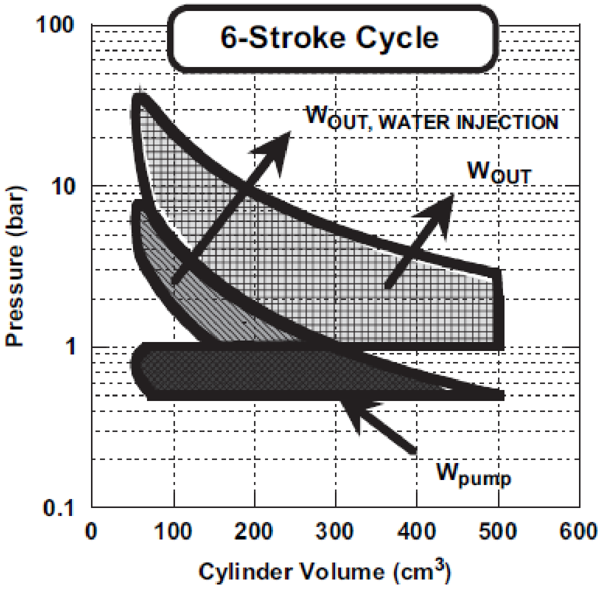


Figure 2.15: Schematic of pressure vs volume for a six stroke engine cycle [4]

2.5. Six stroke engine thermodynamic analysis

Figure (2.16) shows the PV (pressure-volume) diagram for a similar six stroke engine. The area inside the curves represents the work delivered to the drive shaft from both the combustion of gasoline and the evaporation of water, as labeled in the figure. It is important to note that the shape of this curve is completely dependent on the variables chosen by the user. Many of these variables, such as temperatures, must be found experimentally [12]. This analysis will be discussed later in chapter four.

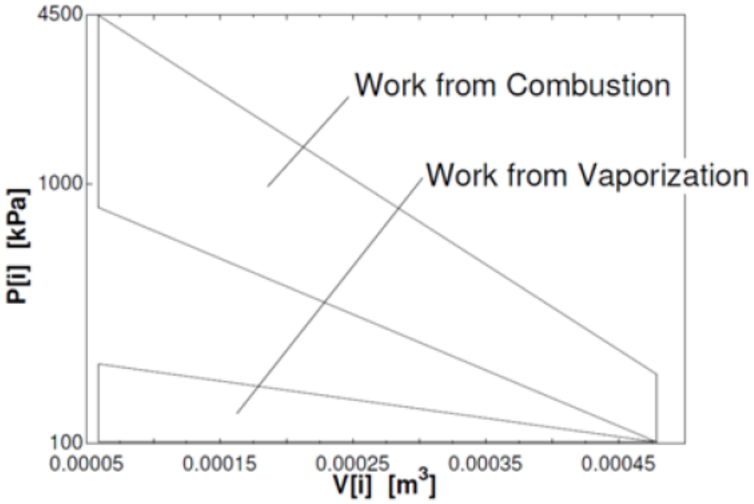
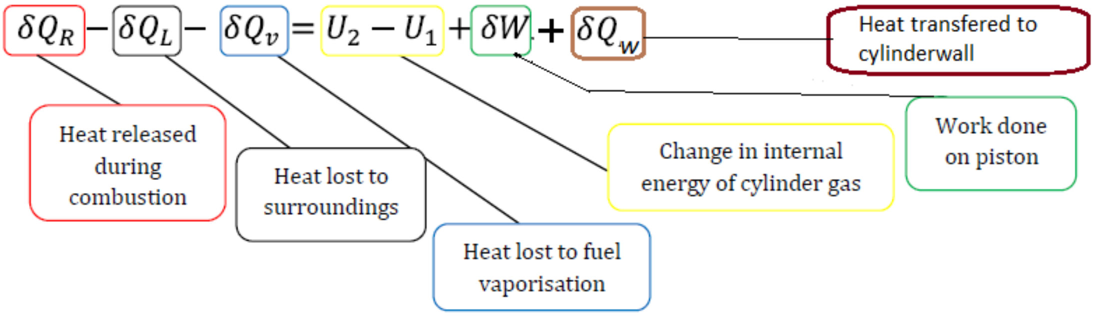


Figure 2.16: ideal six stroke cycle [12]

2.5.1. Thermodynamic analysis of fuel power stroke

From first low of thermodynamic, the network from combustion of fuel can be calculated via the following equation 2.1.

$$\delta QR - \delta QL - \delta QV = U2 - U1 = \delta W + \delta QW \qquad (2.1)[8]$$

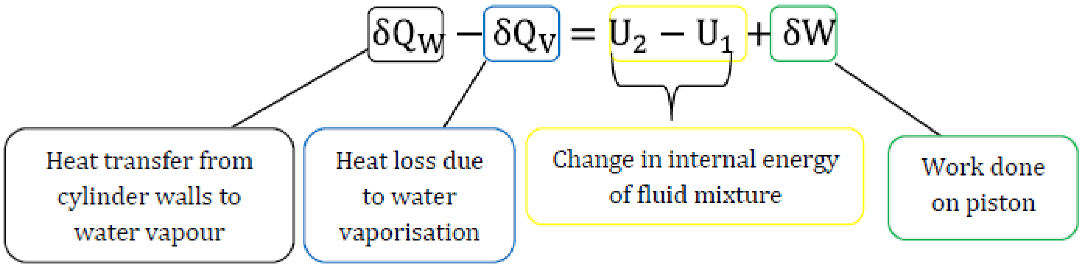


$$\boxed{\delta Q_R} - \boxed{\delta Q_L} - \boxed{\delta Q_v} = \boxed{U_2 - U_1} + \boxed{\delta W} + \boxed{\delta Q_w}$$

2.5.2. Thermodynamic analysis of water injection power stroke

From first low of thermodynamic, the network from combustion of fuel can be calculated via the following equation 2.2.

$$\delta QW - \delta QV = U2 - U1 = \delta W \qquad (2.2)[8]$$



2.6. Conclusion

Six stroke engine has many advantages like high thermal efficiency, low fuel consumption, high break mean effective pressure, and low emission. However drawbacks like initial starting problem, availability of water are also associated. In order for this engine to work properly and overcome all obstacles, it must have the required equipment and modifications, which will be addressed in the next chapter.

CHAPTER THREE

3. Modification of six stroke engines

In order to achieve the project objectives some modifications must be provided to the engine, these are fuel tank, materials used, crank to camshaft modifications and water injection. A camshaft is a rod or shaft to which cams are attached. Cams are noncircular wheels, which operate the cylinder valves of an internal combustion engine. The camshaft is also used to operate other gear-driven engine components. Camshaft design can determine whether the camshaft can help the engine produce heavy torque or higher engine speed. The cams on the camshaft operate the intake and exhaust valves of the engine.

3.1. Fuel tank

- The Fuel tank in a six stroke engine has to be divided into two parts. One part will contain fuel and other part will contain water.
- The water used should be distilled and pure.

3.2. Materials used for engine components

The engine components are subjected to thermal stresses developed due to injection of water into the superheated cylinder. The rapid temperature changes can cause micro cracking or fracture of the engine components due to continuous compression and expansion.

So the engine components should be designed with high thermal resistive metal alloys to withstand the stress and prevent failure of engine. The materials that can be used are:

Silicon Nitride ($Si3N4$).
Silicon Carbide (SiC).
Zirconia ($ZrO2$).
Alumina-Tungsten alloy etc.

3.3. Crankshaft to camshaft modification

In conventional four stroke engine, the gear at crankshaft must rotate 720° while the camshaft rotates 360° to complete one cycle. For six stroke engine, the gear at the crankshaft must rotate 1080° to rotate the camshaft 360° and complete one cycle. Hence their corresponding gear ratio is 3:1[9].

3.3.1. Four stroke camshaft

The original angular speed of the camshaft is one-half that of the crankshaft, such that the camshaft rotates once for every two revolutions (or four strokes) of the crankshaft. The camshaft has two lobes, one for the intake valve and one for the exhaust valve.

The camshaft is shown in Figure (3.1). Each lobe is in contact with a flat follower pushrod which moves a rocker arm inside of the head. The other side of the rocker arms pushes the valve inside of the cylinder. A valve spring returns the valve back to the original position.

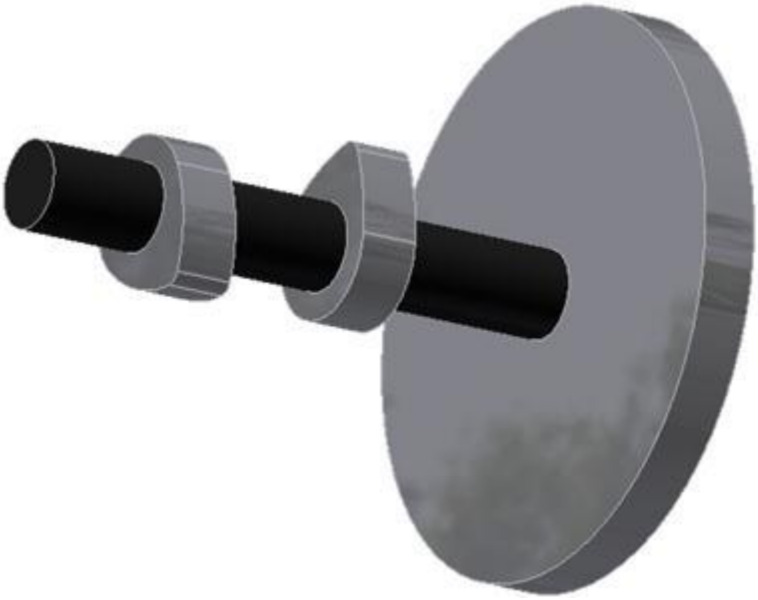


Figure 3.1: The original four stroke camshaft [13]

3.3.2. Six stroke camshaft

In the six stroke engine the 360 degree of the cam has been divided into 60 degree among the six strokes. The exhaust cam has 2 lobes to open the exhaust valve at fourth stroke (first exhaust stroke) and at the sixth stroke to push out the steam. The injector cam has been designed to have a sharp lobe that passes across an inductive sensor which sends a signal to the gasoline direct injection (GDI) injector in the head of the engine. Figure (3.2) shows the new cams and the new camshaft.

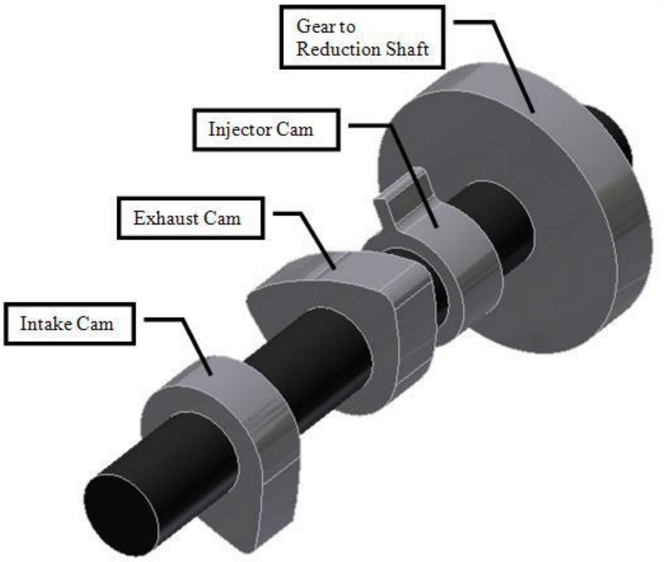


Figure 3.2: six stroke camshaft [13]

The type of gear is helical gear because it is suitable for high-speed, high power application and quite at high speed rotation. Figure (3.3) shows the previous gear (original gear) and a new six stroke gear (modified gear).

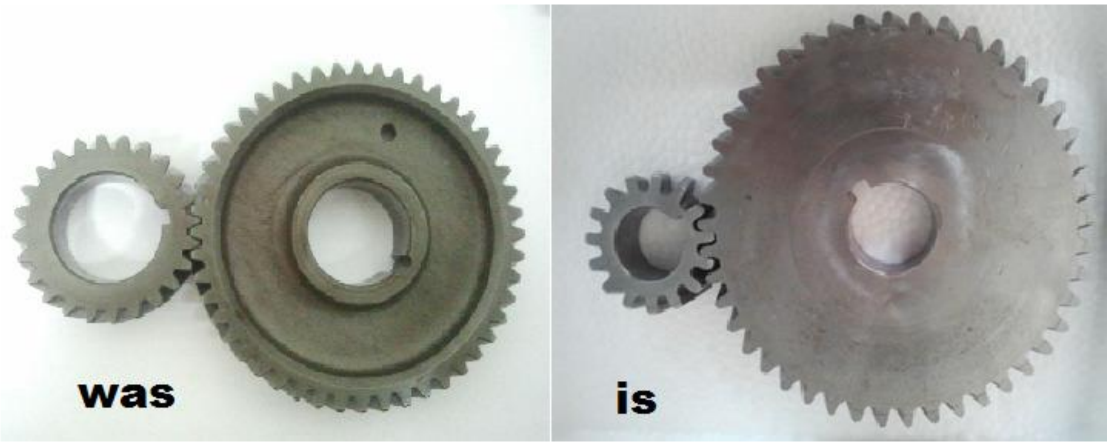


Figure 3.3: Orginal and modified gears [14]

3.4. Water injection system

The main additional system that would be installed in six stroke of ICE is water injection system which is similar with fuel injection system. The types of fuel injection system that widely used are mechanical fuel injection, central port injection (CPI), continuous injection system (CIS), electronic fuel injection (EFI), multipoint fuel injection and direct fuel injection. The concept of water injection was based on direct fuel injection system in. Major components that will be modified are fuel pump, fuel injector, water tank and types of fuel piping connection. Figure (3.4) shows the illustration of water injection system design for six stroke engine.

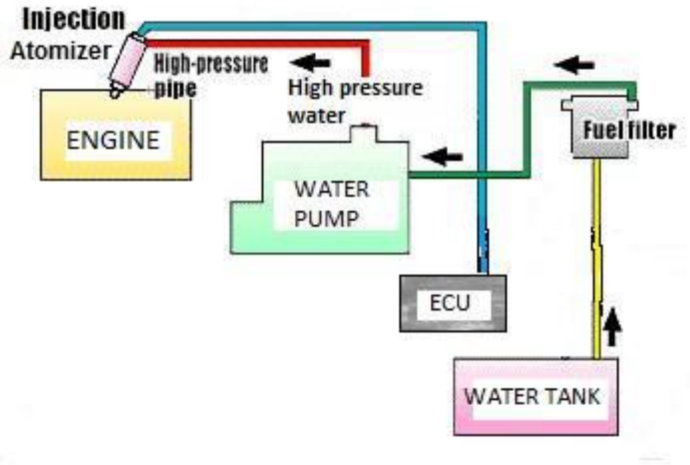


Figure 3.4: Water injection system [15]

3.4.1. Water tank

This is the obvious place to start in any full system explanation. The latest fuel tank model was different with the tanks on early carburetor equipped vehicles which it is a sealed unit that allows the natural gas of the fuel to delivery to the pump by slightly pressurizing the system as shown in Figure (3.5). Present fuel tanks for ICEs are rigid containers made of metal or plastic. The fuel tank can be replaced as water tank to keep the amount of water before it is delivered to the water pump.

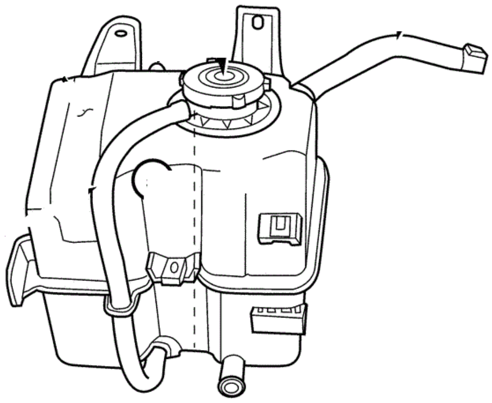


Figure 3.5: Water tank [15]

3.4.2. Water injector

The most important criteria in this system are the water injection timing and the duration of injection, the water distribution in the combustion chamber, the moment in time when combustion starts, the amount of particle of water metered to the engine per degree crankshaft and the total injected water quantity in accordance with engine loading during fifth stroke. Figure (3.6) shows GDI water injector.

Figure 3.6: Water injector [15]

3.4.3. Water Pump

The main component in fuel injection system recently is injection pump and its function as the device that delivery water from fuel tank into the cylinder of petrol engine. Figure (3.7) shows water pump.

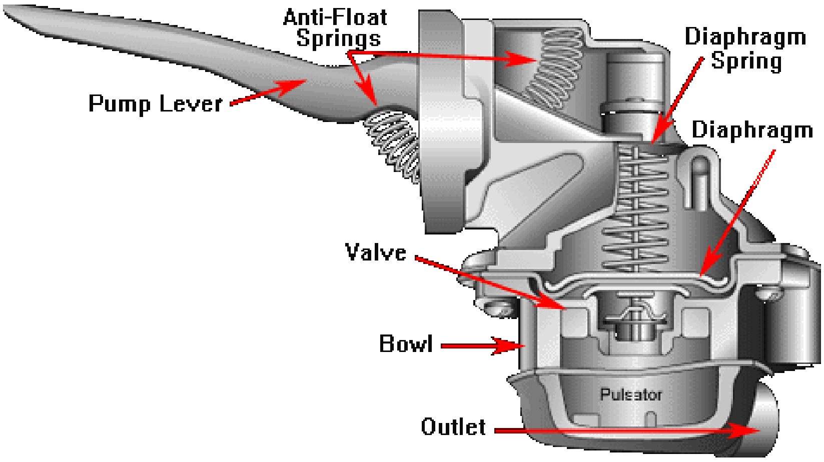


Figure 3.7: Water pump [15]

3.5. Conclusion

Six stroke engine needs a lot of modifications, that requires enormous manufacturing capabilities and very large experiences in addition to very high costs. So in this research the practical model of the engine is a very complex procces.

The studying of six stroke engine can not be confined in this research because its very complex and needs a lot of research and practical studies, Therefore, the scope of the project was limited to thermodynamics and heat transfer analysis.

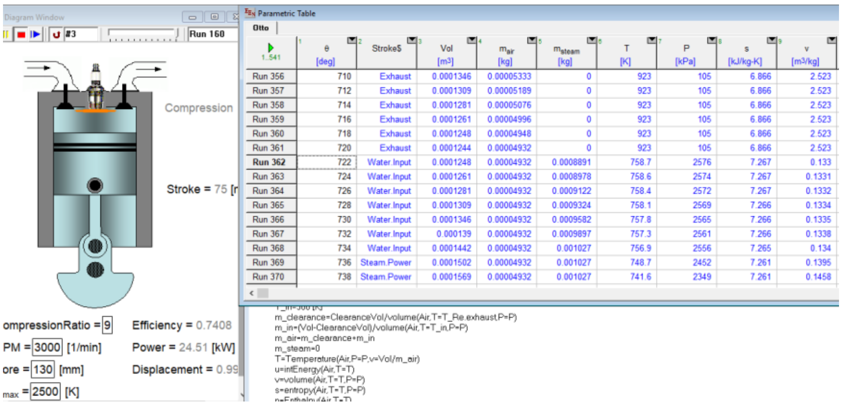
CHAPTER FOUR

4. Thermal modeling and design

4.1. Introduction

In thermal design of the internal combustion engines most researchers use air-standard power cycle models to perform their thermodynamic analyses. In this project, thermodynamics analysis was performed for a single cylinder six stroke gasoline internal combustion engine to identify the effect of added the amount of water injected for the second power stroke and to identify the cylinder pressure, a computer simulation by using engineering equation solver (EES) was developed based on the Otto cycle as shown in Figure (4.1) which basically six stroke is the adding of two stroke into four stroke engine.

The Six Stroke engine is thermodynamically more efficient because the change in volume of the power stroke is greater than the intake stroke and the compression stroke [1].



ompressionRatio = 9
PM = 3000 [1/min]
ore = 130 [mm]
max = 2500 [K]
Efficiency = 0.7408
Power = 24.51 [kW]
Displacement = 0.99

	θ [deg]	Stroke$	Vol [m3]	m_{air} [kg]	m_{steam} [kg]	T [K]	P [kPa]	s [kJ/kg-K]	v [m3/kg]
Run 356	710	Exhaust	0.0001346	0.00005333	0	923	105	6.866	2.523
Run 357	712	Exhaust	0.0001309	0.00005189	0	923	105	6.866	2.523
Run 358	714	Exhaust	0.0001281	0.00005076	0	923	105	6.866	2.523
Run 359	716	Exhaust	0.0001261	0.00004996	0	923	105	6.866	2.523
Run 360	718	Exhaust	0.0001248	0.00004948	0	923	105	6.866	2.523
Run 361	720	Exhaust	0.0001244	0.00004932	0	923	105	6.866	2.523
Run 362	722	Water.Input	0.0001248	0.00004932	0.0008891	758.7	2576	7.267	0.133
Run 363	724	Water.Input	0.0001261	0.00004932	0.0008978	758.6	2574	7.267	0.1331
Run 364	726	Water.Input	0.0001281	0.00004932	0.0009122	758.4	2572	7.267	0.1332
Run 365	728	Water.Input	0.0001309	0.00004932	0.0009324	758.1	2569	7.266	0.1334
Run 366	730	Water.Input	0.0001346	0.00004932	0.0009582	757.8	2565	7.266	0.1335
Run 367	732	Water.Input	0.000139	0.00004932	0.0009897	757.3	2561	7.266	0.1338
Run 368	734	Water.Input	0.0001442	0.00004932	0.001027	756.9	2556	7.265	0.134
Run 369	736	Steam.Power	0.0001502	0.00004932	0.001027	748.7	2452	7.261	0.1395
Run 370	738	Steam.Power	0.0001569	0.00004932	0.001027	741.6	2349	7.261	0.1458

```
m_clearance=ClearanceVol/volume(Air,T=T_Re.exhaust,P=P)
m_in=(Vol-ClearanceVol)/volume(Air,T=T_in,P=P)
m_air=m_clearance+m_in
m_steam=0
T=Temperature(Air,P=P,v=Vol/m_air)
u=intEnergy(Air,T=T)
v=volume(Air,T=T,P=P)
s=entropy(Air,T=T,P=P)
```

Figure 4.1: EES software thermal models

EES contains thermal model four stroke ICE. In this research six stroke model was upgraded by adding two additional strokes. Thermodynamic properties and engine parameters were determined such as pressure, temperature, specific volume, internal energy…etc and there calculating for two degrees of crankshaft angle (CA°) from 0 to 1080 degree. At the end of exhaust stroke 720 CA° water is injected to 734 CA° during steam power stroke.

4.2. Variables and Constraints

In the design of the six stroke engine, the thermodynamic state of each stroke has been determined using a control volume approach. Using the cylinder walls as the control volume, the thermodynamic state of the fluids inside the control volume at the end of each stroke has been determined using EES. Engine variables and design equations are listed in APPENDIX A.

4.3. Six stroke control systems

In this project, the water system used in injection was designed, valve control and water injection timing.

4.3.1. Water Injection System Design

Water system of six stroke engine was designed and drown by AutoCAD program as shown in Figure (4.2). In this design a double pipe heat exchanger with parallel flow fluids as shown in Figure (4.3) was used to heat the water from exhaust gas.

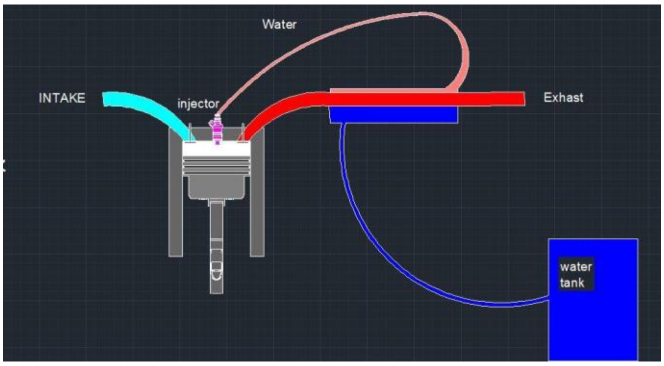


Figure 4.2: Water injection system

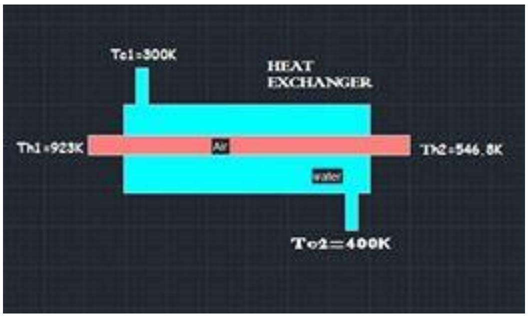


Figure 4.3: Parallel flow heat exchanger

By using the basic principles of heat transfer for a heat exchanger. The energy balance equations 4.1and 4.2 for both fluids give:

$$Q_C = \dot{m}_C (h_{C2} - h_{C1}) \quad (4.1)$$

$$Q_H = \dot{m}_H (h_{H1} - h_{H2}) \quad (4.2)$$

Where:
C: cold, H: hot
h: enthalpy, Q: heat transfer rate.

For constant specific heats with no change of phase equations 4.3 and 4.4 also write:

$$Q_C = \dot{m}_C * cp (T_{C2} - T_{c1}) \quad (4.3)$$
$$Q_H = \dot{m}_H * cp (T_{H1} - T_{H2}) \quad (4.4)$$

Now from energy conservation we know that Qc = Qh = Q, and by using the log mean temperature difference (LMTD) the energy equation 4.5 may be written as :

$$Q = F * U * A * \Delta T_{LMTD} \quad (4.5)$$

Where:
F= 1; correction factor because of double pipe heat exchanger.
U= 7.9w/m^2.K; over all heat transfer coefficient from APPENDIX C.
A: area of heat transfer.

Equation 4.6 shows ΔT_{LMTD} value form:

$$\Delta T_{LMTD} = (\Delta T_2 - \Delta T_1)/\ln(\Delta T_2/\Delta T_1) \quad (4.6)$$

As a result of calculation for the following data :

T_{h1}=923 K, T_{h2}=546.8 K
T_{c1}=300 K, T_{c2}=400 K
$\dot{m}_{water}$=0.0171 Kg/s, $\dot{m}_{air}$=0.019 Kg/s
Q=7.14 KW
ΔT_{LMTD} =329.4 K
L=0.5 m

The required area and pipe diameter for heat exchange between water and exhaust gas is 2.7 m^2 and 4.2 cm respectively.

From the previous calculation the temperature of water in heat exchanger will rise to reach about 400 K ,the saturation pressure in this temperature is 2797.1 KPa ,so a safety valve of 2800 KPa is used in order prevent water to evaporate.

4.3.2. Valves and water injection control systems

To better design a new valve control system for the six stroke engine. A new valve control system have been considered: an alternative six stroke camshaft. Figure (4.4) takes from EES and shows six stroke valves timing, ignition delay, water injection delay.

As shown intake valve opens (IVO) at 0 CA° and closed (IVC) at 180 CA° during intake stroke, Exhaust valve opens (EVO) at 538 CA° and closed (EVC) at 720 CA° during exhaust stroke then intake again at 898 CA° and closed at 1080 CA° during re-exhaust stroke, water injector open at 722 CA° and continue for 14 degrees from CA° during steam power stroke as shown in Figure (4.5).

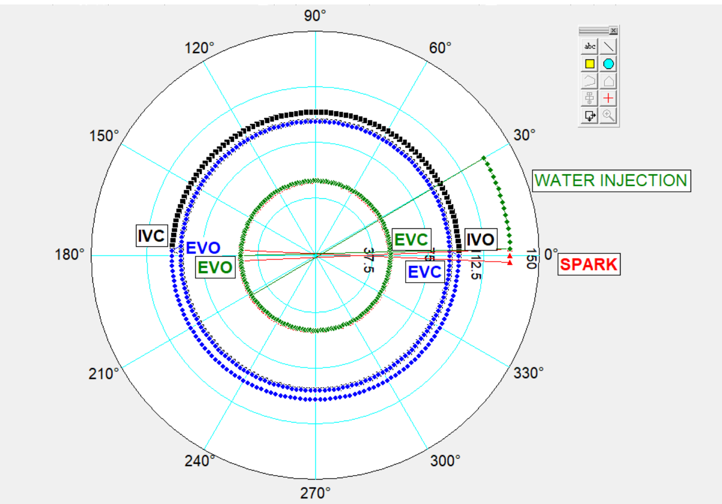
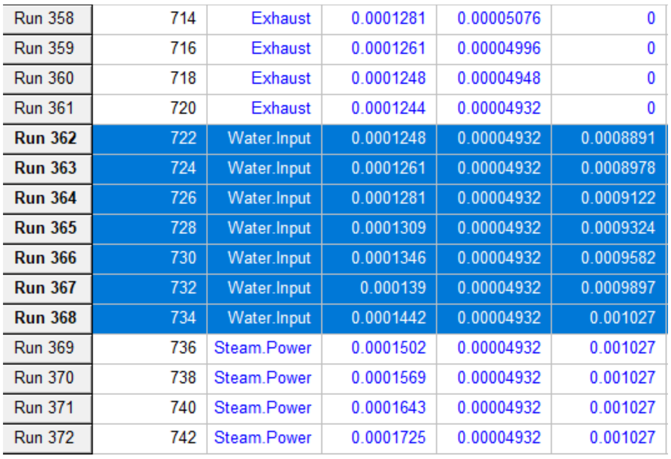


Figure 4.4: Valves and water injection control systems [EES]



Run 358	714	Exhaust	0.0001281	0.00005076	0
Run 359	716	Exhaust	0.0001261	0.00004996	0
Run 360	718	Exhaust	0.0001248	0.00004948	0
Run 361	720	Exhaust	0.0001244	0.00004932	0
Run 362	722	Water.Input	0.0001248	0.00004932	0.0008891
Run 363	724	Water.Input	0.0001261	0.00004932	0.0008978
Run 364	726	Water.Input	0.0001281	0.00004932	0.0009122
Run 365	728	Water.Input	0.0001309	0.00004932	0.0009324
Run 366	730	Water.Input	0.0001346	0.00004932	0.0009582
Run 367	732	Water.Input	0.000139	0.00004932	0.0009897
Run 368	734	Water.Input	0.0001442	0.00004932	0.001027
Run 369	736	Steam.Power	0.0001502	0.00004932	0.001027
Run 370	738	Steam.Power	0.0001569	0.00004932	0.001027
Run 371	740	Steam.Power	0.0001643	0.00004932	0.001027
Run 372	742	Steam.Power	0.0001725	0.00004932	0.001027

Figure 4.5: Water injection timing [EES]

Water injector will only work after the engine reaches its worm up temperature.

4.4. Heat transfer calculations

Six stroke engine is an effective way of heat recovery. So the amount of heat that absorbed by water spray from engine wall cylinder, piston surface and exhaust gas that remain in clearance volume, is very important to see the steam performance inside the combustion chamber to prevent the conversion of steam into the water during the pressure increase so as not to adversely affect the performance of the engine.

Table 4.1 contains thermodynamic and heat transfer data to determine the maximum steam temperature can be reached, which determines the amount of water injected into it. Using the cylinder wall as the control volume with 7 mm thickness.

Table 4.1: Heat transfer data inside engine cylinder

variable	value	unit	calculations
Water injector pressure	3000	[KPa]	Assumption
Exhaust gas temperature	923	[K]	From EES
Cylinder wall temperature	500	[K]	Assumption
Water input temperature	400	[K]	Calculated from heat exchanger
Piston surface temperature	800	[K]	Assumption
Specific heat of piston	0.460548	[KJ/Kg.K]	Cast iron material
Specific heat of cylinder wall	0.460548	[KJ/Kg.K]	Cast iron material
Specific heat of water	4.18	[KJ/Kg.K]	Reference value
Specific heat of exhaust gas	1.005	[KJ/Kg.K]	Reference value
Mass of piston	0.697	[Kg]	m=rho/v ; 7mm thickness
Mass of cylinder wall	0.1	[Kg]	m=rho/v ; 7mm thickness
Mass of exhaust gas	0.00004932	[Kg]	From EES

All calculations assume air fuel mix is air and exhaust gases are ideal gas.

The amount of water injected depending on specific volume of steam inside combustion chamber. EES functions used to determine the amount of water injected during steam power labeled in equation 4.7.

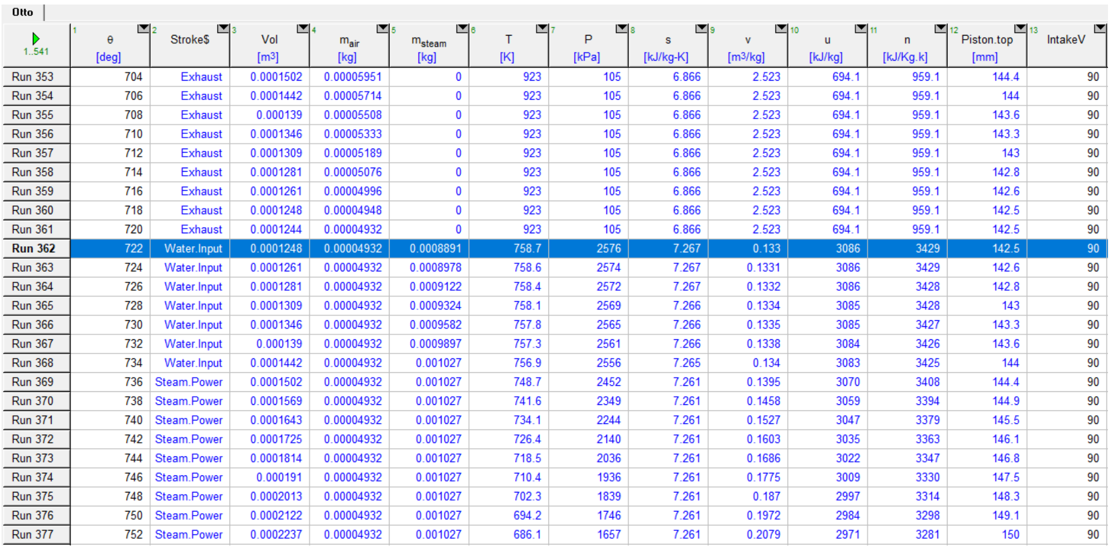
m_{steam} = Vol/Volume(Water, T=$T_{exhaust}$, P=P_{water}) (4.7)[EES]

water spray inters combustion chamber at 400 K as saturated water approximately then will turns to steam by pressure drop then absorbs heat from surrounding during very small delay, this result causes the steam temperature and pressure to rise rapidly. Mass of water per steam power stroke computed as shown in Figure (4.6) that equally 0.001027 Kg/stroke.

From first low of thermodynamic steam temperature after thermal equilibrium and determine using EES as the following equation 4.8.

$$T_{steam} = (m_{piston}*C_{piston}*T_{piston}+m_{cylinder}*C_{cylinder}*T_{cylinder}+m_{air}*Cp_{air}*T_{air}+m_{steam}*Cp_{water}*T_{water})/(m_{piston}*C_{piston}+m_{cylinder}*C_{cylinder}+m_{air}*Cp_{air}+m_{steam}*Cp_{water}) \qquad (4.8)$$

Figure (4.6) shows parametric table six stroke engine from EES, steam temperature, pressure, internal energy, entropy and enthalpy increased into 758.7 K, 2576 [KPa], 3086 [KJ/Kg], 7.627 [KJ/Kg.K] and 3429 [KJ/Kg] respectively.



1..541	1 θ [deg]	2 Stroke$	3 Vol $[m^3]$	4 m_{air} [kg]	5 m_{steam} [kg]	6 T [K]	7 P [kPa]	8 s [kJ/kg-K]	9 v $[m^3/kg]$	10 u [kJ/kg]	11 n [kJ/Kg.k]	12 Piston.top [mm]	13 IntakeV
Run 353	704	Exhaust	0.0001502	0.00005951	0	923	105	6.866	2.523	694.1	959.1	144.4	90
Run 354	706	Exhaust	0.0001442	0.00005714	0	923	105	6.866	2.523	694.1	959.1	144	90
Run 355	708	Exhaust	0.000139	0.00005508	0	923	105	6.866	2.523	694.1	959.1	143.6	90
Run 356	710	Exhaust	0.0001346	0.00005333	0	923	105	6.866	2.523	694.1	959.1	143.3	90
Run 357	712	Exhaust	0.0001309	0.00005189	0	923	105	6.866	2.523	694.1	959.1	143	90
Run 358	714	Exhaust	0.0001281	0.00005076	0	923	105	6.866	2.523	694.1	959.1	142.8	90
Run 359	716	Exhaust	0.0001261	0.00004996	0	923	105	6.866	2.523	694.1	959.1	142.6	90
Run 360	718	Exhaust	0.0001248	0.00004948	0	923	105	6.866	2.523	694.1	959.1	142.5	90
Run 361	720	Exhaust	0.0001244	0.00004932	0	923	105	6.866	2.523	694.1	959.1	142.5	90
Run 362	722	Water.Input	0.0001248	0.00004932	0.0008891	758.7	2576	7.267	0.133	3086	3429	142.5	90
Run 363	724	Water.Input	0.0001261	0.00004932	0.0008978	758.6	2574	7.267	0.1331	3086	3429	142.6	90
Run 364	726	Water.Input	0.0001281	0.00004932	0.0009122	758.4	2572	7.267	0.1332	3086	3428	142.8	90
Run 365	728	Water.Input	0.0001309	0.00004932	0.0009324	758.1	2569	7.266	0.1334	3085	3428	143	90
Run 366	730	Water.Input	0.0001346	0.00004932	0.0009582	757.8	2565	7.266	0.1335	3085	3427	143.3	90
Run 367	732	Water.Input	0.000139	0.00004932	0.0009897	757.3	2561	7.266	0.1338	3084	3426	143.6	90
Run 368	734	Water.Input	0.0001442	0.00004932	0.001027	756.9	2556	7.265	0.134	3083	3425	144	90
Run 369	736	Steam.Power	0.0001502	0.00004932	0.001027	748.7	2452	7.261	0.1395	3070	3408	144.4	90
Run 370	738	Steam.Power	0.0001569	0.00004932	0.001027	741.6	2349	7.261	0.1458	3059	3394	144.9	90
Run 371	740	Steam.Power	0.0001643	0.00004932	0.001027	734.1	2244	7.261	0.1527	3047	3379	145.5	90
Run 372	742	Steam.Power	0.0001725	0.00004932	0.001027	726.4	2140	7.261	0.1603	3035	3363	146.1	90
Run 373	744	Steam.Power	0.0001814	0.00004932	0.001027	718.5	2036	7.261	0.1686	3022	3347	146.8	90
Run 374	746	Steam.Power	0.000191	0.00004932	0.001027	710.4	1936	7.261	0.1775	3009	3330	147.5	90
Run 375	748	Steam.Power	0.0002013	0.00004932	0.001027	702.3	1839	7.261	0.187	2997	3314	148.3	90
Run 376	750	Steam.Power	0.0002122	0.00004932	0.001027	694.2	1746	7.261	0.1972	2984	3298	149.1	90
Run 377	752	Steam.Power	0.0002237	0.00004932	0.001027	686.1	1657	7.261	0.2079	2971	3281	150	90

Figure 4.6: Six stroke engine parametric table [EES]

4.5. Six stroke thermodynamic analysis

The main objective of the research is to increase the thermal efficiency of the ICE. EES used to express the physics six stroke system into thermodynamics functions, this functions Stored in the program's memory and called by program codes.

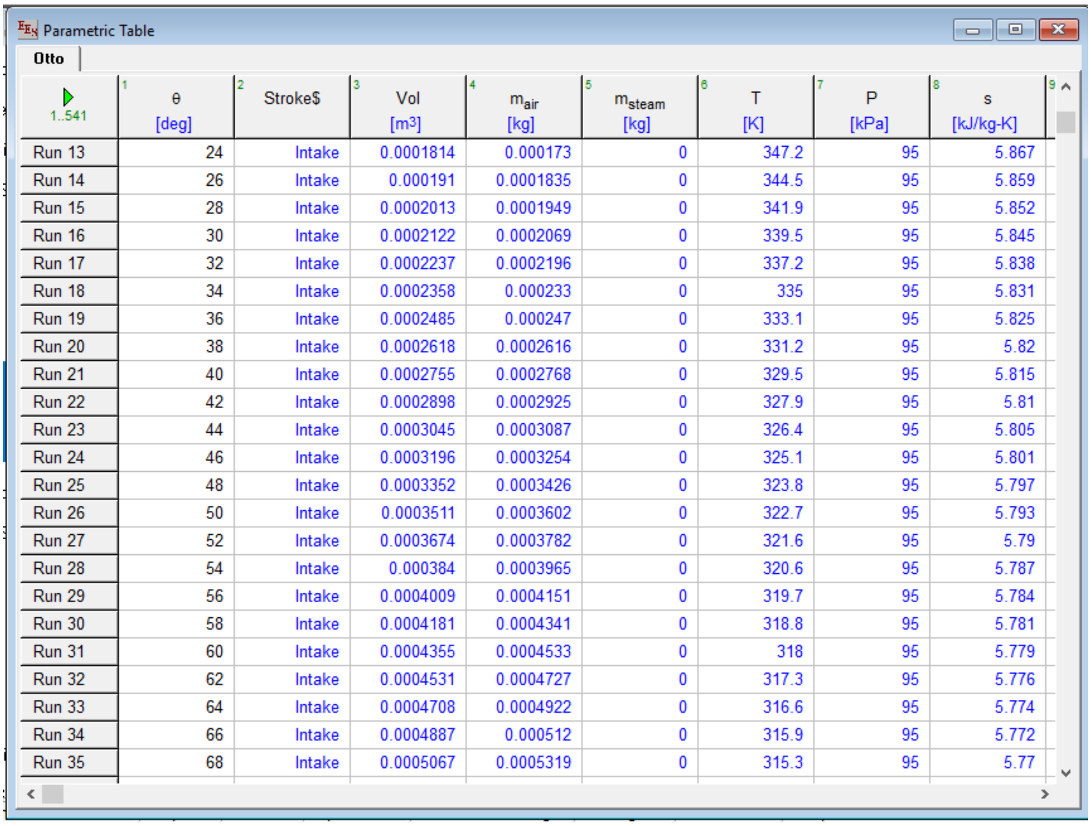
4.5.1. Intake stroke

Air fuel mixture intakes to combustion chamber at ideal states: mixture is air and assumed 95 KPa intake air pressure and 300 K intake air temperature. These two properties are very important to determine the amount of mixture per stroke as shown in equation 4.9.

$$m_{mix}=(Vol-ClearanceVol)/volume(Air,T=T_{in}, P=P) \qquad (4.9)\ [EES]$$

where:
vol: displacement volume depending of position of the piston.
Volume: specific volume for mix.

Gradually decreases of temperature and entropy during this stroke due to the cooling of the mixture as shown in the Figure (4.7).



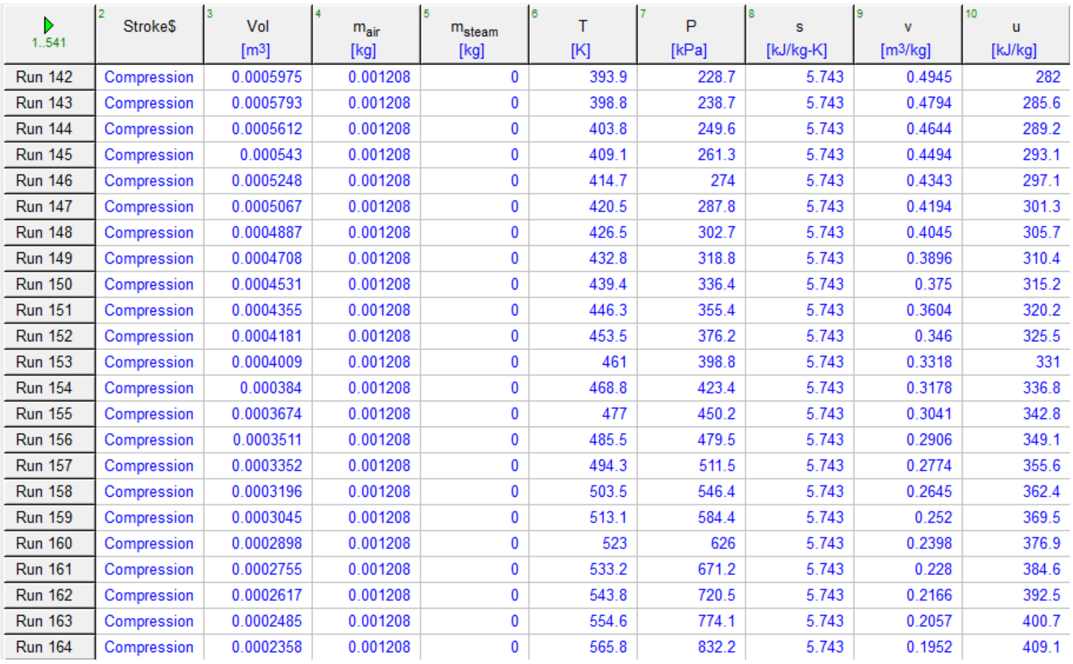
1..541	θ [deg]	Stroke$	Vol [m3]	m_{air} [kg]	m_{steam} [kg]	T [K]	P [kPa]	s [kJ/kg-K]
Run 13	24	Intake	0.0001814	0.000173	0	347.2	95	5.867
Run 14	26	Intake	0.000191	0.0001835	0	344.5	95	5.859
Run 15	28	Intake	0.0002013	0.0001949	0	341.9	95	5.852
Run 16	30	Intake	0.0002122	0.0002069	0	339.5	95	5.845
Run 17	32	Intake	0.0002237	0.0002196	0	337.2	95	5.838
Run 18	34	Intake	0.0002358	0.000233	0	335	95	5.831
Run 19	36	Intake	0.0002485	0.000247	0	333.1	95	5.825
Run 20	38	Intake	0.0002618	0.0002616	0	331.2	95	5.82
Run 21	40	Intake	0.0002755	0.0002768	0	329.5	95	5.815
Run 22	42	Intake	0.0002898	0.0002925	0	327.9	95	5.81
Run 23	44	Intake	0.0003045	0.0003087	0	326.4	95	5.805
Run 24	46	Intake	0.0003196	0.0003254	0	325.1	95	5.801
Run 25	48	Intake	0.0003352	0.0003426	0	323.8	95	5.797
Run 26	50	Intake	0.0003511	0.0003602	0	322.7	95	5.793
Run 27	52	Intake	0.0003674	0.0003782	0	321.6	95	5.79
Run 28	54	Intake	0.000384	0.0003965	0	320.6	95	5.787
Run 29	56	Intake	0.0004009	0.0004151	0	319.7	95	5.784
Run 30	58	Intake	0.0004181	0.0004341	0	318.8	95	5.781
Run 31	60	Intake	0.0004355	0.0004533	0	318	95	5.779
Run 32	62	Intake	0.0004531	0.0004727	0	317.3	95	5.776
Run 33	64	Intake	0.0004708	0.0004922	0	316.6	95	5.774
Run 34	66	Intake	0.0004887	0.000512	0	315.9	95	5.772
Run 35	68	Intake	0.0005067	0.0005319	0	315.3	95	5.77

Figure 4.7: Intake stroke [EES]

4.5.2. Compression stroke

Pressure, temperature and internal energy gradually increase during Isentropic compression process as shown if Figure (4.8). These values are determine at each point of the piston by EES as shown if equations 4.10, 4.11 and 4.12.

T = Temperature (Air, s=s, v = v) (4.10) [EES]
P = Pressure (Air,s=s, v=v) (4.11) [EES]
U = intEnergy (Air,T=T) (4.12) [EES]



1..541	2 Stroke$	3 Vol [m3]	4 m_{air} [kg]	5 m_{steam} [kg]	6 T [K]	7 P [kPa]	8 s [kJ/kg-K]	9 v [m3/kg]	10 u [kJ/kg]
Run 142	Compression	0.0005975	0.001208	0	393.9	228.7	5.743	0.4945	282
Run 143	Compression	0.0005793	0.001208	0	398.8	238.7	5.743	0.4794	285.6
Run 144	Compression	0.0005612	0.001208	0	403.8	249.6	5.743	0.4644	289.2
Run 145	Compression	0.000543	0.001208	0	409.1	261.3	5.743	0.4494	293.1
Run 146	Compression	0.0005248	0.001208	0	414.7	274	5.743	0.4343	297.1
Run 147	Compression	0.0005067	0.001208	0	420.5	287.8	5.743	0.4194	301.3
Run 148	Compression	0.0004887	0.001208	0	426.5	302.7	5.743	0.4045	305.7
Run 149	Compression	0.0004708	0.001208	0	432.8	318.8	5.743	0.3896	310.4
Run 150	Compression	0.0004531	0.001208	0	439.4	336.4	5.743	0.375	315.2
Run 151	Compression	0.0004355	0.001208	0	446.3	355.4	5.743	0.3604	320.2
Run 152	Compression	0.0004181	0.001208	0	453.5	376.2	5.743	0.346	325.5
Run 153	Compression	0.0004009	0.001208	0	461	398.8	5.743	0.3318	331
Run 154	Compression	0.000384	0.001208	0	468.8	423.4	5.743	0.3178	336.8
Run 155	Compression	0.0003674	0.001208	0	477	450.2	5.743	0.3041	342.8
Run 156	Compression	0.0003511	0.001208	0	485.5	479.5	5.743	0.2906	349.1
Run 157	Compression	0.0003352	0.001208	0	494.3	511.5	5.743	0.2774	355.6
Run 158	Compression	0.0003196	0.001208	0	503.5	546.4	5.743	0.2645	362.4
Run 159	Compression	0.0003045	0.001208	0	513.1	584.4	5.743	0.252	369.5
Run 160	Compression	0.0002898	0.001208	0	523	626	5.743	0.2398	376.9
Run 161	Compression	0.0002755	0.001208	0	533.2	671.2	5.743	0.228	384.6
Run 162	Compression	0.0002617	0.001208	0	543.8	720.5	5.743	0.2166	392.5
Run 163	Compression	0.0002485	0.001208	0	554.6	774.1	5.743	0.2057	400.7
Run 164	Compression	0.0002358	0.001208	0	565.8	832.2	5.743	0.1952	409.1

Figure 4.8: Compression stroke [EES]

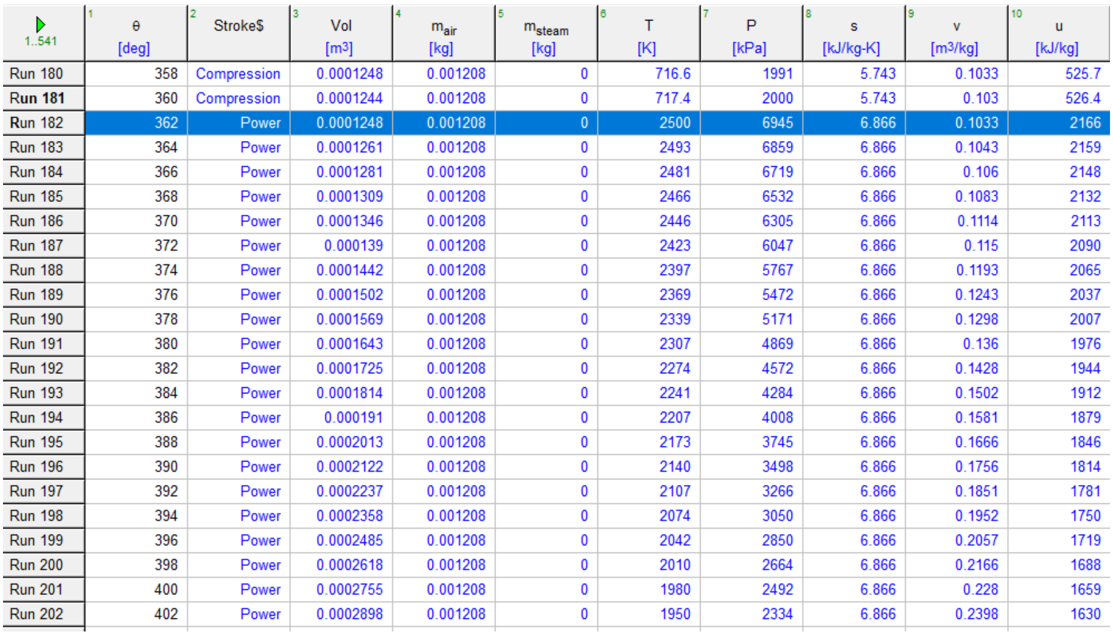
During this stroke engine will loss work, this work determine by change in internal energy multiply mass of the mix using EES functions as shown in equations 4.13.

$\text{Work}_{\text{compression}}=\text{m}_{\text{air}}$*(TableValue('Otto',91,'u')-TableValue('Otto',180,'u')) (4.13)[EES]

Where:
91: crankshaft angle at which start of compression stroke.
180: crankshaft angle at which end of compression stroke.
u: internal energy.

4.5.3. Power stroke

Pressure, temperature and internal energy dramatically rapidly increase at the beginning of this stroke because combustion of the mix and . As shown in Figure (4.9). then this variables will gradually decreasing during expansion process.



1..541	1 θ [deg]	2 Stroke$	3 Vol [m3]	4 m_{air} [kg]	5 m_{steam} [kg]	6 T [K]	7 P [kPa]	8 s [kJ/kg-K]	9 v [m3/kg]	10 u [kJ/kg]
Run 180	358	Compression	0.0001248	0.001208	0	716.6	1991	5.743	0.1033	525.7
Run 181	360	Compression	0.0001244	0.001208	0	717.4	2000	5.743	0.103	526.4
Run 182	362	Power	0.0001248	0.001208	0	2500	6945	6.866	0.1033	2166
Run 183	364	Power	0.0001261	0.001208	0	2493	6859	6.866	0.1043	2159
Run 184	366	Power	0.0001281	0.001208	0	2481	6719	6.866	0.106	2148
Run 185	368	Power	0.0001309	0.001208	0	2466	6532	6.866	0.1083	2132
Run 186	370	Power	0.0001346	0.001208	0	2446	6305	6.866	0.1114	2113
Run 187	372	Power	0.000139	0.001208	0	2423	6047	6.866	0.115	2090
Run 188	374	Power	0.0001442	0.001208	0	2397	5767	6.866	0.1193	2065
Run 189	376	Power	0.0001502	0.001208	0	2369	5472	6.866	0.1243	2037
Run 190	378	Power	0.0001569	0.001208	0	2339	5171	6.866	0.1298	2007
Run 191	380	Power	0.0001643	0.001208	0	2307	4869	6.866	0.136	1976
Run 192	382	Power	0.0001725	0.001208	0	2274	4572	6.866	0.1428	1944
Run 193	384	Power	0.0001814	0.001208	0	2241	4284	6.866	0.1502	1912
Run 194	386	Power	0.000191	0.001208	0	2207	4008	6.866	0.1581	1879
Run 195	388	Power	0.0002013	0.001208	0	2173	3745	6.866	0.1666	1846
Run 196	390	Power	0.0002122	0.001208	0	2140	3498	6.866	0.1756	1814
Run 197	392	Power	0.0002237	0.001208	0	2107	3266	6.866	0.1851	1781
Run 198	394	Power	0.0002358	0.001208	0	2074	3050	6.866	0.1952	1750
Run 199	396	Power	0.0002485	0.001208	0	2042	2850	6.866	0.2057	1719
Run 200	398	Power	0.0002618	0.001208	0	2010	2664	6.866	0.2166	1688
Run 201	400	Power	0.0002755	0.001208	0	1980	2492	6.866	0.228	1659
Run 202	402	Power	0.0002898	0.001208	0	1950	2334	6.866	0.2398	1630

Figure 4.9: Power stroke [EES]

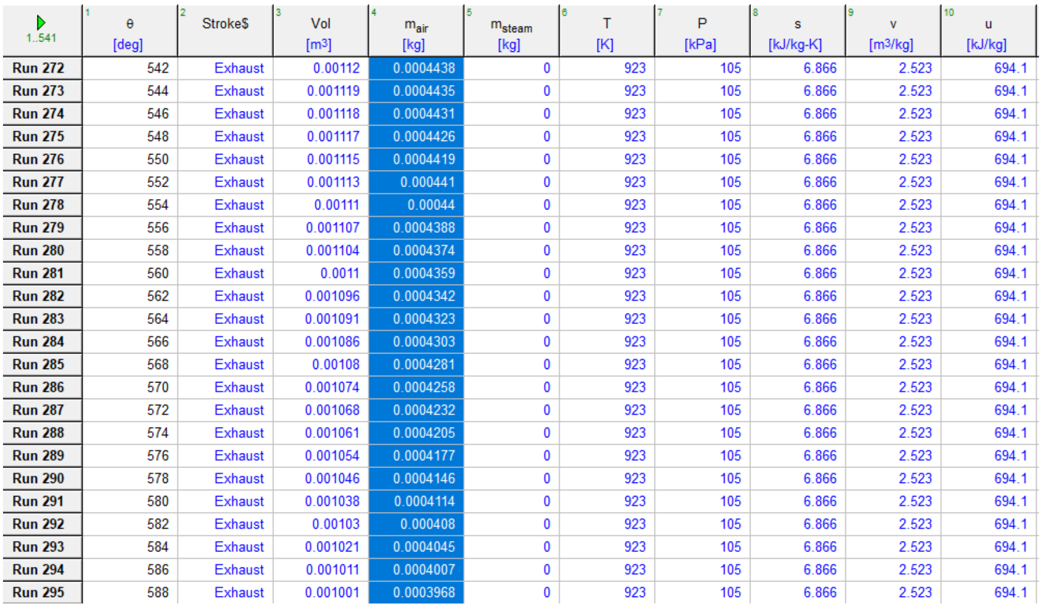
Positive woke done on this crankshaft during this stroke, this work determine from EES function as the following equation (4.14).

$Work_{power}$=m_{air}*(TableValue('Otto',182,'u')-TableValue('Otto',270,'u'))   (4.14)[EES]

Where:
182: crankshaft angle at which start of power stroke.
270: crankshaft angle at which end of power stroke.

4.5.4. Exhaust stroke

Exhaust gases leave gradually form combustion chamber during isentropic process as shown in Figure (4.10).

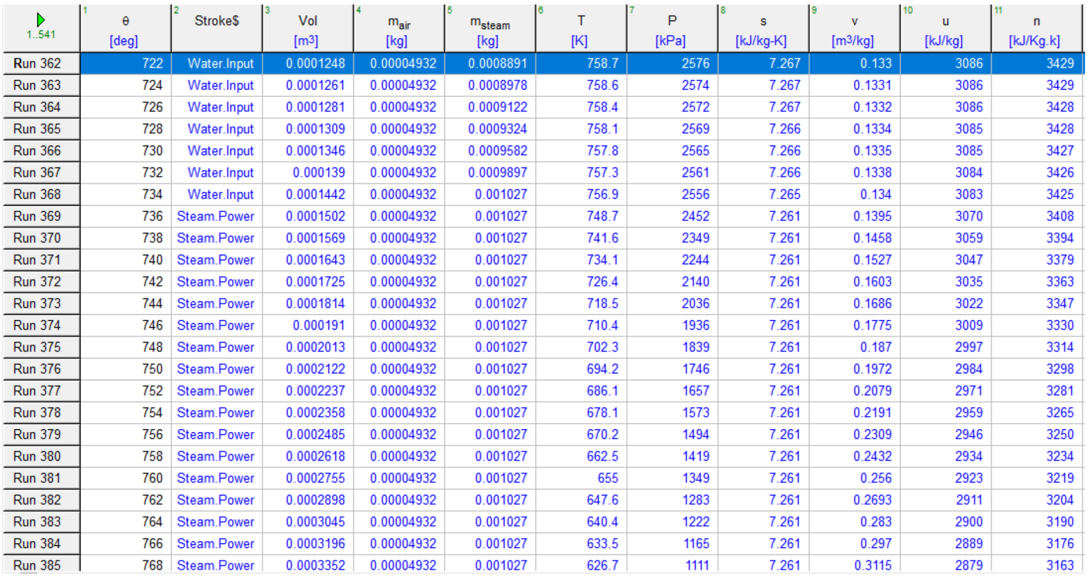


▶ 1..541	1 θ [deg]	2 Stroke$	3 Vol [m3]	4 m_{air} [kg]	5 m_{steam} [kg]	6 T [K]	7 P [kPa]	8 s [kJ/kg-K]	9 v [m3/kg]	10 u [kJ/kg]
Run 272	542	Exhaust	0.00112	0.0004438	0	923	105	6.866	2.523	694.1
Run 273	544	Exhaust	0.001119	0.0004435	0	923	105	6.866	2.523	694.1
Run 274	546	Exhaust	0.001118	0.0004431	0	923	105	6.866	2.523	694.1
Run 275	548	Exhaust	0.001117	0.0004426	0	923	105	6.866	2.523	694.1
Run 276	550	Exhaust	0.001115	0.0004419	0	923	105	6.866	2.523	694.1
Run 277	552	Exhaust	0.001113	0.000441	0	923	105	6.866	2.523	694.1
Run 278	554	Exhaust	0.00111	0.00044	0	923	105	6.866	2.523	694.1
Run 279	556	Exhaust	0.001107	0.0004388	0	923	105	6.866	2.523	694.1
Run 280	558	Exhaust	0.001104	0.0004374	0	923	105	6.866	2.523	694.1
Run 281	560	Exhaust	0.0011	0.0004359	0	923	105	6.866	2.523	694.1
Run 282	562	Exhaust	0.001096	0.0004342	0	923	105	6.866	2.523	694.1
Run 283	564	Exhaust	0.001091	0.0004323	0	923	105	6.866	2.523	694.1
Run 284	566	Exhaust	0.001086	0.0004303	0	923	105	6.866	2.523	694.1
Run 285	568	Exhaust	0.00108	0.0004281	0	923	105	6.866	2.523	694.1
Run 286	570	Exhaust	0.001074	0.0004258	0	923	105	6.866	2.523	694.1
Run 287	572	Exhaust	0.001068	0.0004232	0	923	105	6.866	2.523	694.1
Run 288	574	Exhaust	0.001061	0.0004205	0	923	105	6.866	2.523	694.1
Run 289	576	Exhaust	0.001054	0.0004177	0	923	105	6.866	2.523	694.1
Run 290	578	Exhaust	0.001046	0.0004146	0	923	105	6.866	2.523	694.1
Run 291	580	Exhaust	0.001038	0.0004114	0	923	105	6.866	2.523	694.1
Run 292	582	Exhaust	0.00103	0.000408	0	923	105	6.866	2.523	694.1
Run 293	584	Exhaust	0.001021	0.0004045	0	923	105	6.866	2.523	694.1
Run 294	586	Exhaust	0.001011	0.0004007	0	923	105	6.866	2.523	694.1
Run 295	588	Exhaust	0.001001	0.0003968	0	923	105	6.866	2.523	694.1

Figure 4.10: Exhaust stroke [EES]

4.5.5. Steam power stroke

Pressure, temperature, enthalpy and internal energy rapidly increase at the beginning of this stroke because the phase change in water to superheated steam. These valves determine using EES equally 2576 KPa, 758.7 K, 3429 KJ/Kg, 3086 KJ/Kg as shown in Figure (4.11). then this variables will gradually decreasing during isentropic and isothermal processes.



1..541	1 θ [deg]	2 Stroke$	3 Vol [m3]	4 m_{air} [kg]	5 m_{steam} [kg]	6 T [K]	7 P [kPa]	8 s [kJ/kg-K]	9 v [m3/kg]	10 u [kJ/kg]	11 n [kJ/Kg.k]
Run 362	722	Water.Input	0.0001248	0.00004932	0.0008891	758.7	2576	7.267	0.133	3086	3429
Run 363	724	Water.Input	0.0001261	0.00004932	0.0008978	758.6	2574	7.267	0.1331	3086	3429
Run 364	726	Water.Input	0.0001281	0.00004932	0.0009122	758.4	2572	7.267	0.1332	3086	3428
Run 365	728	Water.Input	0.0001309	0.00004932	0.0009324	758.1	2569	7.266	0.1334	3085	3428
Run 366	730	Water.Input	0.0001346	0.00004932	0.0009582	757.8	2565	7.266	0.1335	3085	3427
Run 367	732	Water.Input	0.000139	0.00004932	0.0009897	757.3	2561	7.266	0.1338	3084	3426
Run 368	734	Water.Input	0.0001442	0.00004932	0.001027	756.9	2556	7.265	0.134	3083	3425
Run 369	736	Steam.Power	0.0001502	0.00004932	0.001027	748.7	2452	7.261	0.1395	3070	3408
Run 370	738	Steam.Power	0.0001569	0.00004932	0.001027	741.6	2349	7.261	0.1458	3059	3394
Run 371	740	Steam.Power	0.0001643	0.00004932	0.001027	734.1	2244	7.261	0.1527	3047	3379
Run 372	742	Steam.Power	0.0001725	0.00004932	0.001027	726.4	2140	7.261	0.1603	3035	3363
Run 373	744	Steam.Power	0.0001814	0.00004932	0.001027	718.5	2036	7.261	0.1686	3022	3347
Run 374	746	Steam.Power	0.000191	0.00004932	0.001027	710.4	1936	7.261	0.1775	3009	3330
Run 375	748	Steam.Power	0.0002013	0.00004932	0.001027	702.3	1839	7.261	0.187	2997	3314
Run 376	750	Steam.Power	0.0002122	0.00004932	0.001027	694.2	1746	7.261	0.1972	2984	3298
Run 377	752	Steam.Power	0.0002237	0.00004932	0.001027	686.1	1657	7.261	0.2079	2971	3281
Run 378	754	Steam.Power	0.0002358	0.00004932	0.001027	678.1	1573	7.261	0.2191	2959	3265
Run 379	756	Steam.Power	0.0002485	0.00004932	0.001027	670.2	1494	7.261	0.2309	2946	3250
Run 380	758	Steam.Power	0.0002618	0.00004932	0.001027	662.5	1419	7.261	0.2432	2934	3234
Run 381	760	Steam.Power	0.0002755	0.00004932	0.001027	655	1349	7.261	0.256	2923	3219
Run 382	762	Steam.Power	0.0002898	0.00004932	0.001027	647.6	1283	7.261	0.2693	2911	3204
Run 383	764	Steam.Power	0.0003045	0.00004932	0.001027	640.4	1222	7.261	0.283	2900	3190
Run 384	766	Steam.Power	0.0003196	0.00004932	0.001027	633.5	1165	7.261	0.297	2889	3176
Run 385	768	Steam.Power	0.0003352	0.00004932	0.001027	626.7	1111	7.261	0.3115	2879	3163

Figure 4.11: Steam power stroke [EES]

During this stroke water input need a pump, that takes work from engine. this lost in work determine by change in enthalpy of steam using EES as shown in equation 4.15.

Work$_{pump}$=m$_{steam}$*(TableValue('Otto',368,'n')-TableValue('Otto',362,'n'))   (4.15)[EES]

Where:
362: crankshaft angle at which start of water injection.
368: crankshaft angle at which end of water injection.

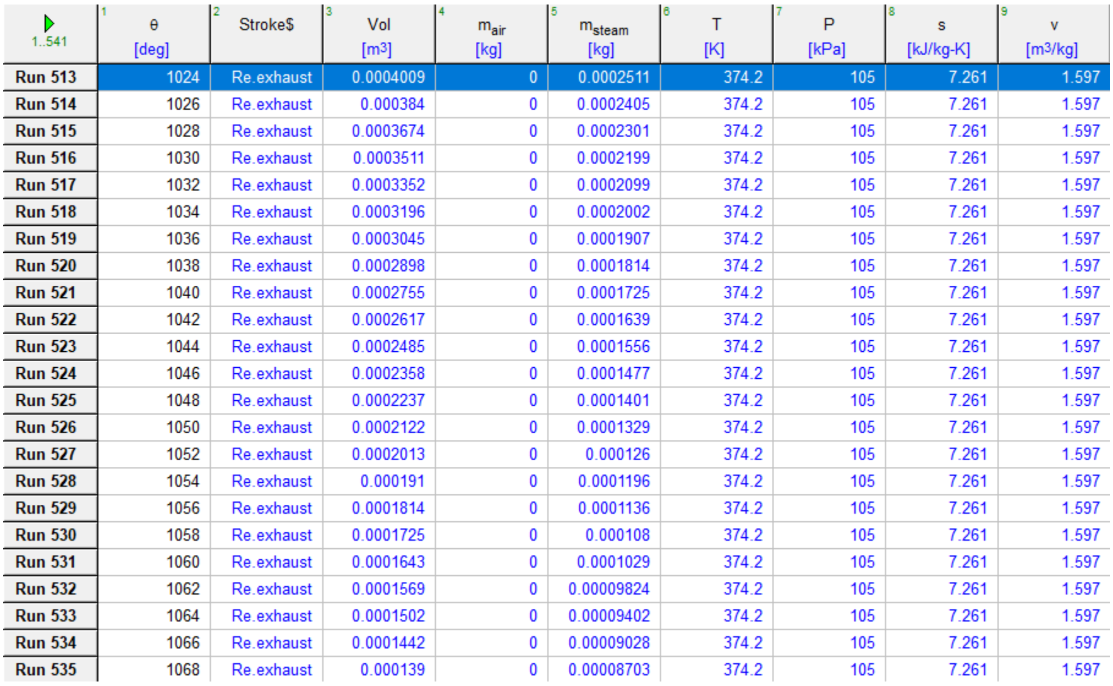
But this stroke led to the addition of a new work to the engine, this work determine by change in internal energy at start and end of steam power stroke multiplied by the mass of steam. As shown in equation 4.16 EES used to determine the work done by steam expansion.

Work$_{steam}$=m$_{steam}$*(TableValue('Otto',362,'u')-TableValue('Otto',450,'u'))   (4.16)[EES]

Where:
362: crankshaft angle at which start of steam power stroke.
450: crankshaft angle at which end of steam power stroke.

4.5.6. Re exhaust stroke

Steam leaves gradually form combustion chamber during isentropic process as shown in Figure (4.12). Here steam must keep its temperature above saturation on exhaust pressure (105 KPa) so as not to turn into water.



1..541	1 θ [deg]	2 Stroke$	3 Vol [m3]	4 m_{air} [kg]	5 m_{steam} [kg]	6 T [K]	7 P [kPa]	8 s [kJ/kg-K]	9 v [m3/kg]
Run 513	1024	Re.exhaust	0.0004009	0	0.0002511	374.2	105	7.261	1.597
Run 514	1026	Re.exhaust	0.000384	0	0.0002405	374.2	105	7.261	1.597
Run 515	1028	Re.exhaust	0.0003674	0	0.0002301	374.2	105	7.261	1.597
Run 516	1030	Re.exhaust	0.0003511	0	0.0002199	374.2	105	7.261	1.597
Run 517	1032	Re.exhaust	0.0003352	0	0.0002099	374.2	105	7.261	1.597
Run 518	1034	Re.exhaust	0.0003196	0	0.0002002	374.2	105	7.261	1.597
Run 519	1036	Re.exhaust	0.0003045	0	0.0001907	374.2	105	7.261	1.597
Run 520	1038	Re.exhaust	0.0002898	0	0.0001814	374.2	105	7.261	1.597
Run 521	1040	Re.exhaust	0.0002755	0	0.0001725	374.2	105	7.261	1.597
Run 522	1042	Re.exhaust	0.0002617	0	0.0001639	374.2	105	7.261	1.597
Run 523	1044	Re.exhaust	0.0002485	0	0.0001556	374.2	105	7.261	1.597
Run 524	1046	Re.exhaust	0.0002358	0	0.0001477	374.2	105	7.261	1.597
Run 525	1048	Re.exhaust	0.0002237	0	0.0001401	374.2	105	7.261	1.597
Run 526	1050	Re.exhaust	0.0002122	0	0.0001329	374.2	105	7.261	1.597
Run 527	1052	Re.exhaust	0.0002013	0	0.000126	374.2	105	7.261	1.597
Run 528	1054	Re.exhaust	0.000191	0	0.0001196	374.2	105	7.261	1.597
Run 529	1056	Re.exhaust	0.0001814	0	0.0001136	374.2	105	7.261	1.597
Run 530	1058	Re.exhaust	0.0001725	0	0.000108	374.2	105	7.261	1.597
Run 531	1060	Re.exhaust	0.0001643	0	0.0001029	374.2	105	7.261	1.597
Run 532	1062	Re.exhaust	0.0001569	0	0.00009824	374.2	105	7.261	1.597
Run 533	1064	Re.exhaust	0.0001502	0	0.00009402	374.2	105	7.261	1.597
Run 534	1066	Re.exhaust	0.0001442	0	0.00009028	374.2	105	7.261	1.597
Run 535	1068	Re.exhaust	0.000139	0	0.00008703	374.2	105	7.261	1.597

Figure 4.12: Re exhaust stroke [EES]

4.6. Six stroke power and Thermal efficiency

In six stroke, engine thermal efficiency and power have been improved and determine from EES as shown in equations 4.17,4.18 respectively where they depend on the output and desired input.

Efficiency=($Work_{power}$+$Work_{compression}$+$Work_{steam}$+$Work_{pump}$)/(m_{air}*(TableValue('Otto', 182,'u')-TableValue('Otto',181,'u'))+ m_{steam}*(TableValue ('Otto',362,'n') TableValue ('Otto',368,'n'))) (4.17) [EES]

Power=($Work_{compression}$+$Work_{power}$+$Work_{steam}$+$Work_{pump}$)*RPM/3 (4.18) [EES]

"Six stroke ICE EES full code listed in APPENDIX B"

CHAPTER FIVE

5. Results and comparison with four stroke engine

5.1. Introduction

In this research, for the same engine geometry a six stroke engine is compare with four stroke engine in thermal efficiency, engine power and fuel consumption, to know effectiveness of six stroke ICE. EES used to determine these variables and plots it.

5.2. Pressure versus volume diagram

Area under pressure volume (P-V) diagram represent work done during Otto cycle. EES plots this cycle as shown in Figures (5.1) and (5.2).

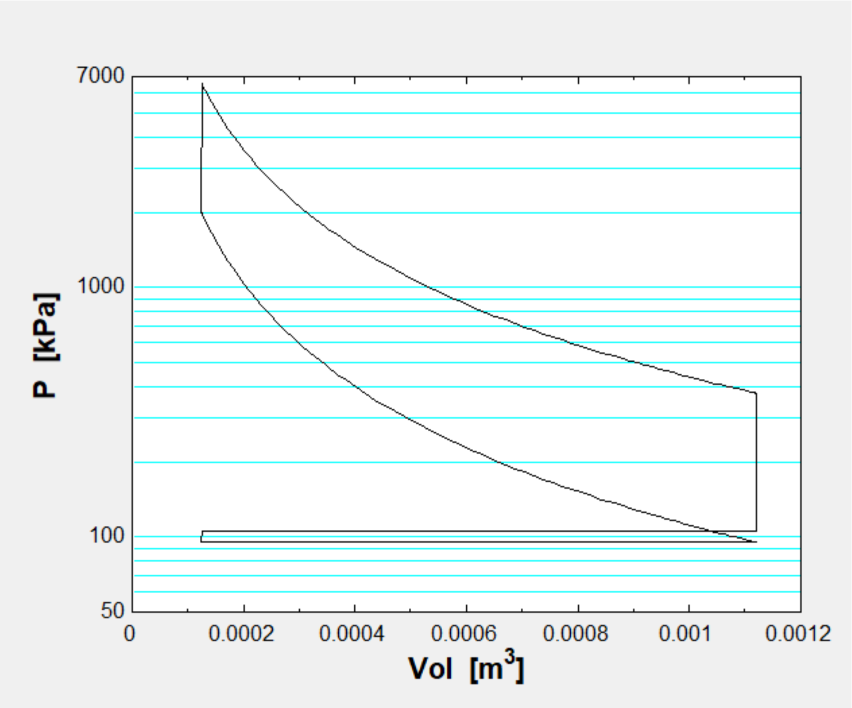


Figure 5.1: Four stroke P-V diagram [EES]

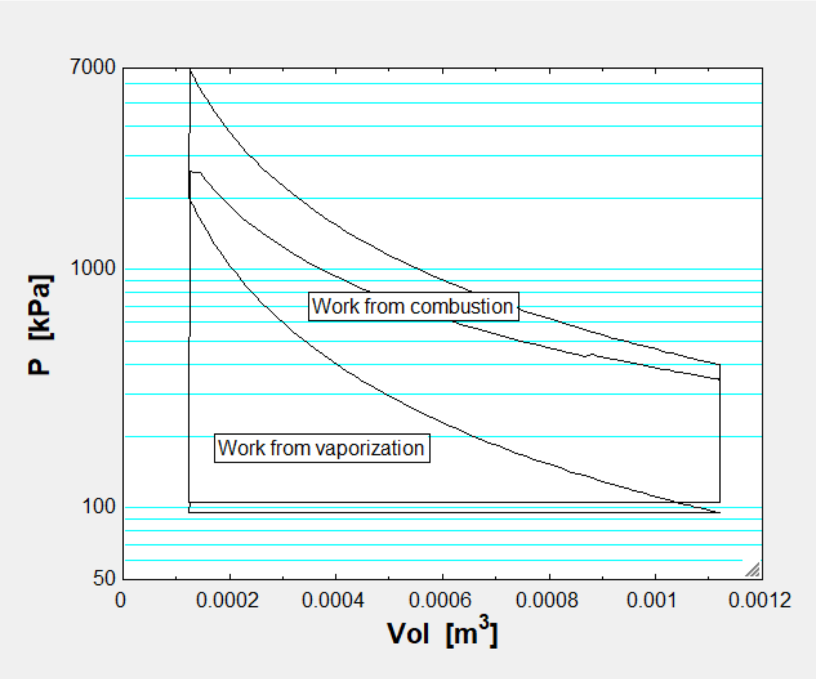


Figure 5.2: Six stroke P-V diagram [EES]

Area under P-V diagram for six stroke that consist of area form combustion of fuel and vaporization of steam larger than four stroke engine. This means the network is lager in six stroke engines.

5.3. Pressure versus crankshaft angle diagram

Figures (5.3) and 5.4 shows pressure with crankshaft angle (P-α) diagram in both four and six strokes engines.

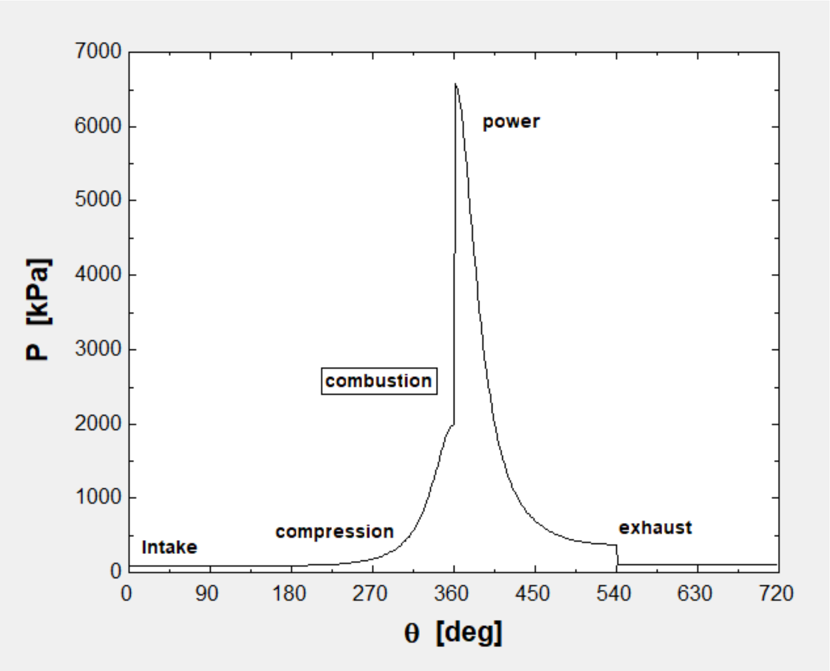


Figure 5.3: Four stroke P-α diagram [EES]

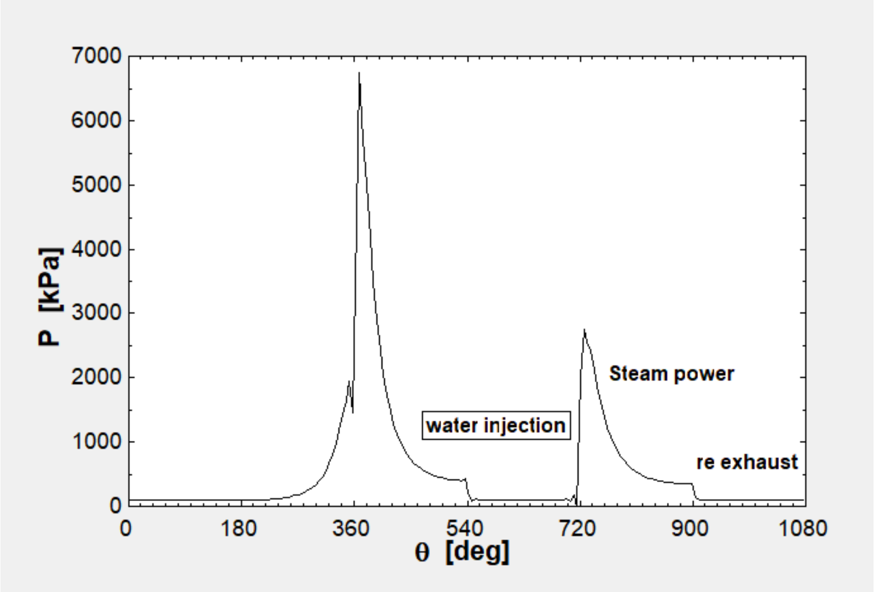


Figure 5.4: Six stroke P-α diagram [EES]

5.4. Temperature versus crankshaft angle diagram

Figures (5.5) and (5.6) show temperature with crankshaft (T-α) diagram in both four and six strokes engines.

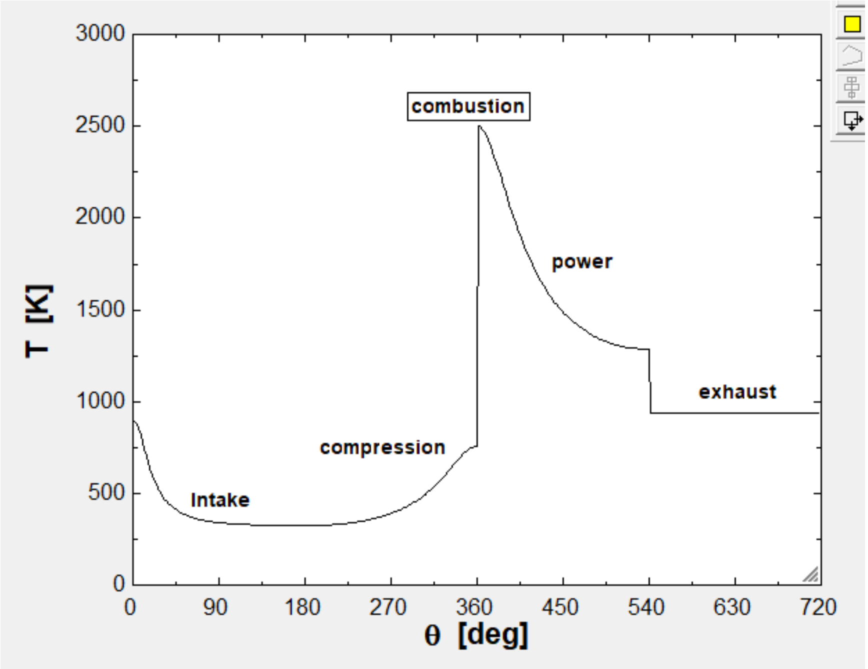


Figure 5.5: Four stroke T-α diagram [EES]

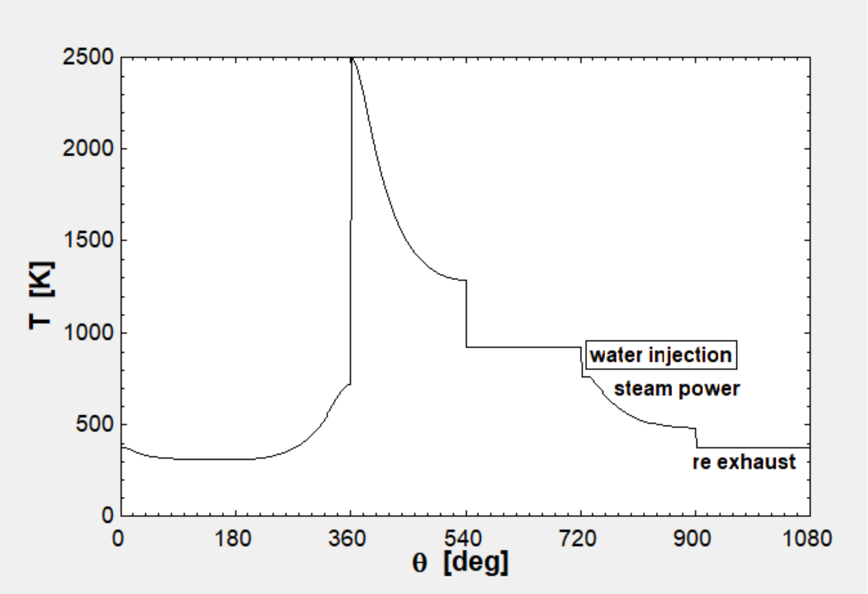
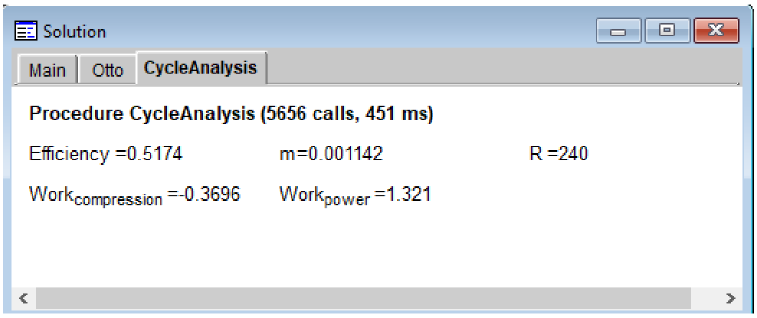


Figure 5.6: Six stroke T-α diagram [EES]

5.5. Six stroke cycle analysis

The results of cycles analysis of six stroke engine is determine using EES and compare these results with four stroke engine as shown if Figures (5.7) and (5.8).

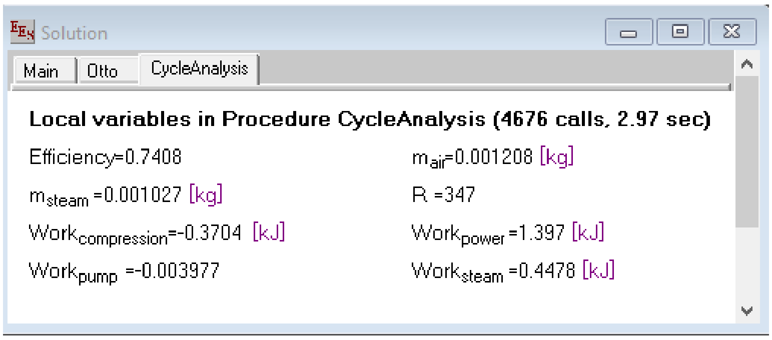


Procedure CycleAnalysis (5656 calls, 451 ms)

Efficiency =0.5174 m=0.001142 R =240

$Work_{compression}$ =-0.3696 $Work_{power}$ =1.321

Figure 5.7: Four stroke cycle analysis [EES]



Local variables in Procedure CycleAnalysis (4676 calls, 2.97 sec)

Efficiency=0.7408 m_{air}=0.001208 [kg]

m_{steam} =0.001027 [kg] R =347

$Work_{compression}$=-0.3704 [kJ] $Work_{power}$ =1.397 [kJ]

$Work_{pump}$ =-0.003977 $Work_{steam}$ =0.4478 [kJ]

Figure 5.8: Six stroke cycle analysis [EES]

Thermal efficiency dramatically increased in six stroke about 30 % and engine power improved by 3% in case of six stroke cycle over four stroke cycle.

Air fuel mixture becomes 0.001208 [Kg/stroke] and was 0.001142 [Kg/stroke] in case of four stroke cycle. These masses flow convert to Kg/sec by the following equations 5.1

$$\dot{m}_{mix}\ [Kg/sec] = (m_{mix}\ [Kg/stroke]*RPM\ [rev/second])/(60*n_d) \tag{5.1}$$

where:
RPM: engine speed.
n_d: number of power stroke per cycle, this term equals 2 in four stroke and 3 in six stroke.

The result of fuel consumption determine at 3000 RPM and assume stoichiometric combustion (air fuel ratio= 14.7 kg air/ kg fuel). This get 0.0013696 Kg/sec in six stroke less than 0.001942177 Kg/sec in four stroke, then consumption reduced about 29.5%. Also reduced in engine emission.

5.6. Conclusion and drawbacks

The results of this study are summarized in the following table 5.1 and compare with four stroke data in table 5.2.

Table 5.1 result data for six stroke engine.

6-stroke ; A/F=14.7 ; RPM= 3000 [rev/min]

M_{steam} [Kg/stroke]	M_{steam} [Kg/s]	W_{comp} [KJ/cycle]
0.001027	0.017116667	-0.3704

M_{mix} [kg/s]	M_{mix} [kg/stroke]	W_{power} [Kj/cycle]
0.020133333	0.001208	1.397

M_{fuel} [kg/s]	W_{steam} [KJ/cycle]	W_{pump} [KJ/cycle]
0.001369615	0.4478	-0.003977

P [KW]	η_{th} [%]	W_{net} [KJ/cycle]
24.51	74.08	1.470423

Table 5.2 result data for four stroke engine.

4-stroke ; A/F=14.7 ; RPM= 3000 [rev/min]

W_{comp} [KJ/cycle]	W_{power} [KJ/cycle]	W_{net} [KJ/cycle]	P [KW]
-0.3696	1.321	0.9514	23.78

M_{mix} [kg/stroke]	M_{fuel} [kg/stroke]	M_{fuel} [kg/s]	η_{th} [%]
0.001142	0.02855	0.001942177	51.74

So six stroke engine is an effective way of recovery of heat lost through the exhaust gases by adding two additional strokes.

Drawbacks and obstacles:

- ✓ Injecting relatively cold water on to a hot metal piston can damage it over time from thermal expansion and contraction so exhaust gases used to pre-heating of water.

- ✓ As the steam is generated in 2nd power stroke, if the water is not neutralized it may react with the cylinder wall and with the piston top which result cavitation and distortion of the metal, it cases the uneven heat transfer between the water droplets and the cylinder wall which may decrease the performance of the engine. And it is difficult to carry neutral water all the time .

- ✓ Separate water tank would have significant weight and space penalties so a condenser can be used instead of a separate water tank which will reuse the distilled water for a period of cycles.

- ✓ Cold climate anti-freezing measures would be needed in the water reservoir.

5.7. Recommendations

- ✓ As a result for the research the amount of water was used in 5th stroke is very large and this is not practical way to charge of the water tank, So It is possible to use a closed cycle of water by condensing steam and returning it to the tank rather than releasing it into the atmosphere

- ✓ To compensate the temperature drop inside the chamber we can further increase the compression ratio which increases the power output making it suitable for high power requirements.

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APPENDX A

"Design Variables and Constraints"

RPM =3000 [rev/min] "engine speed"

T_{max} = 2500 [K] "maximum engine temperature"

Bore = 130 [mm] "engine cylinder bore"

Stroke=75 [mm] "engine cylinder stroke"

L_1=Stroke/2 "length of flywheel connection"

L_2=110 [mm] "length of connecting rod"

Flywheel angle= theta

Piston top=70 [mm]+(L2)*Cos(-Crankshaft angle) L_1*Cos(Flywheel angle)+ L1*sin(abs(Crankshaft angle))*abs(sin(Flywheel angle))

Crankshaft angle= -arc sin(L_1/ L2)*sin(Flywheel angle)

Crankshaft top=Piston top + 65 [mm]- (L2/2)*(1-cos(Crankshaft angel))

Crankshaft left=102 [mm]- (L2/2)*sin(-Crankshaft angle)

"calculate property information"

Bore=130 [mm]

Piston Width= Bore

Piston Left=111 [mm]+(130 [mm]-Bore)/2

Cylinder Width=178 [mm]+(Bore-130 [mm])

Cylinder left=87 [mm]+(130 [mm]-Bore)/2

H=Piston top-Top of Cylinder

Compression Ratio=H_{max}/H_{min}

H_{min} =70 [mm]+L_2 - L_1 –Top of Cylinder

H_{max} = H_{min} + Stroke

Vol =PI * (Bore^2/4)*H "convert(mm^3,m^3)"

Displacement = PI *(Bore^2/4)*Stroke "convert(mm^3,l)"

Clearance Vol = PI *(Bore^2/4)* H_{min} "convert(mm^3,m^3)"

APPENDIX B

Six stroke ICE EES full code with animation model.

```
procedure Otto(Theta, Vol, ClearanceVol, T_max:m_air,m_steam,T,P,u,v,s,n,
Stroke$,IntakeArrowColor,ExhaustArrowColor(

  if (Theta>=1080) then Theta=Theta-1080
  Stroke$='Intake'
  if (Theta>180) then Stroke$='Compression'
  if (Theta>360) then Stroke$='Power'
  if (Theta>540) then Stroke$='Exhaust'
  if (Theta>720) then Stroke$='Steam.Power'
  if (Theta>900) then Stroke$='Re.exhaust'

if (Loop#>1) then
       T_Re.exhaust=TableValue('Otto',540,'T('
else
       T_Re.exhaust=370 [K" [calculated assuming isentropic expansion after exhaust
valves open"
endif

if (Loop#>1) then
        T_exhaust=TableValue('Otto',360,'T ('
else
       T_exhaust=900 [K" [calculated assuming isentropic expansion after exhaust
valves open "
endif

  if (Stroke$='Intake')  then
       IntakeArrowColor=Black#
       ExhaustArrowColor=White#
       P=95 [kPa[
       T_in=300 [K[
       m_clearance=ClearanceVol/volume(Air,T=T_Re.exhaust,P=P(
              m_in=(Vol-ClearanceVol)/volume(Air,T=T_in,P=P(
       m_air=m_clearance+m_in
       m_steam=0
       T=Temperature(Air,P=P,v=Vol/m_air(
       u=intEnergy(Air,T=T(
       v=volume(Air,T=T,P=P(
       s=entropy(Air,T=T,P=P(
       n=Enthalpy(Air,T=T(
}          m=Vol/v{
  endif

  if (Stroke$='Compression') then
       IntakeArrowColor=White#
       ExhaustArrowColor=White#
```

```
       s=entropy(Air,T=TableValue('Otto',91,'T'), P=TableValue('Otto',91,'P(('
       m_air=TableValue('Otto',91,'m_air('
       m_steam=0
       v=Vol/m_air
       T=Temperature(Air,s=s,v=v(
       P=Pressure(Air,s=s,v=v(
       u=intEnergy(Air,T=T(
       n=Enthalpy(air,T=T(
endif

 if (Stroke$='Power')  then
       IntakeArrowColor=White#
       ExhaustArrowColor=White  #
       s=entropy(Air,T=T_max,v=TableValue('Otto',180,'v(('
       m_air=TableValue('Otto',180,'m_air('
       m_steam=0
       v=Vol/m_air
       T=Temperature(Air,s=s,v=v(
       P=Pressure(Air,s=s,v=v(
       u=intEnergy(Air,T=T(
       n=Enthalpy(air,T=T(
endif

if (Stroke$='Exhaust') then
       IntakeArrowColor=White#
       ExhaustArrowColor=Black  #
       P=105 [kPa[
       s=TableValue('Otto',270,'s('
       T=temperature(Air,s=s,P=P(
       }T=TableValue('Otto',270,'T{('
              v=volume(Air,T=T,P=P(
         m_air=Vol/v
       m_steam=0
       u=intEnergy(Air,T=T(
       s=entropy(Air,T=T,P=P(
       n=Enthalpy(air,T=T(
endif

 if (Stroke$='Steam.Power')  then
       IntakeArrowColor=White#
       ExhaustArrowColor=White#
       P_clearnce=TableValue('Otto',361,'P('
       m_air=(ClearanceVol)/volume(Air,T=T_exhaust,P=P_clearnce(

              "heat transfare analysis"

if (Theta <= 734 ) then
       stroke$='Water.Input'
       P_water=3000 [KPa[
       T_piston= 800 [K[
```

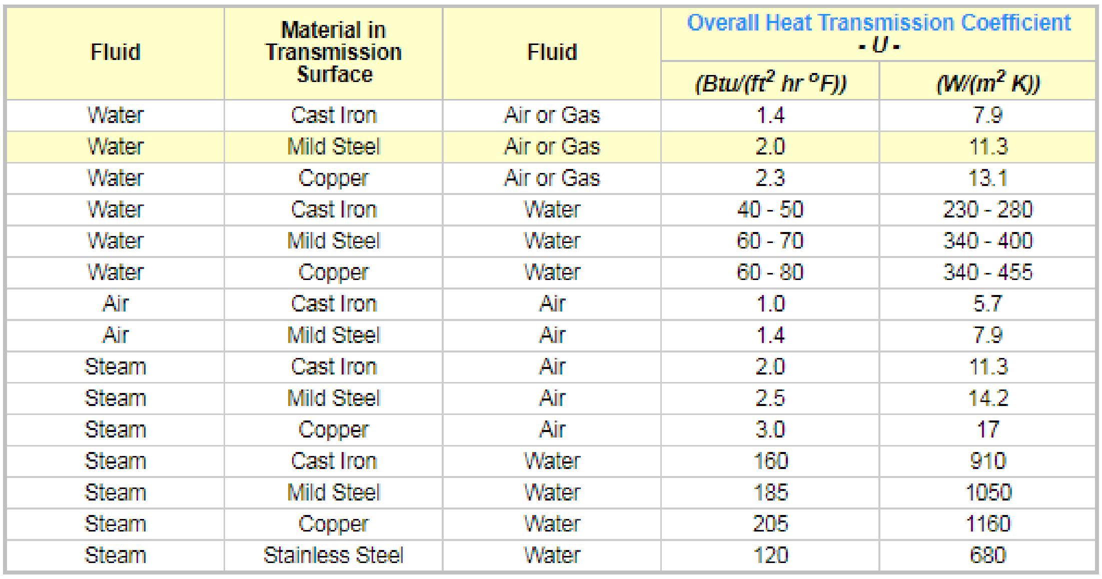
```
        T_air= 900 [K[
        T_water= 400 [K[
        T_cylinder= 500 [K[
        c_piston= 0.460548 [KJ/Kg.K"  [spesific heat for cast iron piston material"
        c_cylinder=  0.460548 [KJ/Kg.K" [spesific heat for cast iron cylinder material"
        cp_water= 4.18 [KJ/Kg.K[
        cp_air= 1.005 [KJ/Kg.K[
        m_piston= 0.697 [Kg" [calculated from m=rho/v ; cast iron material and 7mm
thikness"
        m_cylinder= 0.1 [kg"  [calculated from m=rho/v ; cast iron material and 7mm
thikness"

        m_steam= Vol/Volume(Water,T=T_exhaust,P=P_water(

T_steam=
(m_piston*c_piston*T_piston+m_cylinder*c_cylinder*T_cylinder+m_air*cp_air*T_
air+m_steam*cp_water*T_water)/(m_piston*c_piston+m_cylinder*c_cylinder+m_air
*cp_air+m_steam*cp_water "  (calculated from first low of thermdynamic"

        v=Vol/(m_steam+m_air(
        s=Entropy(steam,T=T_steam ,P=2576(
        P=Pressure(Steam,T=T_steam,v=v(
        T=Temperature(Steam,P=P,s=s(
        u=IntEnergy(Steam,T=T,s=s(
        n=Enthalpy(Steam,T=T,s=s(
else
        m_steam=TableValue('Otto',368,'m_steam('
        v=Vol/(m_steam+m_air(
        s=Entropy(steam,T=TableValue('Otto',368,'t') ,P=2576(
        P=Pressure(Steam,T=TableValue('Otto',368,'t') ,v=v(
        T=Temperature(Steam,P=P,s=s(
        u=IntEnergy(Steam,T=T,s=s(
        n=Enthalpy(Steam,T=T,s=s(
endif
        endif

  if (Stroke$='Re.exhaust')  then
        IntakeArrowColor=White#
        ExhaustArrowColor=White#
        P=105 [kPa[
        s=TableValue('Otto',451,'s('
        T=Temperature(Steam,P=P,s=s(
        v=Volume(Steam,T=T,s=s(
        m_air=0
          m_steam=Vol/v
        u=IntEnergy(Steam,T=T,v=v(
        n=Enthalpy(Steam,T=T,s=s(
endif
```

```
end

procedure CycleAnalysis(R:Work_compression,Work_power,Work_pump
,Work_steam,Efficiency(
        Work_compression=0
        Work_power=0
        Work_steam=0
        Work_pump=0
        Efficiency=0
        m_air=1
        m_steam=1
        if (Loop#>1) then m_air=TableValue('Otto',91,'m_air('
        if (Loop#>1) then m_steam=TableValue('Otto',451,'m_steam('
        if (Loop#>1) then  Work_compression=m_air*(TableValue('Otto',91,'u')-
TableValue('Otto',180,'u(('
        if (Loop#>1) then  Work_power=m_air*(TableValue('Otto',182,'u')-
TableValue('Otto',270,'u(('
        if (Loop#>1) then  Work_steam=m_steam*(TableValue('Otto',362,'u')-
TableValue('Otto',450,'u(('
        if (Loop#>1) then  Work_pump=m_steam*(TableValue('Otto',368,'n')-
TableValue('Otto',362,'n(('
        if (Loop#>1) then
Efficiency=(Work_power+Work_compression+Work_steam+Work_pump)/(m_air*(
TableValue('Otto',182,'u')-
TableValue('Otto',181,'u'))+m_steam*(TableValue('Otto',362,'n')-
TableValue('Otto',368,'n((('

end

"animation information"
Stroke=75 [mm[
L_1=Stroke/2                                   "length of flywheel connection"
L_2=110 ]mm[                                   "length of connecting rod"
Flywheel.angle=theta
Piston.top=70 [mm]+(L_2)*cos(-Crankshaft.angle)-
L_1*cos(Flywheel.angle)+L_1*sin(abs(Crankshaft.angle))*abs(sin(Flywheel.angle((
Crankshaft.angle=-arcsin(L_1/L_2*sin(Flywheel.angle((
Crankshaft.top=Piston.top+65 [mm]-L_2/2*(1-cos(Crankshaft.angle((
Crankshaft.left=102 [mm]-L_2/2*sin(-Crankshaft.angle(
IntakeValve.top=IntakeV
ExhaustValve.top=ExhaustV
Fire.top=SparkY
Water.top=InjectionX

"calculate property information"
Piston.Width=Bore;  Piston.Left=111 [mm]+(130 [mm]-Bore)/2  ;
Cylinder.Width=178 [mm]+(Bore-130 [mm]); Cylinder.left=87 [mm]+(130 [mm]-
Bore)/2
H=Piston.top-TopofCylinder
CompressionRatio=H_max/H_min
```

```
H_min=70 [mm]+L_2-L_1-TopofCylinder ;
H_max=H_min+Stroke
Vol=pi*Bore^2/4*H*convert(mm^3,m^3(
Displacement=pi*Bore^2/4*Stroke*convert(mm^3,l(
ClearanceVol=pi*Bore^2/4*H_min*convert(mm^3,m^3(
Call Otto(Theta, Vol, ClearanceVol, T_max:m_air,m_steam,T,P,u,v,s,n,
Stroke$,IntakeArrow.Color,ExhaustArrow.Color(
Call CycleAnalysis(TableRun#:W_compression,W_power,W_steam,Work_pump
,Efficiency(
Power=(W_compression+W_power+W_steam+Work_pump)*RPM/3
*convert(kJ/min,kW(
m2=pi*Bore^2/4*(H_max-H_min)/volume(Air,T=300,P=100)*convert(mm^3,m^3(
```

APPENDIX C

Overall Heat Transfer Coefficients for Fluids - Heat Exchanger Surface Combinations [16]



Fluid	Material in Transmission Surface	Fluid	Overall Heat Transmission Coefficient - *U* -	
			(Btu/(ft^2 hr °F))	*(W/(m^2 K))*
Water	Cast Iron	Air or Gas	1.4	7.9
Water	Mild Steel	Air or Gas	2.0	11.3
Water	Copper	Air or Gas	2.3	13.1
Water	Cast Iron	Water	40 - 50	230 - 280
Water	Mild Steel	Water	60 - 70	340 - 400
Water	Copper	Water	60 - 80	340 - 455
Air	Cast Iron	Air	1.0	5.7
Air	Mild Steel	Air	1.4	7.9
Steam	Cast Iron	Air	2.0	11.3
Steam	Mild Steel	Air	2.5	14.2
Steam	Copper	Air	3.0	17
Steam	Cast Iron	Water	160	910
Steam	Mild Steel	Water	185	1050
Steam	Copper	Water	205	1160
Steam	Stainless Steel	Water	120	680