THERMODYNAMIC ANALYSIS FOR A SIX STROKE ENGINE FOR HEAT RECOVERY

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ABSTRACT

The concept adding two more strokes to the Otto cycle to increase fuel 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, thermodynamics analysis was performed for a six stroke internal combustion engine to identify the amount of water needed to be injected for the second power stroke and to identify the cylinder pressure. It was divided into two modes. The first mode, the cylinder was analysed with the exhaust gas. The second mode, the calculation was done without the exhaust gas in the cylinder. Next, another kind of approaches is developed. Based on Jong *et al* (2009), a computer simulation by using MATLAB was developed based on the Otto cycle which basically 6-stroke is the adding of 2-stroke into 4-stroke engine. Then, performance results can be obtained and compared the results with Jong *et al* (2009). In the first mode, water is injected depending on the crank angle starting from CA - -20° until CA-2°. From this crank angle, the maximum amount of water needed at CA -20° is 8.8020 × 10^{-7} cm^3 and the minimum amount is 2.7056 × 10^{-9} cm^3 at CA-2°. In the second mode, the calculation was depending on the piston surface and without the exhaust gas in cylinders. This gives the amount of water injected is 29.2188 cm^3. From these two modes, the best mode was chosen to calculate the amount of water needed. Next, by using MATLAB, a wide range of engine parameters was studied, such as cylinder pressure and temperatures, density of air, entropy, enthalpy and volume of air in each cycle. For example, for the combustion cycle, the cylinder pressure temperatures, density of air, entropy, enthalpy and volume of air is 2660 K, 7170 kPa, 0.366 $kmol/m^3$, 107000 kJ/kg, 277.96 $kJ/kg.K$, and 0.0000588 m^3. From the results, the P-V and T-S diagram were plotted and analysis. Thus, the value of pressure is determined.

ABSTRAK

Konsep menambah dua lagi lejang kepada kitaran Otto untuk meningkatkan kecekapan bahan api dikaji dan dibentangkan di sini. Ia boleh dianggap sebagai kitaran Otto empat lejang diikuti oleh dua strok haba kitaran pemulihan stim atau juga dikenali sebagai enjin enam lejang. Dalam projek ini, analisis termodinamik telah di laksanakan kepada enjin pembakaran dalaman enam lejang untuk mengenal pasti jumlah air yang perlu disuntik untuk lejang kuasa kedua dan untuk mengenal pasti tekanan silinder. Ia telah dibahagikan dalam dua mod. Mod pertama, silinder telah dianalisis dengan gas ekzos. Mod kedua, pengiraan telah dilakukan tanpa gas ekzos di dalam silinder. Seterusnya, pendekatan jenis lain telah dibangunkan. Berdasarkan Jong *et al* (2009), simulasi komputer dengan menggunakan MATLAB telah dibangunkan berdasarkan kitar Otto yang pada asasnya, 6-lejang adalah hasil tambah 2-lejang ke dalam enjin 4-lejang. Kemudian, keputusan prestasi boleh diperolehi dan dibandingkan dengan keputusan Jong *et al* (2009). Dalam mod pertama, air disuntik bergantung kepada sudut engkol bermula dari CA -20°sehingga CA -2°. Dari sudut ini engkol, jumlah maksimum air yang diperlukan di CA -20° adalah 8.8020×10^{-7} cm^3 dan jumlah minimum adalah 2.7056×10^{-9} cm^3 di CA -2°. Bagi mod kedua, pengiraan bergantung kepada permukaan omboh dan tanpa gas ekzos di dalam silinder. Ini memberi isipadu air suntikan $29.2188\ cm^3$. Dari ke dua mod ini, mod yang terbaik telah dipilih untuk mengira isipadu air yang diperlukan. Seterusnya, dengan menggunakan MATLAB, pelbagai parameter enjin telah dikaji, seperti tekanan silinder dan suhu, ketumpatan udara, entropi, entalpi dan kelantangan bagi udara dalam setiap kitaran. Sebagai contoh, untuk kitar pembakaran, suhu tekanan silinder, ketumpatan udara, entropi, entalpi dan kelantangan bagi udara ialah 2660 K, 7170 kPa, 0.366 $kmol/m^3$, 107000 kJ/kg, 277.96 $kJ/kg.K$, and 0.0000588 m^3. Daripada keputusan, rajah P-V dan T-S telah diplotkan dan analisis. Oleh itu, nilai tekanan ditentukan.

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LIST OF SYMBOLS

A_s	Surface Area, m^3
CO	Carbon Monoxide
CO_2,	Carbon Dioxide
C_V	Volume Specific Heat, $kj/kg.K$
C_p	Pressure Specific Heat$kj/kg.K$
$C_{p_{mix}}$	Pressure Specific Heat for Air/Fuel mixure $kj/kg.K$
C_8H_8	Ethanol
$E_{mass,in}$	Energy Of Mass In
$E_{mass,out}$	Energy Of Mass Out
ΔE	Total Energy
exp	Exponent
Gr_L	Grashof Number
g	Gravitational Acceleration, m/s^2
H_2O	Hydrogen
HC	Hydrocarbon
h_{fg}	Latent Heat Of Vaporization, kj/kg
h	Convection Heat Transfer Coefficient, $W/m^2.K$
h_{air}	Specific Enthalpy Of Air, kJ/kg
h_{fuel}	Specific Enthalpy Of Fuel, kJ/kg
hum_{rat}	Huminity Ratio
k	Thermal Conductivity, $W/m.K$
L_c	Characteristic Length Of The Geometry, m
m	Mass, kg
M	Molar Mass, $kg/kmol$
m_f	Mass Of Fuel, $kg/kmol$
m_{water}	Mass Of Water, kg or cm^3
m_{air}	Mass Of Air, $kg/kmol$
m_{fuel}	Mass Of Fuel, $kg/kmol$
m_{mix}	Total Molar Mass of mixture, $kg/kmol$
m_m	Total Molar Mass, $kg/kmol$

n_{water}	Number Of Mole Of Water, $kmol$
n_{fuel}	Number Of Mole Of Fuel, $kmol$
n_{air}	Number Of Mole Of Air, $kmol$
$n_{\mathrm{CO_2}}$	Number Of Mole Of Carbon Dioxide, $kmol$
$n_{\mathrm{h_2O}}$	Number Of Mole Of Hydrogen, $kmol$
$n_{\mathrm{n_2}}$	Number Of Mole Of Nitrogen, $kmol$
$n_{\mathrm{O_2}}$	Number Of Mole Of Oxigen, $kmol$
Nu	Nusselt Number
N	Mole Number, $kmol$
Pr	Prandtl Number
P_i	Pressure At *I*th Condition, kPa
P_{max}	Pressure At Maximum Condition, kPa
$\mathrm{Q_{in}}$	Heat Transfer In, kJ
$\mathrm{Q_{out}}$	Heat Transfer Out, kJ
ΔQ	Total Heat Transfer, kJ
$\dot{Q}$	Rate Of Heat Transfer, kJ
Q_{HV}	Heating Value, kJ
Ra_L	Rayleigh Number
r	Radius, m
r_c	Compression Ratio
s_{air}	Specific Entropy Of Air, $kJ/kg.K$
s_{fuel}	Specific Entropy Of Fuel, $kJ/kg.K$
T_E	Exhaust Temperature, ℃
T_W	Water Temperature, ℃
T_s	Temperature Of The Surface, ℃
T_∞	Temperature Sufficiently Far From The Surface, ℃
T_{max}	Temperature At Maximum Condition, ℃
T_i	Temperature At *I*th Condition, ℃
T_f	Film Temperature, K
ΔT	Temperature Difference, ℃
ΔU	Total Potential Work
V	Volume, m^3

v	Kinematics Velocity Of The Fluid, m^2/s
v_S	Swept Volume, m^3
v_{TDC}	Top Dead Centre Volume, m^3
v_{BDC}	Bottom Dead Centre Volume, m^3
V_{air}	Volume Of Air, m^3
W_{1-2}	Work Done For Cycle 1-2, kJ
W_{3-4}	Work Done For Cycle 3-4, kJ
W_{net}	Total Work Done, kJ
$\dot{W}_{\text{net}}$	Total Work Done Rate, kg/s
W_{in}	Work Done In, kJ
W_{out}	Work Done Out, kJ
x_i	Mass Fraction at ith
α_s	Number Of Moles Of Air At Stoichiometric Condition, Dimensionless
α	Number Of Carbon Atoms In The Fuel
β	Coefficients Of Volume Expansion, 1/K (β=1/T for ideal gas)
γ	Number Of Hydrogen Atoms In The Fuel
ϕ	Equivalence Ratio
θ	Angle / Degree
π	Pi
μ	Dynamic Viscocity, $kg/m.s$
ρ	Density, kg/m^3
ρ_{air}	Density Of Air, kg/m^3
ρ_{fuel}	Density Of Fuel, kg/m^3
η	Efficiency, %
η_{th}	Thermal Efficiency, %

LIST OF ABBREVIATIONS

BDC	Bottom Dead Center (piston location)
CA	Crank Angle
Eq.	Equation
CI	Compression Ignition
ICE	Internal Combustion Engine
LHS	Left Hand Side
PV	Pressure *versus* Volume
RHS	Right Hand Side
SI	Spark Ignition
TDC	Top Dead Center (piston location)
TS	Temperature *versus* Entropy
WOT	Wide Open Throttle

CHAPTER 1

INTRODUCTION

1.1 BACKGROUND

It has been a long years taken to find the ways to increase the efficiency of internal combustion engines, particularly engines utilized in automobiles and the like. In order to increase the efficiency of such engine, it is desirable to reduce mechanical loss within the engine and to improve the efficiency of combustion of the fuel itself.

In two stroke engine, its name is from the fact that the required strokes are completed in one revolution. For this engine, there is one power stroke in one revolution. In the case of four stroke engines, the four strokes are completed in two revolutions, or there is a power stroke in two revolutions.

Next, for the six stroke engine, it adds a second power stroke, which will give much more efficient with less amount of pollution. This engine differentiates itself entirely, due to its thermodynamic cycle and a modified cylinder head with two supplementary chambers. Combustion does not occur within the cylinder but in the supplementary combustion chamber, does not act immediately on the piston, and its duration is independent from the 180° of crankshaft rotation that occurs during the expansion of the combustion gases (Liu, 2010).

The term six stroke engine itself, describes different approaches in the internal combustion engine which developed since the 1990s. Taking the first approach, the engine captures the waste heat from the four stroke Otto cycle or Diesel cycle and uses it to get an additional power and exhaust stroke of the piston in the same cylinder. The idea was using steam as the working fluid for the additional power stroke. These six stroke engines will have 2 power strokes: one by fuel, one by steam. By this additional stroke, the temperature of the engine will be reduced, as well as extracting power. The additional stroke cools the engine and does not need for a cooling system making the engine lighter and giving 40 % increased efficiency (Bellows, 2006).

The currently notable six stroke engine designs in this kind are the Crower's six stroke engine, invented by Bruce Crower of the U.S.A; the Bajulaz engine of the Bajulaz S A company, of Switzerland; and the Velozeta's Six-stroke engine built by the College of Engineering, at Trivandrum in India.

Particularly, there are few papers that discussing about the thermodynamic of 6-stroke. In Conklin *et al* (2009), they studied the thermodynamics with relation to the crank angle. In this project, another approach will be discussed. The thermodynamics analysis will be divided into two modes. . The first mode, the cylinder was analysed with the exhaust gas. This mode will need us to modify the timing of the exhaust valve. The second mode, the calculation was made without the exhaust gas in the cylinder.

Next, another kind of approaches is developed. Based on Jong *et al* (2009), a computer simulation was developed by using MATLAB. It will be based on the Otto cycle which basically the 6-stroke is the adding of 2-stroke into 4-stroke engine. Then performance results can be obtained and compared with Jong *et al* (2009).

1.2 PROBLEM STATEMENT

This study is needed to analyse the thermodynamics condition of the 6-stroke engine in order to determine the amount of water to be injecting into the cylinder and to find the pressure for the water injection condition.

1.3 OBJECTIVE

To perform a thermodynamics analysis for a six stroke internal combustion engine and to identify the amount of water needed to be injected for the second power stroke and to identify the cylinder pressure.

1.4 SCOPES

This study investigates the effect of the additional two strokes and next continues with the analysis of the combined combustion and water injection events. The analysis was divided into two modes. The first mode, the cylinder was analysed with the exhaust gas. The second mode, the calculation was done without the exhaust gas in the cylinder. From these two modes, the best modes will be decided and will be chosen to be the amount of water needed. Next, another kind of approaches is developed. Based on Jong *et al* (2009), a computer simulation by using MATLAB was developed based on the Otto cycle which basically 6-stroke is the adding of 2-stroke into 4-stroke engine. Then, performance results can be obtained and compared the results with Jong *et al* (2009).

CHAPTER 2

LITERATURE REVIEW

2.1 INTRODUCTION

Six stroke engines are more efficient and powerful than the existing four stroke engines. The engine is also having the scope of using heavy fuels and bio-fuels. The engine with varied thermodynamic cycles of operation has better thermodynamic efficiency, reduced fuel Consumption, reduced pollution. Nearly 40 % more fuel efficiency can be obtained. In six stroke engine, there will add two more stroke to the current 4 stroke engine which adding the steam stroke and second exhaust stroke.

2.2 HISTORY OF INTERNAL COMBUSTION ENGINE

In the year 1876 Nikolaus August Otto built his first four-stroke engine. From the engine, a P-V diagram was produced as shown in Figure 2.1. Wilhelm Maybach (1846-1929), one of the most important German engineers, perfected the construction, which was produced in large quantities already at the end of the year 1876. Nikolaus August Otto first designed what is known as the Otto engine or simply the 4 stroke internal combustion engine. Conversion of heat energy liberated by the combustion of the fuel into mechanical energy which rotated the crankshaft was the basic principle of this engine. The 4 stroke engine worked on the principle of the Otto cycle.

The 4 stroke engines comprise of the intake stroke, compression stroke, power stroke and finally the exhaust stroke. Fuel injected in the intake stroke and power from the fuel was derived in the 3rd stroke i.e. the power stroke which used the heat energy released by the combustion of the fuel. This 4 stroke engine forms the basis of all modern vehicles used till date.

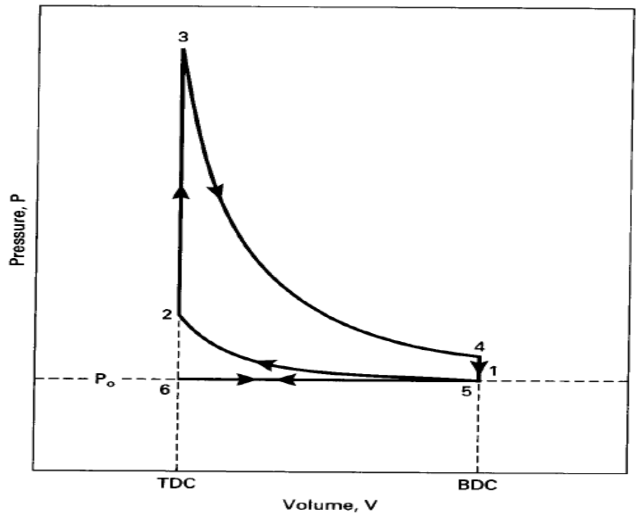

Figure 2.1: Otto cycle P-V diagram

Source: Pulkrabek (2003)

2.3 ENGINE CYCLES

The operating cycle of internal combustion engine can be divided into a sequence of separate processes which is intake, compression, expansion, and exhaust. With models for each process, a simulation of a complete engine cycle can be built which can be analysed to provide information on engine performance.

2.3.1 4-Stroke Engine

1. Intake stroke: Figure 2.2 shows the state of piston in the intake stroke. The fuel enters the combustion chamber due to the pressure of mixture formed in the chamber by the downward motion of the piston which also results in the half cycle rotation of the crankshaft. The work needed to push the piston is provided by cranking.

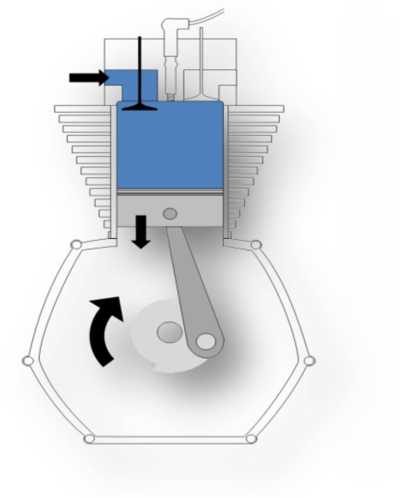

Figure 2.2: Intake Stroke

Source: Jong *et al* (2009)

2. Compression stroke: The piston moves upwards as shown in Figure 2.3, resulting in an increase in pressure and the fuel is ignited by the spark plug when the piston reaches the cover end. The work for this upward motion is again provided by cranking. The crankshaft rotates 1 complete cycle at the end of the 1st and 2nd stroke.

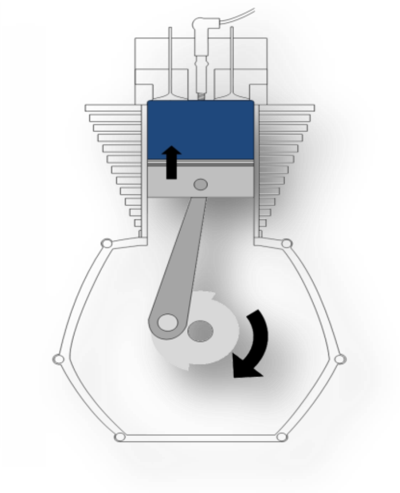

Figure 2.3: Compression Stroke

Source: Jong *et al* (2009)

3. Power stroke: Due to the explosive reaction of the fuel air mixture, huge amount of heat is generated in the engine which drives the piston downwards which forms the power stroke as shown in the Figure 2.4.

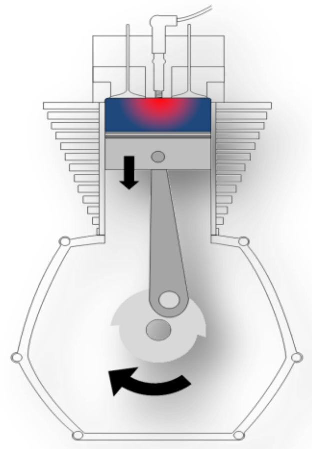

Figure 2.4: Power Stroke

Source: Jong *et al* (2009)

4. Exhaust stroke: Finally the piston moves upwards as shown in Figure 2.5, resulting in the removal of the exhaust gases via the exhaust valve. The huge amount of heat is lost in this process.

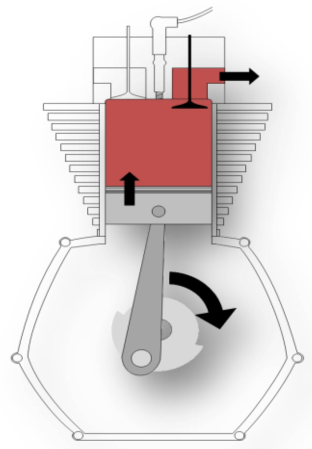

Figure 2.5: Exhaust Stroke

Source: Jong *et al* (2009)

2.3.2 6-Stroke Engine

The six stroke engine cycle involves utilizing these same strokes, but adds an additional power and exhaust stroke using water instead of fuel. These two extra strokes are designed to utilize the previously lost thermal energy. As a result, there is no longer need for a coolant system.

Based on 4-stroke engine, after the exhaust stroke, a second power stroke will begin. Figure 2.6 shows the 5th stroke. This stroke uses the heat evolved in the exhaust stroke directly as heat required by the expansion of steam from water injected under pressure at an elevated temperature through steam/water injection nozzle, which pushes the piston downward for the second power stroke thereby rotating the crankshaft for another half cycle.

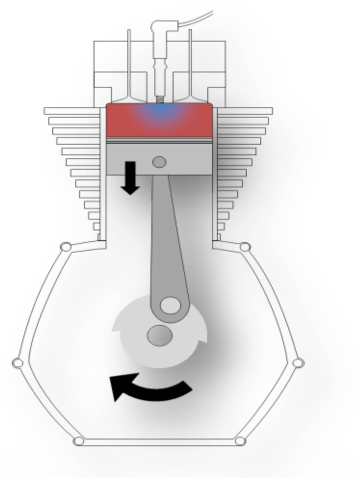

Figure 2.6: Water Injection Stroke

Source: Jong *et al* (2009)

As heat evolved in the 4th stroke is not wasted, the requirement for a cooling system is eliminated. Here the fuel is injected once in every 3 complete cycles of the crankshaft which is anytime better than a 4 stroke ICE where fuel is injected once in 2 complete cycles of the crankshaft. It should be noted that efficiency of the 6 stroke ICE is more than the existing 4 stroke ICE.2 major type of secondary fuels used in the 5^{th} stroke are air and water.

Next, 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.

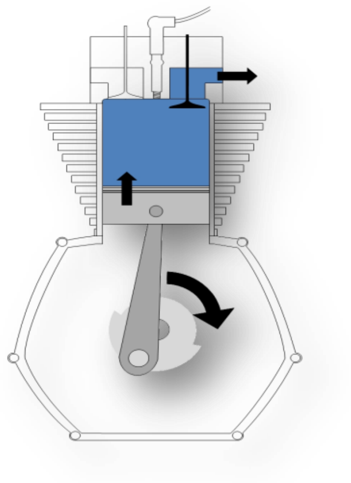

Figure 2.7: Second Exhaust Stroke

Source: Jong *et al* (2009)

Figure 2.8 shows the PV diagram for a similar six stroke engine from Jong *et al* (2009). 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 labelled 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.

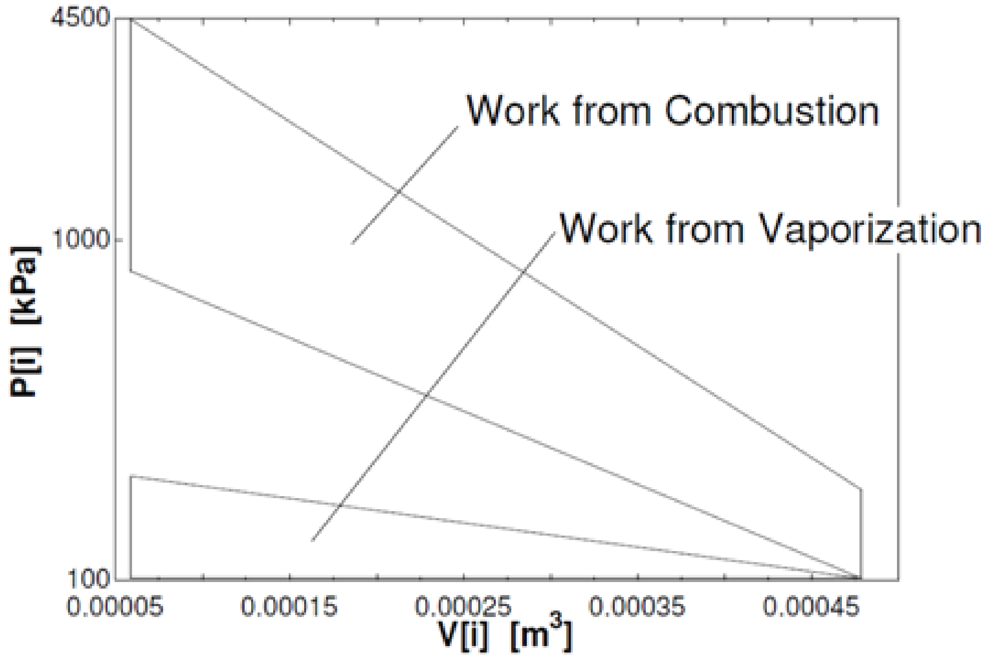

Figure 2.8: Proposed ideal six stroke cycle

Source: Jong *et al* (2009)

2.3.3 Crower Six Stroke Engine

In a six-stroke engine patented in the U.S. by Bruce Crower (Figure 2.9), after the exhaust stroke, fresh water is injected into the cylinder, and is quickly turning to superheated steam, which causes the water to expand to 1600 times its volume and forces the piston down for an additional stroke. This design also claims to reduce fuel consumption by 40 %.

Crower's six stroke engine features:-

- 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 2.9: Crower's 6-stroke engine

Source: Bellows (2006)

2.4 AIR-STANDARD CYCLES

The cycle experienced in the cylinder of an internal combustion engine is very complex. First, air (CI engine) or air mixed with fuel (SI engine) is ingested and mixed with the slightest amount of exhaust residue remaining from the previous cycle. This mixture is then compressed and combusted, changing the composition to exhaust products consisting largely of CO_2, H_2O and N_2 with many other lesser components. Then, after an expansion process, the exhaust valve is opened and this gas mixture is expelled to the surroundings. Thus, it is an open cycle with changing composition, a difficult system to analyse. To make the analysis of the engine cycle much more manageable, the real cycle is approximated with an ideal air-standard cycle which differs from the actual by the following (Pulkrabek, 2003):

1. The gas mixture in the cylinder is treated as air for the entire cycle, and property values of air are used in the analysis. This is a good approximation during the first half of the cycle, when most of the gas in the cylinder is air with only up to about 7 % fuel vapor. Even in the second half of the cycle, when the gas composition is mostly CO_2, H_2O, and N_2, using air properties

does not create large errors in the analysis. Air will be treated as an ideal gas with constant specific heats.

2. The real open cycle is changed into a closed cycle by assuming that the gases being exhausted are fed back into the intake system. This works with ideal air standard cycles, as both intake gases and exhaust gases are air. Closing the cycle simplifies the analysis.

3. The combustion process is replaced with a heat addition term Q_{in} of equal energy value. Air alone cannot combust.

4. The open exhaust process, which carries a large amount of enthalpy out of the system, is replaced with a closed system heat rejection process Q_{out} of equal energy value.

5. Actual engine processes are approximated with ideal processes.

   (a) The almost-constant-pressure intake and exhaust strokes are assumed to be constant pressure. At wide open throttle, WOT, the intake stroke is assumed to be at a pressure P_o of one atmosphere. At partially closed throttle or when supercharged, inlet pressure will be some constant value other than one atmosphere. The exhaust stroke pressure is assumed constant at one atmosphere.

   (b) Compression strokes and expansion strokes are approximated by isentropic processes. To be truly isentropic would require these strokes to be reversible and adiabatic. There is some friction between the piston and cylinder walls but, because the surfaces are highly polished and lubricated, this friction is kept to a minimum and the processes are close to frictionless and reversible. If this were not true, automobile engines would wear out long before the 150-200 thousand miles which they have now lasted if properly maintained. There is also fluid friction because of the gas motion within the