DESIGN, MANUFACTURABILITY, AND SUSTAINABILITY ANALYSIS OF AN HCCI COMBUSTION ENGINE UTILIZING GASOLINE AND RENEWABLE FUELS

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Abstract: The global quest for new forms of energy is constantly growing. Extensive research is conducted to test and analyze new blends of fuels to meet these requirements. Due to the concern about the continued availability of fossil fuels, such as crude oil and natural gas, it has become a worldwide quest to face these challenges with renewable forms of fuels and new approaches to internal combustion (IC) engine designs. The IC engine has established a robust utility in various sectors, such as transportation, agriculture, aerospace, defense, and other small power plants, to name a few. However, not all conventional IC engines have the capability to operate on multiple types of fuels. Blended fuels have proven to have slight lower power outputs with increased CO and CO2 emissions; however, yielding a lower fuel consumption is also a factor. In order to eliminate some of the major fuel issues, we have designed, developed and manufactured homologous charge compression ignition (HCCI) engine system. The benefit of this successful HCCI engine is that it can operate without a spark plug or direct injection while operating on regular gasoline. To prove this, various experiments have been conducted with different engine designs and fuels. This paper will explore the superiority of the HCCI engines over the traditional spark ignition, direct ingestion, and compression engines. These HCCI engines have successfully passed testing on different fuels such as gasoline, rubbing alcohol, and blended E10 gasoline. Because of the high engine performance and efficient burning, low particulate emissions (micro and nanoparticles) are expected from these studies.

Key Words: *IC Engines, Alternative Fuels, HCCI Engines, Emissions.*

1. INTRODUCTION

1.1 General Background

Internal combustion engines are the most frequently utilized and widely deployed power- generation systems in use today. Gasoline engines, diesel engines, gas turbine engines, and rocket propulsion systems are examples of these IC Engine systems. In these engine designs, the reactants of combustion, the fuels and oxidizers, and combustion products serve as the working fluid (source of power). The propulsion energy is obtained from the heat released in the combustion process. The combustion process occurs within the closed engine system, which is a part of the thermodynamic cycle. In contrast to an external combustion engine, which uses a separate combustor to burn the fuel, internal combustion (IC) engine releases the chemical energy of the fuel inside the engine and uses it directly for mechanical work.

The CI engine was conceived and constructed during the early 18^{th} century. It had a significant influence on society and is regarded as one of the most important innovations of the 18^{th} century (Benson & Whitehouse, 2013) as it is considered to be the primary propulsion method for equipment manufacturers (OEMs) (Davani, 2019). Earlier attempts to design an IC engine by Christian Huygens, a Dutch physicist, in 1680 fueled by gun powder were regarded impractical (Benson & Whitehouse, 2013). Later in 1807, Isaac De Rivaz invented an IC engine that utilized a mixture of oxygen and hydrogen as a fuel to power his cart (Benson & Whitehouse, 2013).

Although the design was unsuccessful, it was used as a foundation by other scientists. The IC has served as the basis for the successful developments of a wide range of commercial systems. The most beneficial sector is the transportation industry, enabling the developments and improvements in aircraft, trucks, automobile, and train propelling systems. Since the 1800s, the reciprocating IC engine elements designs, such as the piston, block, crankshaft valves, and connecting rod, have remained constant (Benson & Whitehouse, 2013). The primary distinctions between a modern IC engine and one manufactured years ago are thermal efficiency and the levels of emissions.

The global quest for new forms of energy is constantly growing. The automotive industry is one of the leading industries in the emission of greater greenhouse gas (GHG) (Davani, 2019). Extensive research is conducted to test and analyze new blends of fuels and engine designs to reduce carbon emissions. Due to concern about the continued availability of fossil fuels, such as crude oil and natural gas, it has become a worldwide quest to face these challenges with renewable forms of fuels and new approaches to the IC engine designs.

1.2 Progress in Combustion Engines

Internal Combustion Engines: Many scientists have tried to develop and improve the IC engines. However, Jean Etienne Lenoir, in 1960, patented the first commercial IC engine (Forrest, 2019). During that time, the engine was made of only one cylinder and was characterized by overheating. Nevertheless, it powered the vehicle for 2 miles per hour. It was a massive step in the design since Lenoir proved that the IC engine could run continuously. By the year 1879, Nikolaus Otto created a more efficient four-stroke engine (Forrest, 2019). In the same year, Clerk Dugald developed a two-cycle IC engine ("Two-Stroke Cycle Diesel Engine," 2016). The IC engine has established a robust utility in various sectors, such as transportation, agriculture, aerospace, and other small power plants, to name a few. However, not all conventional IC engines have the capability to operate on multiple types of fuels. Blended fuels have proven lower power outputs as well slight increase in CO and CO_2 emissions; however, yielding a lower fuel consumption is also a factor. Clerk's design employed a separate cylinder that served as a pump to transfer the fuel-air mixture to the compression cylinder. Later in 1899, the design was simplified by John Day to a two-cycle engine that is widely used in today's automobile ("Two-Stroke Cycle Diesel Engine," 2016).

Several configurations have been developed to improve the IC engine performance, for instance, the V engine configuration. In this design, the pistons are arranged to appear like a "V" to reduce the overall length and weight as opposed to the straight arrangement. The V engine design was developed by Wilhelm Maybach and Gottlieb Daimler in 1888 (Johnson, 2014). The V engine designs include V4, V6, V8, V10, and V12. The number after V represents the number of cylinders. Inline engine configuration (straight) has all cylinders lighted in one row (Wilson, 1995). The design is characterized by simplicity (Johnson, 2014). However, the engine length can longer and bulky. In the flat design, the cylinders are located on the opposite sides of the crankshaft. The flat design was first used by Karl Benz in 1897. This has advantageous since it offers a shorter engine length and allows air cooling. Finally, in the radial design, the cylinders are arranged radially around the crankcase. This engine design is mainly used in aircraft and gas turbines.

Spark Ignition Engines**:** Spark ignition engines are also referred to as petrol or gasoline engines. These types of engines utilize the four-stroke Otto cycle (Breeze, 2018). The four stages are illustrated in Figure 1.

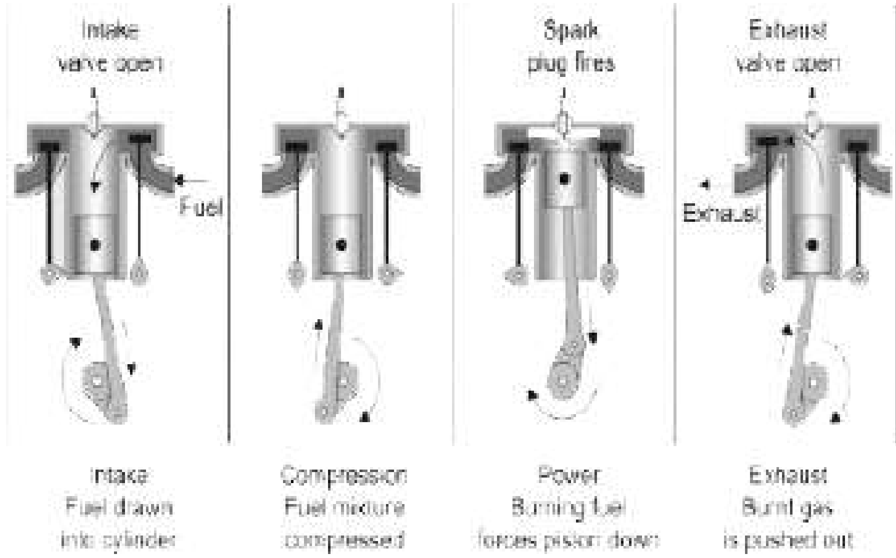

Figure 1 Four-stroke engine stages (Breeze, 2018)

According to Foster and Hermann (2003), the universal spark-ignition engine uses low flammability fuels that include liquified petroleum gas (LPG), gasoline, methanol, Liquified Natural Gas (LNG) and hydrogen (Naber & Johnson, 2014). The combustion process is initiated by the spark plug in these spark-ignition engines (Davani, 2019). These engines were an improvement from an earlier engine that utilized hot tube ignition. The hot tube was an invention of Gottlieb Daimler in 1884 to power his car (Merrygold, N.D.). Before starting a vehicle, two platinum tubes beside the engine were heated to red hot. The tube extended to the combustion chamber. During the compression stroke, the fuel mixture was pushed along the tube to the red- hot spot where the ignition takes place. Unfortunately, the ignition process was faced with inaccuracy which necessitated Bosch to develop the magneto, which became the source of power to the spark plug (Naber, & Johnson, 2014; Merrygold, N.D.).

The thermal efficiency of the spark-ignition engine is significantly dependent on the compression ratio (Davani, 2019). However, it considerably suffers engine knocks (spontaneous fuel ignition due to lower octane number). Fuel additives suppress the engine knock effect, such as lead, tetramethyl, tetraethyl, and many other compounds being researched (Bhatia, 2014). However, the elements like lead have been found to be harmful to the environment, making fuels with the additive quite impractical (Bhatia, 2014). The spark-ignition engine runs on a combination of air and atomized fuel generated by fuel injection into frequently used induction pipe, popular combustion chamber, or the classical carburetor (Foster and Hermann 2003). The ignition process, basically by an electric spark, is dictated by the correct quantity of oxygen and fuel (close to being stoichiometrically correct) (Foster and Hermann, 2003). For petrol fuel, a one kilogram of fuel will require 14.5 kilograms of air (λ=1). Since the fuel-air ratio is always kept near to stoichiometry under all conditions (pressure and temperature) within the combustion cylinder, output control can only be achieved by varying air density, accomplished mainly by intake air throttling (Foster and Hermann, 2003). Although the spark ignition engines run smoothly, they are limited to low efficiency at partial loading due to energy losses in air throttling (Auer, 1982). They are also disadvantaged by engine knocks, inaccurate fuel-air mixture ratio, location of spark plugs, and many other factors (Auer, 1982).

***Direct Injection Engines*:** Direct injection engines differed from the convention spark- ignition engines in how the fuel is delivered into the combustion chamber. The fuel is directly squirted into the combustion cylinder with the assistance of high precision management computer systems when the chamber is hottest. Bosch designed the direct injection concept in 1951 to increase the IC engine efficiency. The engine design was to allow reduced emissions and low fuel consumption. As Parker (2021) illustrates, the fuel-air mixture significantly determines the engine performance, emission levels, and fuel efficiency. The direct-injection engine uses a fuel-air mixture with a high amount of air compared to the fuel (lean mixture). The lean mixture constitutes 40 parts of air for every part of fuel (40:1), allowing a conservative combustion process.

According to Yi (2010), a direct injection engine operates efficiently in various modes. It uses a stratified air-fuel ratio at partial loads and lower speeds, whereas at full loads and higher speeds, it uses a 'homogeneous' ratio (Yi, 2010). As a result, the engine is characterized by reduced pumping losses, higher thermal efficiency due to high compression ratio, and lower heat losses through cylinder walls since the fuel is injected at lower temperatures. However, this type of IC engine has a high maintenance cost due to its complexity; it requires high-quality fuel, expensive design components, and problem diagnosis can be complex.

***Compression Ignition Engines*:** Breeze (2018) argues that the Compression Ignition (CI) engine is stronger and more efficient than ignition engines. The CI (or sometimes the diesel engines) uses a higher compression ratio than SI engines to heat and ignite the fuel-air mixture. According to Davani (2019), the CI engines depend on the combination of stratified charge (SI) and compression ratio to create ignition. Usually, the fuel used is diesel which much denser than gasoline. Only air and residual exhaust gases (EGR) are sucked into the combustion chamber in CI engines. The air mixture is compressed and fuel-injected when the compression stroke approaches TDC. The already heated air mixture causes the fuel to auto-ignite to produce power. Since the CI is based on autoignition, the run-on higher compression ratio ranges between 16 to 20 (Naber & Johnson, 2014).

2. EXPERIMENTAL PROCEDURE

In this study, to eliminate some of the major fuel, power and emission issues, we have designed, developed and manufactured a homogeneous charge compression ignition (HCCI) engine system. The HCCI incorporates the characteristics of both SI and CI to increase its capabilities and efficiency (Davani, 2019). The major advantages of both SI and CI engines are expected to be delivered by engines that operate unthrottled at modest loads with a homogeneous charge (Riley, 2018). Rather than employing an electrical spark for ignition, the HCCI engine design injects fuel during the intake stroke where the compression increases the fuel mixture's density and temperature until it spontaneously ignites (Riley, 2018). This compression combustion process produces a flameless, low-temperature auto-ignition that is fundamentally more efficient, with less fuel than in a typical SI engine. In addition, SI engines use air more efficiently than diesel engines under partial loads. Therefore, it is critical to harvest the benefits of gasoline engine performance with CI engine advantages to achieve enhanced fuel efficiency and specific power outputs over the load range. Working in a meager air-fuel ratio, the HCCI can provide light-load engine performance without throttling; an event referred to as lean combustion.

The Nautilus GEN 2 engine is designed based on the HCCI system and utilizes characteristics from a spark ignited engine as well as a compression ignition engine. The redesign in the piston and cylinder head make it possible to achieve homogeneous charge compression ignition. Prior to machining the redesignation and cylinder head, a laser 3D printer was used to manufacture the finalized parts. This cost-effective method served its purpose in mitigating errors that could have otherwise been overseen. Figure 2 shows the 3D printed Nautilus GEN 2 piston and cylinder head.

Figure 2 Laser 3D Printed Piston and Cylinder Head (Davani, 2019)

3. DESIGN, MANUFACTURING AND TESTING

Various experiments have been done around the world with different engine designs ranging from gasoline to diesel engines. According to Davani (2019), there are presently no HCCI engine prototypes on the market that has been produced. The notion of HCCI has the potential to revolutionize the notion of the IC engine and enable it to maintain its global appeal of low carbon emission (Davani, 2019), as shown in Figure 3.

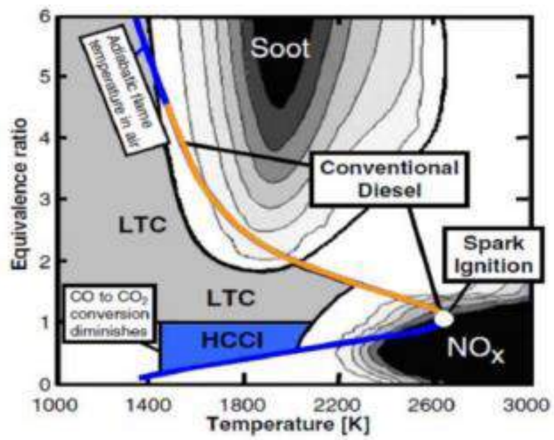

Figure 3 The link between temperature and air-fuel ratio and soot and NOx emissions in SI, LTC, and HCCI engines (Davani, 2019)

Nautilus team has taken a huge step in designing an HCCI engine (Nautilus Gen II) that can greatly harvest most power from the fuel through two power stroke stages (primary and secondary power stroke) while cutting down levels of emissions. The engine design is capable of operating on multiple fuels depending on the applicability. However, at this design stage, gasoline E-30 and E-80 are preferred due to their higher energy value and higher burning rate (Riley, 2018). In addition, the engine's piston design plays a bigger role in the improved power efficiency, as shown Figure 4.

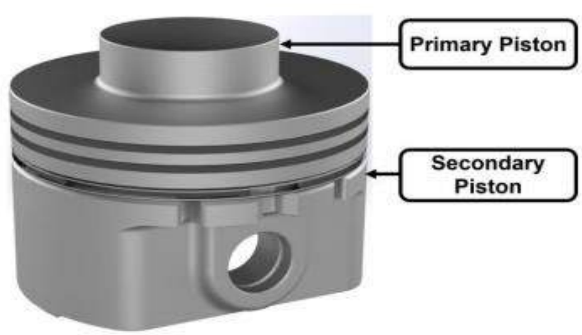

Figure 4 Nautilus GEN II piston design (Davani, 2019)

The piston is redesigned to allow multiphasic combustion, which involves primary force- controlled and secondary forced-controlled complete combustion (Davani, 2019). The piston material proposed is titanium due to its durability, lightweight, and resistance to corrosion at elevated temperatures. Also, the engine's cylinder head is configured to incorporate the piston, and the 2 staged power strokes. According to Davani (2019), the Nautilus GEN II engine's primary combustion chamber (PCC) is positioned dead center to the piston. The secondary combustion area in the cylinder head was redesigned for the improved dynamic flow of the premixed air-fuel mixture across the valves into the secondary combustion chamber (SCC), as shown Figure 5. In addition, the ability of the mixture to flow through the chamber is improved by increasing the capacity in the cylinder head (Davani, 2019).

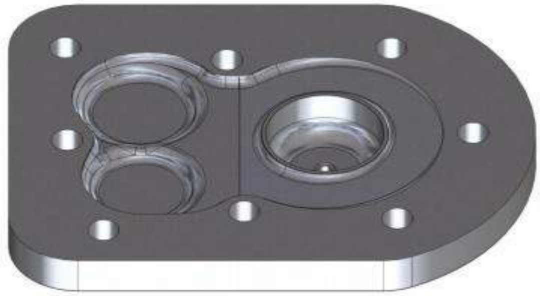

Figure 5 Nautilus GEN II cylinder head (Davani, 2019)

Aluminum is used to make the cylinder head. The primary combustion chamber of the cylinder head, on the other hand, accepts the installation of a cooper puck to improve thermal insulation for the main auto-ignition (Davani, 2019). As seen, the copper topping of the main combustion also houses a miniature Radio-Controlled (RC) glow plug (Davani, 2019). The glow plug assists in preheating the primary combustion chamber head for primary combustion to occur. Figure 6 displays the primary combustion chamber with cooper glow plug in the middle, while Figure 7 shows the cylinder head piston assembly of Nautilus GEN II engine (Davani, 2019).

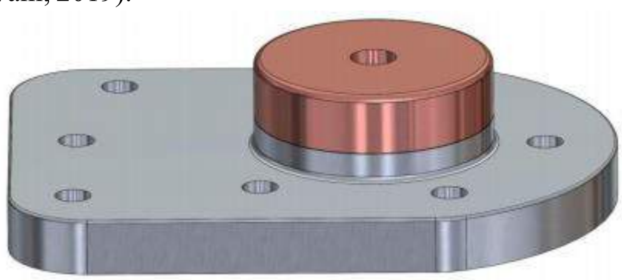

Figure 6 Primary combustion chamber with cooper glow plug in the middle. (Davani, 2019)

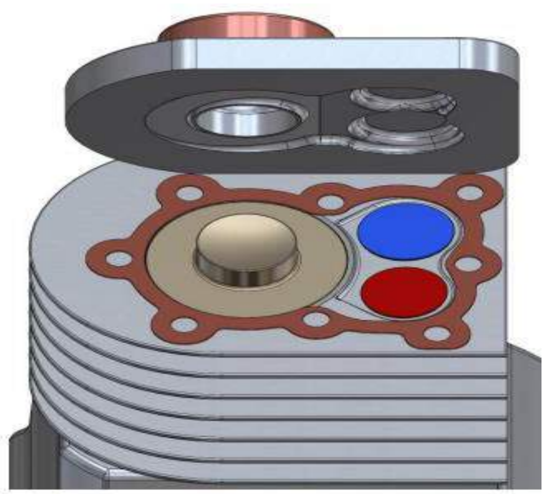

Figure 7 Cylinder head piston assembly of Nautilus GEN II engine. (Davani, 2019)

The Nautilus GEN III engine, which is being developed by Nautilus engineers, is a four- stroke, six-cycle dynamic multiphasic combustion engine III is designed for automotive applications since it can operate at a variety of loads and RPM ranges. With the inclusion of port injection and throttle body injection, it is now feasible to consume several fuels simultaneously. Figure 8 shows the Nautilus GEN III engine design for improved performance in terms of power, torque and gas and particulate emissions (Davani, 2019).

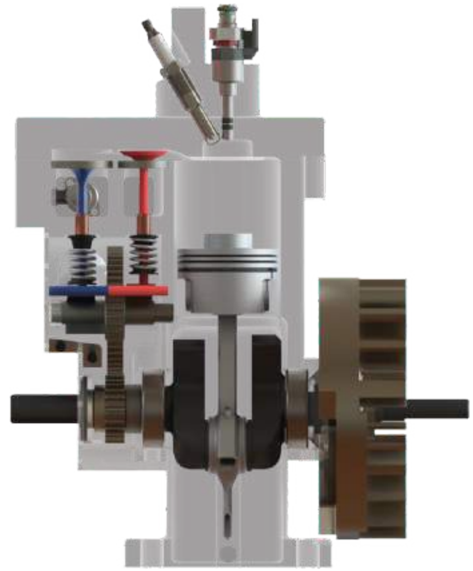

Figure 8 Nautilus GEN III engine design (Davani, 2019)

The new HCCI engine system was tested at Wichita State University for its capabilities. This system does not have a spark plug since the fuels of different kinds (rubbing alcohol, gasoline, and octanol) were preheated before injecting into the newly designed engine system. The test results showed that engine performance, rpm, power and torque of the HCCI system were considerably increased (20-40%) while the gas emissions (CO_2, CO, SO_2, NOx, and HC) were drastically reduced (approximately 10-20%). Owing to the high engine performance and efficient burning of the system, low particulate emissions (micro and nanoparticles) are expected from these studies.

As a comparison, some studies have been conducted on improving the CI engine to avoid wear and tear of moving parts using nanomaterial known as nanoflakes (NASA, 2020). This material has two sides, smooth and sticky sides. The sticky side is drawn to areas of friction in the moving parts, for instance, the cylinder bore. The sticky side adheres to them, leaving the smooth side facing out. This process is repeated over and over, building up layers of nanoparticles until a rough or worn-out spot is completely repaired, similar to filling in a roadway pothole (NASA, 2020). The technology has been tested over a range of temperatures, and the results are promising for the transport industry. The technology will further reduce the emissions and leakages produced by worn-out engine parts and improve the IC engine performance (Moradiya, 2019); however, the new HCCI engine system provided substantially higher engine performance. In the future, more experiments will be conducted in this field.

4. CONCLUSIONS

The A new HCCI engine system (Nautilus GEN II) was successfully designed, manufactured and tested. This prototype uses a 2-Stage combustion method to control HCCI and operate with different blended and unblended fuel types. The introduction of a fully atomized mixture of fuel and air in the combustion chamber allows the complete burn of fuel eliminating the chance for engine knock. After testing the three fuels, it is certain that the Nautilus GEN II prototype is fully operable without the aid of a spark plug for the SI system. It was observed that the flameless combustion engine was able to run on much lower peak temperatures during the testing period compared to conventional SI and CI engines. With the elimination of a flame front caused by a spark plug, lowering operating temperatures are possible, resulting very low production of CO and CO_2 gases. The NOx production did not surpass 40 PPM in any of the experiments. This study will open new avenues for the future designs of the internal combustion engine system with high performance and low emissions.

5. ACKNOWLEDGMENT

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