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A Comprehensive Study and Analysis of Fossil Fired Engines

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Abstract

With the advent of knowledge, complex machineries were invented through efficiency or out-put focused design. Human civilization advanced along with the new invention through knowledge sharing and idea generation for ultimate machine performance. These machines were applied for agricultural purposes, transportation, and even electricity production. This paper thorough covers the efficiency of heat energy conversion (using fossil fuel) into mechanical work by those different types of engines as well as the theoretical backgrounds for it. A comparison of these engines will be conducted at the end of this paper. Results show that out fo different types, diesel engine has the highest out-put efficiency.

Keywords: Engine, efficiency, thermodynamic, cycles, work output, pressure, temperature

Introduction

Energy is defined as the capacity to do work whether if it is moving a crate from one point to another or when an electron is pushed to move through an outer circuit (Çengel, (2002)). These works require a specific type of energy that is not always available or easy to grasp. According to the law of conservation of energy, energy cannot be created nor destroyed but it can be transformed or change from one form to another. This principle leads to the inventions of an engine which is to convert energy. The engine is used to overcome the limitations of said energy-specific requirement, usually from mechanical energy to other forms of energy or vice versa (Ganesan (1996)). A heat engine converts heat energy / thermal energy into mechanical energy whereby the heat is provided from the burning of fuel (usually fossil fuel such as coal, liquid petrol, and natural gas) (Ganesan (1996)).

There are two classifications of heat engines which are the External combustion (EC) and the Internal Combustion (IC) engine (Çengel, 2002). External combustion engines such as steam engines and Stirling engine obtain their heat source from outside the engine system, and only the working fluid is flown within the engine component (Ganesan (1996)). As for Internal combustion engines such as Diesel engines and Otto engines, the ignition of fuel and air mixture is done inside the engine chamber that functions where the product of its combustion is the working fluid in the engine (Çengel, 2002).

Further classification of heat engines centers on the type of motion it produces when it is fuelled. The 2 main classes are the reciprocating engine and rotary engine which suitability is dependent on the type of work it needs to perform as certain types are more advantages than the others (Shell, 1952). Though there are many types of engines throughout history, most of the basic working principle is the same. As required in this topic, the 3 types of engine to be discussed in detail would be the Steam engine, Diesel engine, and Otto engine.

Carnot Cycle: Theoretical perfection

Understanding the Carnot cycle is important as ideal cycles were created to overcome the problems faced by the Carnot cycle. In 1824, a French Engineer that goes by the name of Sadi Carnot proposed a completely reversible cycle that has since been the object of comparison to other cyclic theories. Heat engines were compared to as well to greater efficiency of energy conversion (Prasad (1993), Siddique, et al., (2017) and Mubarak et al., (2016)). This is because the Carnot cycle is the maximum efficiency a heat engine can achieve (Wong, (2014)). Hence the maximum possible efficiency of any heat engine or cycles is lower than using changeable phase working fluid:

$$Efficiency_{Carnot} = 1 - \frac{T_L}{T_H} \quad (1)$$

In Kelvin-Planck statement, to complete the cycle, heat rejection to a low-temperature reservoir (heat sink) must occur. Hence, 100% conversion efficiency is not possible (Wong, (2014)). This leads to the second law of thermodynamics is expressed as:

"It is impossible for any device that operates on a cycle to receive heat from a single reservoir and produce a net amount of work."

The theoretical heat engine, also known as Carnot Heat Engine, is composed of four reversible process – (1-2) reversible isothermal expansion, (2-3) reversible adiabatic heat injection, (3-4) reversible isothermal compression and (4-1) reversible adiabatic heat rejection (Çengel, 2002). The P-V graph and T-s graph below will show the state of each process. The problem with the Carnot cycle or Carnot Engine is that it suffers from several problems with its practicality in the real-life application (Çengel, (2002), Tabassum, et al., (2016) and Shabrin et al., (2017)). Due to the low-temperature difference between heat reservoir and working fluid temperature, the heat rate transfer between the two temperatures is very low. This produces very low to virtually zero power (Prasad (1993)). Besides that, as a totally reversible process that takes place in the Carnot cycle is very difficult to achieve, ideal cycles are used instead as they resemble actual cycles. The ideal cycle works on the basis that the process is only internally reversible which means that the changes to the surroundings or atmosphere are not considered (Wong, (2014)). Figure 1 shows the (a) Temperature vs. Entropy graph and (b) Pressure vs. Volume graph (Prasad (1993)).

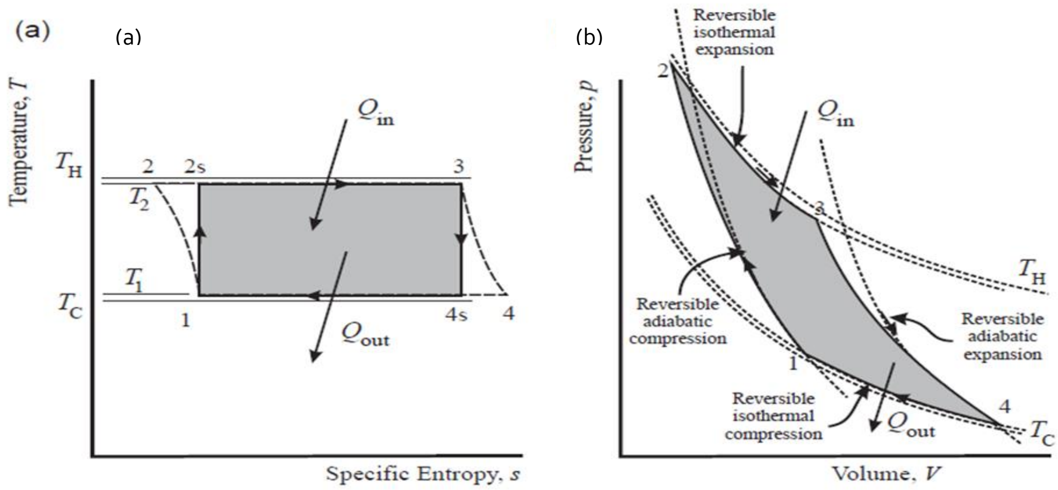

Figure 1: (a) T-s and (b) P-v diagram of Carnot cycle

Steam Engines

The Discovery of steam-powered devices or using steam for work dates back to 150 BC in Egypt but the first workable coal pumped was invented by Thomas Savery in 1698. However, Thomas's steam pump was only able to raise 9-10 m of water which leads to limited applications in the mining industry. A superior pump was designed by Thomas Newcomen and in 1712 his steam pump of larger pumping capacity was the first to be installed in a coal mine (Spear, (2008)). The drawback of Newcomen's design was that it is extremely inefficient which poses a problem to some mining activities that were far from any coalfield. James Watt has overcome the efficiency problems in Newcomen's engine model by installing a separate condenser (Spear, (2008), Kashem et al., (2020), and Nabipour-Afrouzi et al., (2018)). In partnership with Matthew Boulton (in 1775), James Watt engines have seen further improvement with the addition of rotary motions and overall power output.

General steam engine functions based on Ideal Rankine's cycle which consists of 4 major processes that are responsible for the energy conversion and its efficiency. The four processes are a) Isentropic compression in a pump b) Constant pressure heat addition in boilers c) Isentropic expansion in turbine d) Constant pressure heat rejection in the condenser (Wong, (2014)). Rankine's Cycle overcomes the Carnot cycle impracticality such as heat transfer limitations to two-phase systems, passing steam with high moisture content (leads to erosion of turbine fans), and designing compressors that handles two phases (Wong, (2014)). The efficiency of the Rankine cycle is denoted as follows:

$$Efficiency_{Rankine} = 1 - \frac{Q_L}{Q_H} \quad \text{...(2)}$$

Q_L is the heat transfer of the working fluid into the condenser and Q_H is the heat transfer from the boiler to the working fluid.

Note that the efficiency of the Rankine cycle is lower than the Carnot cycle (Badr et al., (1991)). The difference is that the Rankine cycle uses the rate of heat transfer between working fluids and heat reservoir and heat sink instead of the temperature of the heat reservoir and the heat sink. According to Badr et al., (1991), a well-made steam engine operating at the low-temperature difference (approximately 800C) is capable of achieving 60-70% of Carnot cycle efficiency while vapor cycle working under high-temperature difference may only have 50-60% of Carnot cycle efficiency (Badr et al., (1991)). However, old steam engines only have an average efficiency of 6% (Winterbone and Turan (2015)). The figure below, Figure 2, depicts the basic Rankine cycle operation and the T-s diagram of the Rankine cycle. State 1 is the compression of liquid to form compress liquid. State 2 is where heat injection at constant pressure in the boiler, followed by evaporation through state 3-4, then comes back to condensing (heat rejection) in the condenser.

Actual steam engines have several limitations and unavoidable problems that contribute to the inefficiencies of the system. The two common problems are fluid frictions, heat loss to the surrounding, and the performance of boilers and compressors. The friction between the working fluid and the engine itself causes pressure drops during heat additions in the boilers, heat rejection in condensers, and within the piping of the engine (Heywood (2006)). Unwanted heat loss from the engine forces the cycle to increase the amount of heat added to obtain similar output (Kuniaki (2006)). The performance of individual components directly contributes to the efficiencies of the system as a whole (Heywood (2006)). Figure 2 shows the basic Temperature vs. entropy graph of a Rankine cycle.

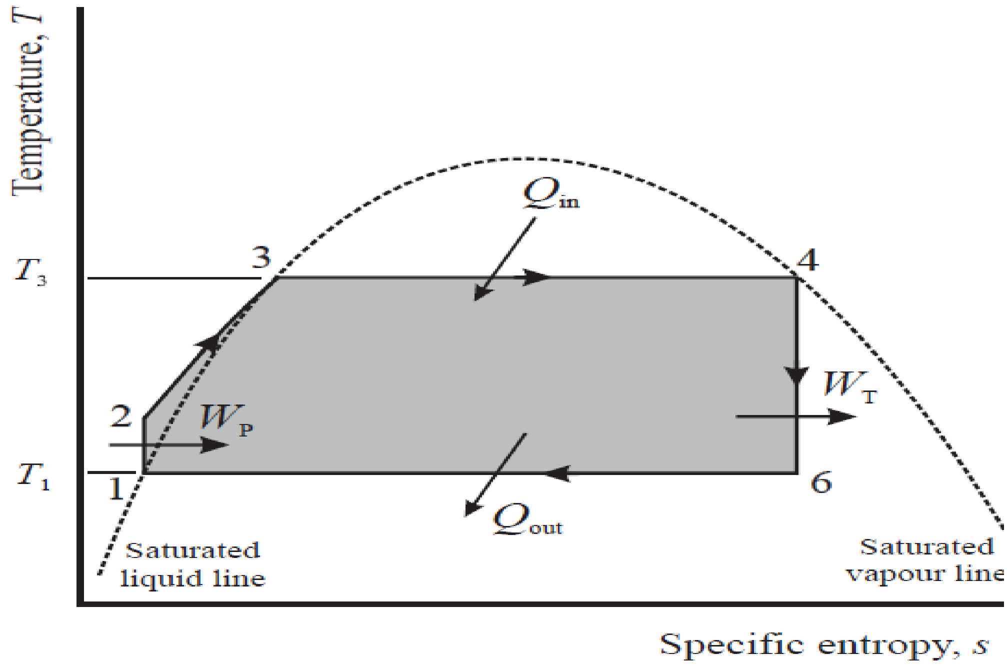

Figure 2: Ideal cycle of Rankine cycle

Introduction to Internal Combustion Engine (ICE)

ICE is a power-producing engine where the fuel and mixed air is combusting inside the engine which also becomes the working fluid of the engine. It is not technically considered as a heat engine (due to mass flow into and out of the engine) but more to a gas power cycle (Ganesan (1996)). The working fluid follows the air-standard assumption where it is assuming to behave like an ideal gas. Two types of engines or cycles that can be found today are the Spark-ignited (SI) Engine and the Compression-Ignited (CI) engine. SI engine is based on the Otto cycle theory while the CI engine is based on the Diesel cycle theory. The differences and comparisons between the two will be discussed later on. Two important theories that make up the ICE cyclic theories are the reciprocal motion of the piston (which produces power through the expansion process) and the air-standard assumption (Heywood (2006)).

Reciprocating mechanism

The reciprocating engine has received more recognition throughout history due to its wide variety of applications and simple working mechanics (Bahrami (2015), Safe, et al., (2014), and Shaila et al., (2018)). The general internal combustion engine (ICE) consists of four thermodynamic processes with variations to the process for different types of cyclic theory used. Each process is done under the reciprocating motion of a piston within a cylinder or a chamber. Hence, it is understandable that the piston and chamber motion is one of the most important parts of the ICE to achieve maximum possible efficiency (Fernando (1996)). Figure 3 shows the arrangement of the piston and cylinder.

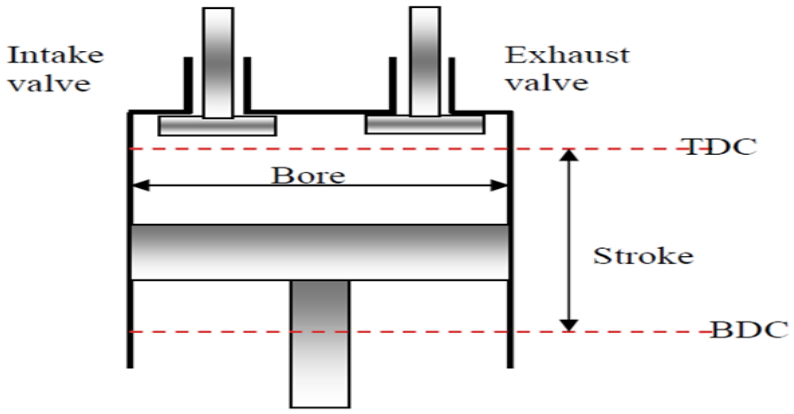

Figure 3: Piston & Cylinder

Top dead center (TDC): The position of the piston is farthest from the crankshaft or the formation of the volume of the internal chamber is the smallest.

Bottom dead center (BDC): The position of the piston is the closest to the crankshaft or the position of the piston where the internal volume forms in the chamber are the largest.

Stroke: Distance between TDC and BDC

Bore: Diameter of the inner cylinder/ piston diameter

Clearance volume: The volume when the piston is at TDC

Displacement volume: Volume covered by stroke distance

Compression ratio: Ratio of largest volume to smallest volume, VBDC/VTDC

Mean effective pressure: Pressure value which will produce work when acted on the piston.

Air standard assumption

The four main points of air standard assumptions are (Bahrami (2015)):

1. Air (ideal gas) is the working medium and is in a closed-loop cycle
2. All processes in ideal power cycle are internally reversible
3. The heat-addition process from an external source is assumed to be the combustion process
4. Heat rejection process is replacing with air removal where fresh air during air intake becomes the initial state of the working gas in the cycle

Types of Combustion Engines

The two most well-known types of ICE will be discussed in the following subsections.

Otto engine

The first type of an internal combustion engine is the spark-ignited engine which is based on the Otto cycle. Otto Engines are the basis for most of the modern petrol car engine (spark-ignited engine or SI engine) today (Heywood (2006)). The working principle of Otto engines is the Otto cycle which was developed by Nicolaus Otto in 1876. Otto cycle worked around the Carnot cycle impracticalities which utilize high pressure and high volume ratio to relatively low effective pressure by proposing constant volume processes during heat addition and heat rejection (Bahrami (2015)).

Schematic of an Ideal Otto cycle is as the following:

1→2 Isentropic compression

Air is compressed from the bottom dead center (BDC) to the top dead center (TDC) inside the cylinder by the piston. Work is done onto the air (negative work).

2→3 Constant volume (isochoric) heat addition

Heat supplied to the compressed air. In the actual Otto engine, the heat is provided through the combustion of a fuel-air mixture with the help of a spark-ignition.

3→4 Isentropic expansion

The expansion of the air inside the cylinder occurs following gas law. The piston moves from TDC to BDC.

4→1 Constant volume (isochoric) heat rejection

Removal of heat from the air results in lower internal pressure as well as temperature. This state is the same as state 1 (pressure-wise and temperature-wise). The cycle is complete and ready to start anew. In the actual engine, the air is removed from the engine back into the atmosphere through the exhaust. The cycle is considered complete because air for the compression is taken from the atmosphere. It is considered to be a cycle if the inclusion of the atmosphere is considered. Figure 4 shows the ideal Otto Cycle (Bahrami (2015)).

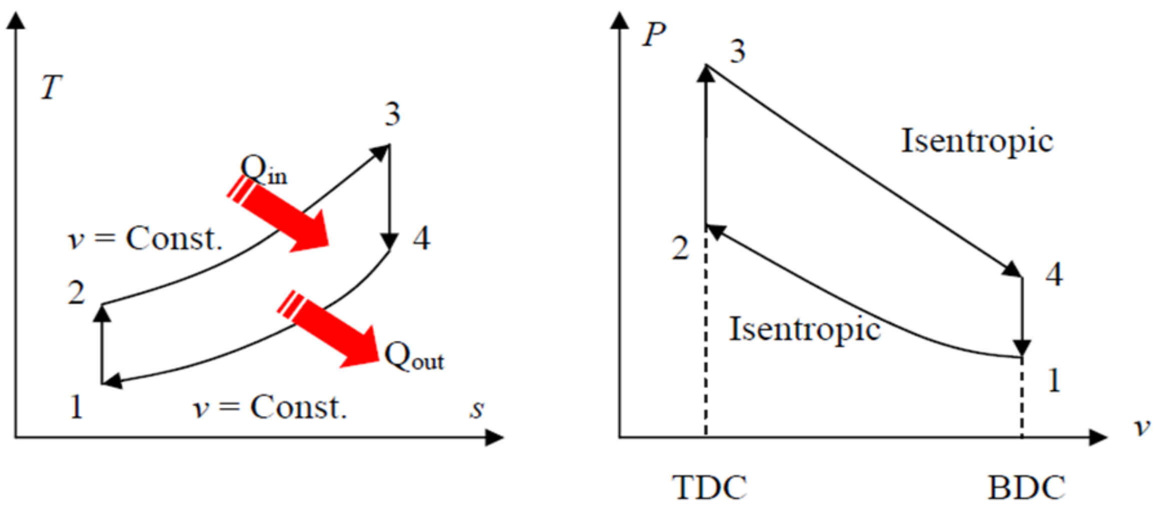

Figure 4: T-s &P-v diagram of Ideal Otto cycle

The efficiency of the Otto cycle (Çengel and Boles (2002)) is given as:

$$Efficiency_{Otto} = 1 - \frac{1}{r^{(\gamma-1)}} \quad \text{........(3)}$$

Where 'r' is the compression ratio and the 'γ' is the specific heat ratio.

It can be concluded that the efficiency of the Otto cycle is dependent on the compression ratio used and the type of air (air with higher specific heat capacity is more efficient) used in the engine (Ganesan (1996)). Since the type of air used is difficult to change, due to combustion factors and the availability as well as the effect of exhaustion into the atmosphere, natural atmospheric air is used. That leaves the compression ratio as the only component that affects the efficiency of the ideal Otto cycle. Increasing the maximum efficiency of the Otto cycle indirectly increases the maximum efficiency of the actual cycle (Sheikh et al., (2017), and Kashem et al., (2018)).

For actual SI engines, the air is taken from an external source and exhausted back into the atmosphere. The actual spark-ignition engine cycle includes the air intake and expulsion of air from the engine (Winterbone and Turan (2015)).

Several operating conditions affect the performance of a SI engine aside from the usually fluid friction and the heat loss to the surrounding atmosphere. One of them is the spark timing of the engine. If the spark is initiated too soon, before the piston reaches the TDC, the amount of work done by the piston displacement will be less (Heywood (2006)). The same thing happens when the spark timing lags (Heywood (2006)). Besides that, fuel to air mixture may not be as exactly stoichiometric (1:1 ratio of fuel to air) (Heywood (2006)). Figure 5 below shows the actual operations of an Otto engine cycle (Fernando (1996)).

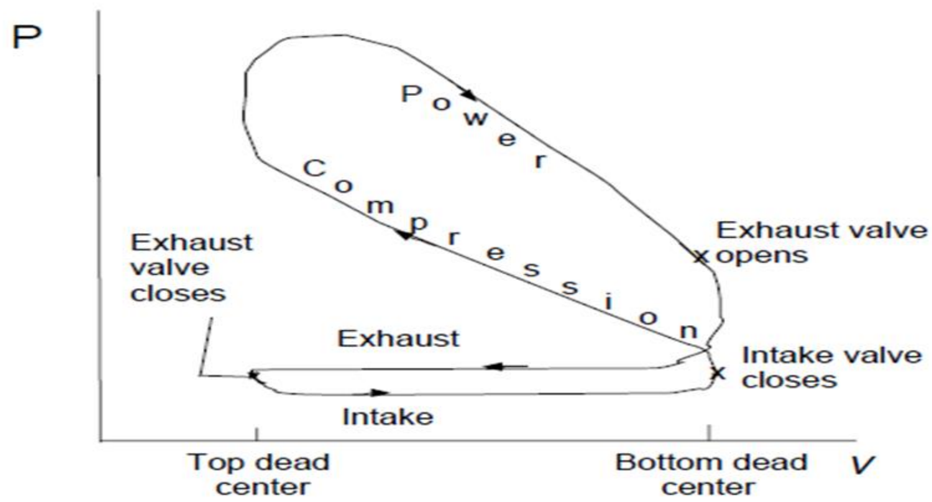

Figure 5: Actual Otto engine Cycle (Includes air intake and air removal)

Diesel Engine

Another type of internal combustion engine is the diesel engine which runs according to the diesel cycle. Diesel cycle was discovered and theorized in 1892 by Rudolf Diesel who was determined to increase efficiency. His four principles to achieve a much higher efficiency was turning away from steam engines, using air as the working medium, combustion must take place inside the cylinder and using high compression to allow maximum expansion (Chowdhury et al., (2019), Hong et al., (2018) and Kashem et al., (2016)). The combustion mechanism was adapted from the fire piston, which uses compression to ignite tinder which was attached to the end of the piston (Shell (1952)). During the first testing of a working diesel engine in 1894, invented by Rudolf Diesel based on Herbert Akroyd Stuart engine, the efficiency was about 27% which was the highest efficiency of the time among other engines such as steam engine and gasoline engine (Shell (1952)). By 1912 the first diesel-powered ship was built (Shell (1952)).

The diesel cycle operates similarly to the Otto cycle whereby they have four internally reversible processes. The difference between them is that the heat addition process is carried out within constant pressure (isobaric) (Fernando (1996)). This is due to the difference in the method of fuel ignition. The four processes are:

1→2 Isobaric heat addition

For the actual engine, the fuel is induced to the high pressure and temperature of the compressed gas which results in self-combustion of the fuel without the use of spark ignition. The fuel injection system is required to bypass the high pressure in the combustion chamber.

2→3 Isentropic expansion

The expansion of the volume inside the cylinder occurs by displacement of the piston from TDC to BDC.

3→4 Isochoric (constant volume) heat rejection

Heat rejection is done by expelling the working gas out from the engine along with the heat energy through the exhaust pipe.

4→1 Isentropic compression before the compression, fresh air taken from the atmosphere after the gas expulsion by expansion (this expansion has zero work). The cycle is complete is ready for the next cycle. Figure 6 shows the basic Ideal Diesel Cycle (Bahrami (2015)).

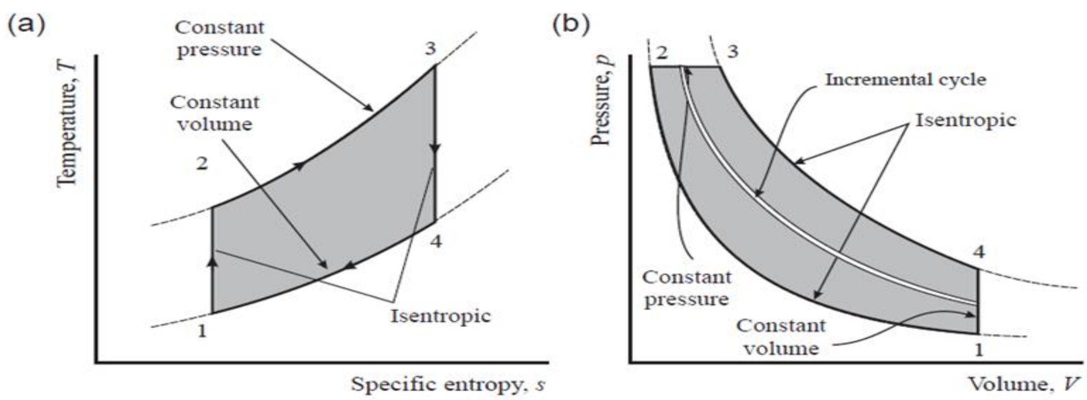

Figure 6: T-s &P-v diagram of Ideal Diesel cycle

The efficiency of the Diesel cycle is written as:

$$Efficiency_{Diesel} = 1 - \frac{1}{r^k}\left[\frac{r_c^k - 1}{k(r_c - 1)}\right] \quad (4)$$

Where:

r = compression ratio

r_c = cut-off ratio

k = specific heat ratio (Cp / Cv)

From simple observation, the diesel efficiency is almost the same as the Otto cycle if not for the cut-off ratio. As proof, for the Otto cycle, the value k is equal to 1 and the whole equation becomes the Otto cycle (Shell (1952)). This is because the specific heat value for air is not the same for constant volume and constant pressure (Çengel and Boles (2002)).

Comparison

A comparison between the two types of Internal Combustion Engine (ICE) and External Combustion and Internal Combustion Engine is discussed in the following subsection.

Comparison between Compression-ignited (CI) engine and Spark-ignited (SI) engine

As mention before, the main difference between these two engines is the source of ignition or how the ignition of fuel was made (Prasad (1993)). For spark-ignition (SI) engines, the fuel and air mixture is ignited from the small spark created by the spark plug at high pressure. However, the high pressure is only used for the expansion requirement (work output increases with a higher compression ratio) and not for the self-ignition. Different ignition methods lead to different designs of the combustion chambers. Spark-ignited engines have to accommodate a spark plug which creates the spark needed for combustion. As for compression-ignited engines, the fuel injection system may not have sufficient pressure to enter the chamber thus a better fuel injection system that can overcome the much higher pressure as compared to the Spark-ignited engines (Kashem et al., (2017)).

Besides that, for the spark-ignition engine, the amount of fuel and air must be the same or the ratio of fuel to air is 1:1 (Fernando (1996)). For this, the amount of air intake must also be regulated by the SI engine. This adds up more to the complexity of the engine design.

The efficiency of the systems also differs due to the process of combustion. This is because specific heat at constant volume, Cv, is always lower than Cp (Çengel, 2002). Hence, the k value is always more than 1 which increases the value of the denominator, thus lower the efficiency value according to the formula described by Khandakar et al., (2019), and Kho et al., (2017) stated that. This means that at the same compression ratio, the Otto cycle will have higher efficiency compared to the diesel cycle. Hence, spark-ignited engines will have higher efficiency compared to the compression-ignited engine if and only if the compression ratio is the same and the other parameters that affect the efficiency are the same (Bahrami (2015)).

Even though the spark-ignited engine has the advantage of having a higher efficiency at the same compression ratio, the compression ratio for the SI engine is limited because of the possibility of self-ignition of the engine. If the compression ratio is too high, engine knocking may occur which may harm the piston component of the engine and the overall engine itself. The compression-ignited engine does not have this problem because only air is compressed and not the fuel thus the compression ratio limitation is much higher than the SI engine (Kashem et al., (2018), and Ahmed et al., (2019)).

The type of fuel used is also different for each engine. CI engines generally use a higher octane fuel or fuel which is less volatile and the self-ignition temperature is relatively low such as diesel fuel. SI engines are the exact opposite as it uses highly volatile fuels and with high self-ignition temperature such as gasoline (Ganesan (1996) and Touti et al., (2020)).

SI engines are generally lighter due to the relatively low peak pressure due to the amount of component needed for the same material is fewer than CI engines. The speed of the SI engine is also higher than CI engines (Ganesan (1996)).

The table below shows the comparison and differences between the two types of the engine which was derived from multiple sources.

	Otto Engine	Diesel
Combustion Method	Require a spark to reach ignition temperature	Highly compressed air is hot enough to promote self-ignition
Efficiency	SI > CI for same compression ratio	
Compression Ratio	CI > SI as 'engine knocking' does not occur in CI engines	
Fuels used Weight	Uses volatile and high ignition temperature fuel. Lighter	Uses low volatile and low Ignition temperature fuel Heavier

Table 1: Comparison between the Otto engine and Diesel engine

Comparison between Steam Engine and Internal Combustion Engines

The fundamental difference between a steam engine and an SI-engine or a CI engine is that the steam engine is an external combustion heat engine while the SI engine and CI engine are internal combustion engines. An external combustion engine has a more flexible choice of heating fuels as compared to the internal combustion engine. Since combustion needs to happen inside the confines of the combustion chamber/ piston cylinder, the fuel used must be liquefied or in a gaseous state. Hence coal-powered internal combustion engines were impossible (Scully (2002) and Tay et al., (2017)).

Steam engine efficiency is harder to maximize compare to internal engines that use gas as the working medium as the fluid flow friction is within the walls of the engine is much higher than airflow. Besides, the formation of water droplets within the engine pipes aside from the condensers further reduces the performance of the steam engine Chowdhury et al., (2018), and Ahmed et al., (2017). Despite the low efficiency, the steam engine itself operates quietly and less vibration compares to internal combustion engines. This is most likely caused by the ignition process for the internal combustion engine where the vibration of the fuel combustion (explosion) is transmitted throughout the engine (Riley (1999), Monros (2015), and Matsuda (2015)).

The lifespan of a steam engine is generally longer than ICE engines because of the rigid build and the quieter operation. It is easier to find a steam engine operating for one hundred years than an IC engine that lasts more than 20 years.

Although the efficiencies of the engine may vary due to many variables such as size and power requirement, there were average assumptions made. The graph in Figure 7 below depicts the efficiency of the engine that was derived from the education video titled 'A Diesel Story' (Shell (1952)).

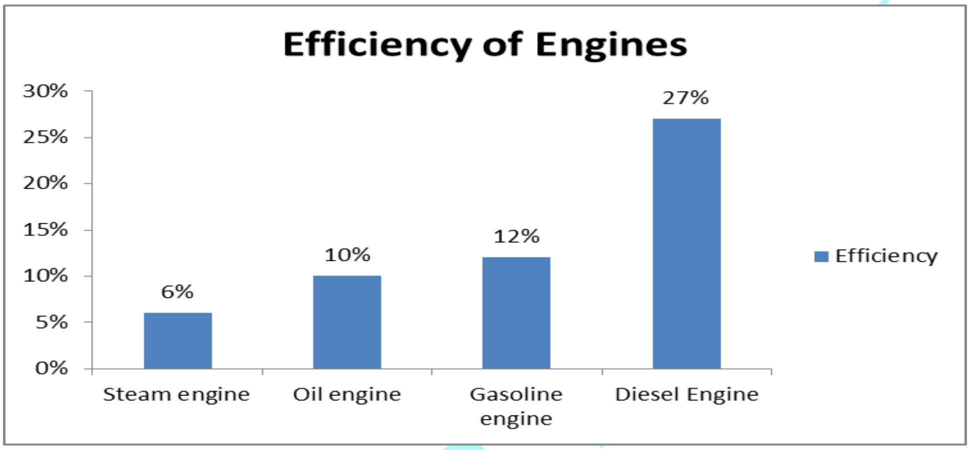

Figure 7: Average Efficiencies of Engines

Conclusion

In this research, the different types of engines and their working principle have been reviewed. Comparison has been done on the two different types of Internal Combustion Engine. The comparison between external and internal combustion engine was also made. Results show the diesel engine has the highest efficiency of its time which was 27%.

Although the engine efficiency was relatively low back when they were first discovered and tested, there have been significant improvements to the engines throughout history. For example, the steam-powered device invented by Thomas Newcomen was extremely inefficient and the efficiency was raise through the insight of James Watt incorporating a separate condenser to the steam device, effectively raising the efficiency of the machine. Sometimes the requirement for power generating devices depends on the specifications of its application. For example, although the Sterling engine has a much higher efficiency compare to the steam engine, the applications were limited due to the lack of power it produces. History has also proven that technological advancement is driven by the needs and demands of economic and social growth.

Cyclic theories are made based on several assumptions that are usually impractical in actual application. However, it is still important to learn the cycles as they represent to maximum possible efficiency of an engine. This is because it serves as the baseline to study the problems encountered by actual engines and finding alternatives to overcome the shortcomings of the engine.

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