Research Progress of Two-Stroke Internal Combustion Engines

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Abstract. In a world that is gradually moving towards renewable sources of energy, the 2-stroke motor with it is low efficiency and high emission is being phased out. However, there are some applications which require the unique characteristics of the 2-stroke motor, making it the only suitable form of power for those applications. This paper will discuss the operating principle of the 2-stroke motor, how its construction is able to be simplistic and light, and how it has a high power-to-weight ratio. This paper will also discuss the relatively inefficient scavenging process caused by the simplistic nature of the 2-stroke engine, leading to high emission, low efficiency, short engine life, and noise. To solve these problems, mechanical solutions such as electronically controlled direct injection, delayed charging, and variable compression have been developed and are now common, while recent research into the use of bioethanol and hydrogen as fuel can further decrease emissions and increase efficiency. Therefore, the purpose of this paper is to summarize past and recent research regarding the strengths and limitations of 2-stroke internal combustion engines and the future developmental direction of 2-stroke engines in alternative fuel.

Keywords: 2-stroke, internal combustion engines, fuel short circuiting, bioethanol fuel, hydrogen fuel.

1. Introduction

From the steam engines that powered the First Industrial Revolution, to the 4-cylinder gasoline engine found in the Ford Model T that defined the Second Industrial Revolution, to the piston engine that powers automobiles and power generators in the modern world internal combustion piston engines have played a crucial role in the development of the modern world. One common type of internal combustion piston engine is the two-stroke engine, which exists alongside 4-stroke, 5-stroke and 6-stroke engines. In the modern world, development of propulsion systems and power-generating machinery are making strides towards developing systems which decrease the greenhouse gas output of the power generation process set in place by the increasingly stringent emission standards such as the Euro 1 and Euro 2 in the European Union [1] and carbon neutralization goals set by many counties around the world. Technology such as hybrid-power systems, electric motors, and hydrogen fuel cells have developed at a rapid rate and is replacing many conventional internal combustion engines in many applications. However, the 2-stoke internal combustion engine still is irreplaceable in applications that require a low-cost, lightweight, and high-power density power generator, such as motorbikes, marine outboard engines, or power tools such as chainsaws or lawnmowers.

The two-stroke motor operates by using a piston and crank system to complete the internal combustion process in two strokes of piston movement to convert chemical potential energy to kinetic energy in the form of the rotation of the crankshaft.

This paper will first introduce the operating principle of the two-stroke engine, then explore the strength and limitations of the two-stroke engine, and based on the strength, it will provide an overview of the current applications of the two-stroke engine. After that past improvements of 2-stroke engines will be discussed, followed by future developments and further improvement in the 2-stroke engine.

2. Operating Principle

2-stroke engines refer to internal combustion engines that use two strokes, to complete the 4 phases of internal combustion which are intake, compression, combustion, and exhaust phase. Each stroke is one up or down motion of the piston and half a rotation (180°) of the camshaft, with the first phase completing the compression and ignition phase, and the second phase completing the exhausts and intake phase. The second phase is also the phase where scavenging is completed, where the exhaust gases are expelled and replaced with fresh air.

In the compression phase during the upstroke of the combustion cycle, the intake port is no longer blocked by the cylinder, meaning a fuel-air mixture created by the carburetor is allowed to enter the space in the crankcase. Once combustion occurs created by the spark plug, in the combustion chamber, the piston is moved down by the increase in pressure created by the combustion. This movement is converted to a rotation motion of the crankshaft of the crankshaft by the connecting rod. At this time, the exhaust port opens, allowing the exhaust to flow out; at the same time, the transfer port opens, allowing the fuel-air mixture previously in the crankcase to travel into the combustion chamber. This is also the scavenging phase. However, since the transfer port and the exhaust port are open at the same time during the downstroke, this means some of the unburnt fuel-air mixture will flow directly out of the exhaust port before the piston closes the exhaust port during the upstroke [2]. With the momentum of the flywheel which is attached to the crankshaft, the piston begins the upstroke and the cycle repeats.

3. Strength of a 2-Stroke Engine

3.1. Simplicity

The 2-stroke engine is the simplest form of widely adopted gasoline engine in the world right now, this is because, unlike the 4-stroke engine, many parts on the 2-stroke engine are able to complete more than one task. For example, the piston of the 2-stroke engine acts as a valve both on the upstroke and downstroke of the piston movement, by blocking the intake port and exhaust port respectively, which is contrary to a 4-stroke engine where there needs to be at least 2 valves, one covering the exhaust port and the other covering the intake port. There would also need to be shafts, linkages, and rocker arms connected to the camshaft to control the timing of the valves on a 4-stroke engine to ensure the valves open and close at the appropriate time to ensure a continuous combustion cycle, this would add significant complexity and cost to the manufacturing of the engine. Furthermore, a 2-stroke engine does not need dedicated systems for lubrication, unlike a 4-stroke engine which would either require an oil sump or an oil pump system since the oil is either directly injected into the engine where it will mix with the fuel or be mixed with the fuel when putting in a fuel tank, further increasing the simplicity and decreasing the manufacturing complexity and cost [2]. As a result of the above, in most cases, a 2-stroke engine is lighter, smaller, and cheaper to produce than a 4-stroke engine of the same power output.

3.2. Power Output

The power output of a 2-stroke engine is much higher than of that a 4-stroke engine of the same displacement in an ideal situation especially at lower rpm (rotations per minute). This is because 2-stroke engines have 1 combustion every 2 strokes, while a 4-stroke engine has 1 combustion every 4 strokes. The stroke with the combustion can also be known as the power stroke, meaning that the movement of the camshaft is completely unpowered ¾ of the time while the movement of the camshaft is only unpowered ½ of the time in a 2-stroke engine. Since the equation for power is $P = \frac{W}{\Delta t}$ and the equation for work is $W = Fs$, the work that is being done is twice of that a 2-stroke engine, which results in twice the power output. Although this not the exact same as it is in real life, where engine temperature and speed is a significant factor, this difference is still significant [3]. This increase in power stroke frequency is also the reason why 2-stroke engines have a much faster engine response time compared to other types of gasoline engines.

4. Application of 2-Stroke Motors

As a result of the 2-stoke motor being light, cheap, and small while still having much higher power output than its 4-stroke counterpart, these characteristics mean the 2-stroke motor can be commonly found in applications where the engine needs to fit into a small space while still producing a large amount of power, such as small marine outboard motors, scooters, off-road motorcycles, ultralight aircraft, and handheld power tools such as lawnmowers, weed trimmers, and chainsaws, or larger marine diesel engines [4].

5. Limitations of a 2-Stroke Engine

5.1. Poor Fuel Efficiency

The cause of the poor fuel consumption of a 2-stroke engine is a result of it not having a separate stroke for scavenging and one for the exhaust of waste gases. Therefore, during the downstroke of the combustion cycle, when the exhaust port opens, the transfer port also opens to allow scavenging to occur by allowing new fuel and air to enter the combustion chamber. However, since the transfer port and the exhaust port are open at the same time this allows a portion of unburnt fuel to escape before the exhaust port closes. This issue is also known as fuel short circuiting [5]. The fuel loss because of this can be as high as 50%. There are three main types of scavenging models, i.e., loop scavenging, uniflow scavenging, and cross scavenging. It can be seen from Figure 1 that all three scavenging systems have a high fuel loss. The effectiveness of the scavenging process can be found by comparing the charging efficiency η_C and the delivery ratio λs which is defined as $\eta_C = \frac{m_{fC}}{m_0}$ and $\lambda_S = \frac{m_i}{m_0}$, where :$m_i$ is the mass of the delivered charge, m_0 is the displaced volume × ambient density and m_{fC} is the mass of delivered charge retained [5]. This means that the higher the deliver ratio and the lower the charging efficiency are, the greater the fuel loss will be.

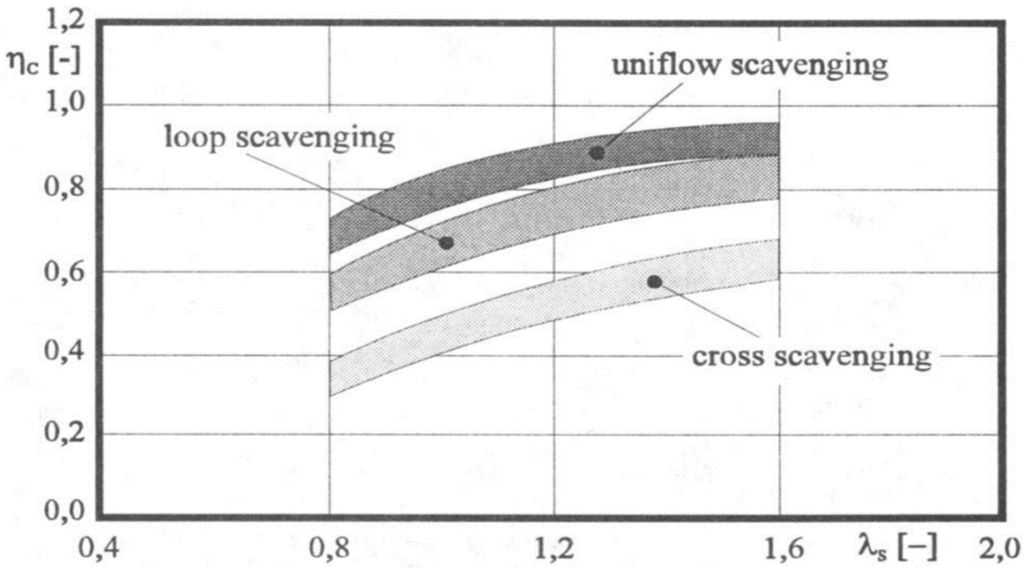


Fig. 1 Comparing the effectiveness of three different types of scavenging systems [5]

5.2. Emissions

There are two types of emissions that can be emitted from a 2-stroke engine, i.e., particulate matter (PM) and gaseous emissions such as CO, NO_x, and CO_2. High PM levels in the atmosphere are known to have negative effects on human health, HC, and $CO$are toxic while $CO_2$and NO_x are both greenhouse gases. In most 2-stroke engines, HC makes up the majority of the PM emissions, at above 90% [1], which is due to the fuel circuiting issue mentioned earlier, and the fact that the lubricant is mixed with the fuel, this allows some of the lubricant and fuel to escape unburnt, creating unburnt HCin the form of particulates of unburned lubricant. As can be seen from Figure 2, the PM emission from 2-stroke engines is significantly higher than their 4-stroke counterparts for this reason. This is also the primary reason why 2-stroke emissions are so much higher than 4-stroke engines since the CO, and CO_2 are similar in 2-stoke and 4-strokes while 2-stoke engines is known to have low levels of NO_x emissions [1].

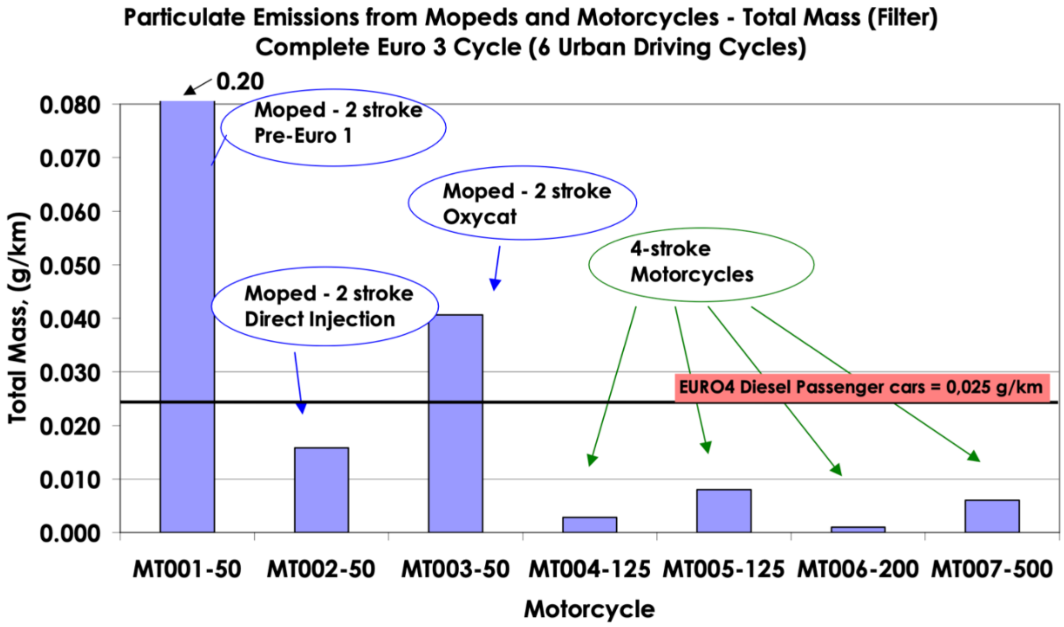


Fig. 2 Comparing the PM emission of different types of 2-stroke engines against different types of 4-stroke engines [1].

5.3. Irregular Combustion

Also known as misfire cycles, it refers to when the combustion phase fails to occur in an engine, the cause for this is again the result of short-circuited gas during the scavenging process. Research has shown that irregular combustion occurs with several cycles of successful combustion followed by a misfire, this cycle repeats. Irregular combustion occurs because during the short circuiting of gas, some fresh charge composed of fresh air and fuel can escape without burning [6], the engine's ability to retain the fresh charge is known as trapping efficacy and is represented as ηtr_1 in fig 3. However, since both the transfer port and the exhaust port are open at the same time during the downstroke, burnt gases can also fail to be fully exhausted and remain in the combustion chamber. Over several engine cycles, this can result in the build-up of burnt gas in the combustion chamber, which will result in a misfire, since no new exhaust gases are produced during a misfire, no new exhaust gas will be created, meaning the weight of exhaust gas will decrease in the following cycle, allowing combustion to occur once again. Irregular combustion is known to cause high levels of vibration and noise [6], which can lead to shorter engine life.

Fig 3 has been simplified where there is one misfire every 2 cycles but in reality, it's usually one misfire in serval cycle.

In fig 3,
Gn = Weight of fresh charge in the cylinder
Go = Weight of fresh charge in one cycle
Gr = Weight of burnt gas in the cylinder before combustion
Gr" = Weight of burnt gas in the cylinder after combustion

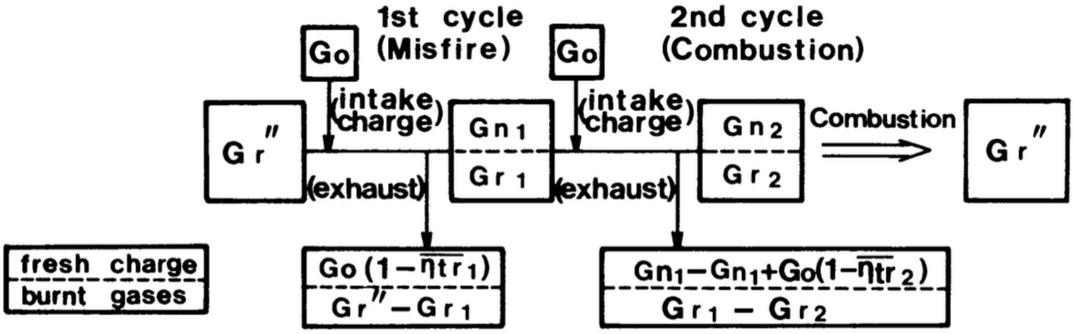


Fig. 3 Model of the irregular combustion cycle in a 2-stroke engine [6]

6. Sustainable Development of the 2-Stroke Engine

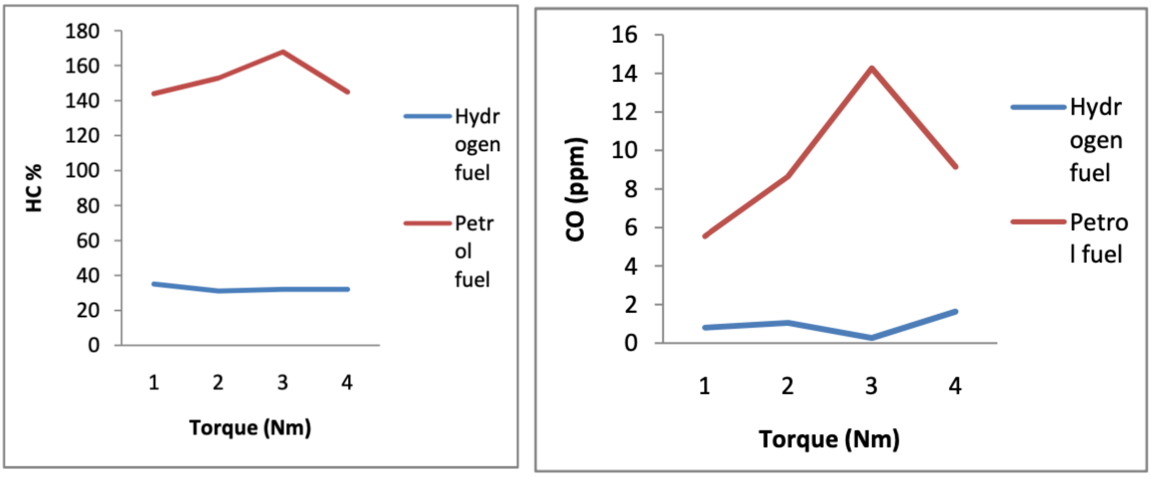
Many of the drawbacks have been improved in modern 2-stroke engines with technology such as adjusting charging timing to decrease the amount of short, circuited gas [7], electronically controlled direct injection, and variable compression ratio to maximize the fuel efficiency of 2-stroke engines [8,9] and to meet the increasingly stringent emission regulation. However, there is still room for improvement. The following subsections will discuss the recent sustainable developments of 2-stroke engine technology.

6.1. Bioethanol Fuel

The use of bioethanol as fuel for 2-stroke engines promises less toxic emission since bioethanol can burn cleaner. It has been shown that a 2-stroke generator running on bioethanol can produce up to 61% less hydrocarbon and 6% less CO_2 which as mentioned earlier is toxic and carcinogenic for the human body. There is also a lower level of soot build-up compared to gasoline. Soot is a sign of the HC left over from fuel short circuiting. Therefore, a low level of soot indicates the engine runs more smoothly and is less likely to misfire. However, since ethanol and oil do not mix well, research shows only certain types of 2-stroke oil can work well with bioethanol and the ratio between the two also must be controlled at 1/50. Other bioethanol-based fuels have also been developed for harsh environments such as isobutanol-extended fuel for marine outboard engines [10,11].

6.2. Hydrogen Fuel

The use of gaseous hydrogen fuel for 2 stroke engines has been achieved without much modification to the engine itself, and the results are very promising. Unlike petroleum, hydrogen is one of the most abundant elements on earth, also unlike petroleum, hydrogen combustion can be very clean and in an ideal world, would not contribute to the carbon, and PM emissions of the world. The use of hydrogen as fuel can also make the engine more efficient, since the combustion of hydrogen itself does not produce any HC. It means there would be very little soot build-up in the engine unlike when running on gasoline, allowing the engine to run smoother, more efficiently, and potentially have a longer engine life [12]. In a test conducted in 2015, a 2-stroke running on hydrogen was recorded to have a higher thermal and mechanical efficiency than running on gasoline, the CO, HC both being significantly lower than running on gasoline at being close to zero, with the NO_x emission being 10 times less than running on gasoline (Figure 4) [12]. The second reason why the use of hydrogen can be much more fuel efficient than petrol fuel is the low minimum ignition energy required for combustion, at 0.02 mJ at 1 bar, compared to 0.24 mJ of gasoline or diesel fuel, allowing for faster flame propagation, more complete combustion, and less chance of a misfire [13]. The third reason is that hydrogen has a gravimetric energy density at a heating value (MJ/kg) of 119.9 MJ/kg, compared to 43.9 MJ/kg of gasoline and 42.5 MJ/kg of diesel fuel. Since hydrogen itself has a low volumetric energy density, to achieve the high volumetric energy density, it is required for the hydrogen to be stored compressed, and at a low temperature [13].



(a) (b)

Fig. 4 Emission characteristics of hydrogen-fuelled 2-stroke engines (a) HC emission against torque; (b) CO emission against torque [12]

Although many existing 2-stroke engines and 4-stroke engines are able to be modified to run on hydrogen, the use of hydrogen fuel engines has presented many challenges. For example, due to the low ignition temperature, fuel mixture in the combustion chamber has been known to prematurely ignition, causing a backfire, or leaks of the fuel injector caused by the poor lubricating properties of hydrogen and the heat generated by friction, all of which can result in backfires [13].

7. Conclusion

In conclusion, the two-stroke motor has the characteristics of having a simplistic structure, thus reducing the components needed to have each stroke complete a dedicated function and having a higher power-to-weight ratio than 4-stroke motors. This allows the 2-stroke motors to be suitable for applications where a small, cheap, and powerful engine is required. The two-stroke motor also has several limitations because of its operating principle. First is the poor fuel efficiency, second is the high emissions and third is the irregular combustion, leading to high levels of noise, vibration, and decreased engine life. As a result of these limitations, mature mechanical and electronic solutions have developed over the past 30 years. And new fuel-directed solutions which promise to further lower the emission of the 2-stroke motor such as the use of bioethanol fuel and hydrogen fuel, are being researched and will be the area of research in the future. This research has been a summary of all the major advantages and disadvantages of 2-stroke motors and a summary of the past and recent developments of the 2-stroke engine. Currently with more and more internal combustion engines being replaced by electric motors and batteries, the lowcost, simplistic, and power-dense nature of 2-stroke engines is unique. Therefore, future research in the field of hydrogen and biofuel can help maximise the advantages while minimising the limitation of the 2-stroke engine.

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