2023 2nd International Conference on Computational Modelling, Simulation and Optimization (ICCMSO) | 979-8-3503-2666-6/23/$31.00 ©2023 IEEE | DOI: 10.1109/ICCMSO59960.2023.00046

Computational and combustion analysis of a dual fuel CI engine operated on hydrogen as a primary fuel

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***Abstract*— A computational and experimental study has been conducted on a common rail direct injection (CRDI) dual-fuel CI engine operated on hydrogen as the primary fuel. This study also includes the supply of hydrogen through open electronic control unit (ECU) and port fuel injection (PFI) in to the engine cylinder. Diesel has been used as pilot ignition fuel to initiate the combustion cycle. The diesel has been directly injected inside the combustion chamber through a solenoid injector. The maximum cylinder pressure has been observed as 68.2 bar at 7° after TDC. The mean gas temperature of 1310 °C and combustion duration of 16° after TDC at the compression ratio of 18 and 12 kg of engine load have been observed.**

Keywords— Combustion, hydrogen, pilot fuel injection, CRDI, maximum cylinder pressure.

I. INTRODUCTION

Today the world is 1.1 °C warmer than the preindustrial era. Because of the global warming effect and the consequences of global warming, all are facing sudden climatic changes like cyclones, floods, droughts, landslides etc. According to the UN Environment Program's Emission report of 2021, greenhouse gas emissions should fall by 7.6% globally each year from 2020 to 2030 to achieve the temperature rise target below the 1.5℃ set by Paris Agreement. And according to the report, the automobile industry contributes around 14% of greenhouse gas emissions globally on average, and road transportation is growing strongly and primarily responsible [1], [2]

Prices of petroleum fuels are increasing daily because of the limited available resources of fossil fuels and high energy demand. The direct combustion of biomass can also fulfil the energy demand, but it also contributes carbon content in the emission [3]. The world's scientists and researchers are looking for an alternative green energy fuel to reach the energy demand. Hydrogen is an alternative fuel that can completely replace conventional fossil fuel due to its unique physical and chemical properties like high calorific value and flame speed.

Hydrogen as fuel in CI engines can save its existence and bring back its popularity with minor modifications. It can also reduce the emissions contributing to global warming and work much more efficiently than diesel engines.

The Compression ignition engine was invented by a French scientist Rudolf Diesel' in 1892, and in the name of Rudolf Diesel, the engine was known as the Diesel engine. The diesel engine usually works on four-stroke cycles: suction, compression, power, and exhaust. The CI engine introduces fresh air into the cylinder combustion chamber via the intake manifold system. Diesel injection into the combustion chamber occurs directly by the DI system before combustion initiates. Fresh air is introduced when the piston goes down, and the intake valve opens. The quantity of introduced fresh air will be high at higher engine speed, and then the piston goes upward from BDC to compress the freshly introduced air when the intake and exhaust valves are closed. The diesel is injected at a very high speed through a small nozzle or orifice, which atomizes the diesel just before a few degrees of CA when the piston is about to reach TDC. After the compression pressure and air temperature goes high, it gets mixed with vaporized diesel fuel. When the mixed air-fuel charge's temperature is higher than the auto-ignition temperature of diesel fuel, the chemical reaction starts spontaneously, leading to rapid auto-ignition [4]. Then temperature and pressure in the cylinder rise to a high level. When the piston goes down from TDC during the expansion process, injected diesel fuel is atomized, and evaporation occurs because of high combustion temperature. After the end of injection (EOI), the combustion process takes place up to a certain degree of CA. When the piston is about to reach BDC, the exhaust valve opens because of the difference in exhaust and cylinder pressure. It lets the burned gases escape through the exhaust valve. During the exhaust stroke, the piston pushes the burned gases through the exhaust manifold, and the new cycle starts. As discussed above, the four main working processes of the CI engine, whereas the combustion process also includes some undesired processes, which four are discussed and given below;

a) Ignition delay

The lagging time between the start of injection (SOI) and the start of fuel combustion (SOC) is known as ignition delay. The ignition delay is mainly affected by cylinders inside conditions like pressure, temperature, charge concentration and availability of oxygen, and physical and chemical conditions.

b) Premixed combustion

Premixed combustion occurs because of heat increment released inside the cylinder by which premixed air-fuel charge combustion occurs within the flammability range.

c) Diffusion combustion

Diffusion in combustion is controlled by the rate at which the air-fuel charge is available for burning.

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DOI 10.1109/ICCMSO59960.2023.00046

d) Late combustion

Late combustion happens during the expansion stroke and is determined by the available unburned air-fuel mixture. In the late combustion phase, the heat release rate is less because of less air-fuel charge availability, and the cylinder temperature decreases.

As a renewable energy source, the hydrogen added with diesel increased thermal efficiency by 5% at 80% loading condition. It increased the maximum cylinder pressure at the above loading condition, according to an experiment conducted by Santosh and Kumar. Advanced injection time of 1-hexanol and hydrogen enhances engine performance [5].

Sharma and Kaushal did an ANOVA analysis of a hydrogen-fuelled CI engine and found the optimum engine performance at various compression ratios [6].

Lalsangi et al. found the influence of hydrogen injection timing on dual fuel diesel engines and studied the combustion duration. The injection timing was varied from the top dead center to 15 °CA and found improvement in efficiency [7].

Sharma and Kaushal did an experimental study on downdraft gasifiers, produced the producer gas with pistachio shells, and found a calorific value of 7.35 MJ/m3 [8]. The producer gas as the fuel in diesel has been utilized, and the performance of the VCR dual fuel CI engine is observed at 23.81% and compared with the diesel-run engine, which is 25.71% [9].

Benaissa et al. used numerical simulation with the 0-D SEKIN and 1-D premix codes to conduct a computational analysis and look into how the addition of hydrogen affected the combustion parameters with premixed biogas/hydrogen/air mixture. The research results demonstrate that introducing hydrogen to biogas improves flame quality and ignition delay. The small amount of hydrogen addition improves low-temperature combustion and increases laminar combustion speed. Increasing laminar speed increases the reactivity up to four to nine times. An increase in laminar speed solves the problem of lower reactivity, flame quenching and narrow flammability [10], [11].

Wang et al. did a theoretical investigation of ammonia hydrogen's combustion performance in a marine diesel engine, and ammonia is a suitable hydrogen carrier and mixing ability with hydrogen. Mixing hydrogen with ammonia increases the laminar flame velocity of ammonia and reduces the combustion temperature, which leads to lower NOx emissions [11].

Li et al. analyzed the impact of equivalence ratio on knock and performance of direct hydrogen injection at different compression ratios in an internal combustion engine. This demonstrates that the knocking intensity rises more quickly with a steady increase in the equivalency ratio at a high CR of 17.5. In contrast, at 11 CR, the knocking limits the ignition timing to 4 °CA earlier than at 18 CR, and engine performance was better in the low knocking zone [12].

The study carried out by Lai et al. [13] suggested that high injection pressure of hydrogen could reduce the chances of knocking which is the main obstacle in thermal efficiency improvement. Kumar and Lata's experiments show that the temperature is reduced by 2 and 10%, respectively, when hydrogen is substituted for 14% and 1% of the fuel, and by 72% and 1.3%, respectively, when hydrogen is substituted for 40% of the fuel [14].

Pyrc et al. investigated the combustion of ammonia with hydrogen in a VCR SI engine and found out the highest indicated mean effective pressure and engine efficiency as compared with ammonia combustion [15].

In order to simulate direct injection conditions in CI engines, Yip et al. illustrated the evolution and combustion of hydrogen jets with injection pressures ranging from 84 to 140 bar and air temperatures ranging from 1000 to 1140 K. Their research shows that the hydrogen jet's ignition delay varies only with ambient temperature and not with injection pressure and that a specific kernel initially starts the hydrogen jet's combustion before spreading to engulf the entire jet volume downstream of the ignition location. The flame returns to the nozzle after being ignited and appears linked to it, creating a diffusion flame structure [16], [17].

According to Yilmaz et al., the combustion of hydrogen-enriched CI engines has no undesired combustion, and increasing hydrogen intake also raises cylinder pressure in the pilot injection stage [17].

Yip et al. did a study on the direct injection of hydrogen in IC engine and suggested that port fuel injection with direct hydrogen injection can reduce the chances of pre-ignition, backfire and knocking. Compression loss and high compression ratio in the CI engine pilot ignition method can make the combustion fast [18].

Yang et al. studied the different injection modes and investigated the effect on the combustion performance of hydrogen IC engine. Dual injection with a port can reduces the backfire. Still, the high cylinder temperature increases the amount of NOx in the exhaust at an equivalent ratio of 0.67 and combustion velocity also improved at the same equivalence ratio. In contrast, with an increment in nozzle diameter, the indicated power and thermal efficiency increase and decrease [[19]. Backfire can quickly occur in manifold injection at a higher equivalence ratio. A decrement in the equivalence ratio will reduce the power output, but ignition delay can reduce pre-ignition chances [20].

II. METHODOLOGY AND MATERIALS

The piezoelectric pressure transducer (apex made) was used to measure the cylinder pressure, which was mounted at the engine's cylinder head and connected with a national instrumentation data acquisition board (NI USB-6210 data storage unit). A digital shat encoder was used to record the crankshaft position. Apex-made "enginesoft" was used for combustion analysis and data acquisition. Some other engine apparatus were attached with engine setup like RTD, PT100 and K type thermocouple were used to measure inlet, exhaust air and oil temperature. While conducting the experiment, atmospheric pressure, temperature and humidity were also monitored. The average of 10 working cycles' data was taken by engine software to analyze the maximum cylinder pressure, net heat release and other combustion parameters.

A. Pilot ignition method

Hydrogen has a relatively higher auto-ignition temperature than conventional fuels like diesel and gasoline. Because hydrogen has a high auto-ignition temperature, it wasn't used in compression ignition engines very much, and not much research has been done. Here we used diesel fuel as a source of ignition for hydrogen fuel, i.e. diesel is the pilot ignition method for compression ignition engine. The "pilot ignition method" refers to the compression process whereby hydrogen, which is uniformly mixed with air, is compressed until it reaches high temperatures and pressures. At this point, diesel is directly injected into the combustion chamber. The high temperatures of the compressed air mixture burn the diesel fuel, which leads to burning hydrogen and starts the combustion reaction in the combustion chamber.

III. Results and discussion

A. Maximum cylinder pressure

As the load increases, the fuel inside the combustion chamber also increases. For hydrogen, the maximum values of cylinder pressure were observed at 7 degrees crank angle after TDC, which is due to the late combustion of hydrogen and high flame speed of the hydrogen, which increases the pressure in the cylinder during the combustion. Diesel serves as the pilot ignition source. Figure 1 depicts the fluctuation of maximum cylinder pressure with relation to crank angle under loading conditions with compression ratios of 18 and 12 kg.

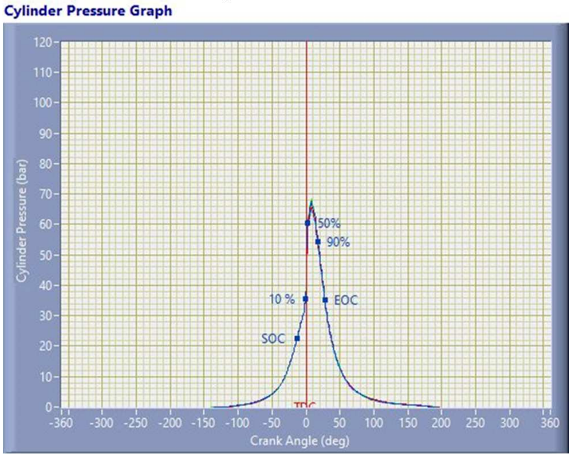

Fig 1:Cylinder pressure variation with crank angle of hydrogen fueled engine at a compression ratio of 18 and 12 kg of load.

B. Combustion duration

The term "combustion duration" refers to the time between 10% of the mass of fuel burned (10° CA) and 90% of the total amount of fuel burned (30° CA) based on cumulative heat transfer. The combustion starts at about 15° BTDC and ends at approximately 30° ATDC for hydrogen engine. The combustion duration inside the cylinder was about 20° of crank movement. The addition of hydrogen decreased the concentration of combustion air, which altered the charge's characteristics and slowed diffusion combustion due to the bulkiness of the fuel. As the load increases, the concentration of hydrogen also rises due to the longer combustion time caused by the presence of oxygen. The experimental result shows that 90% of the fuel burned when the crank was at 16° after the top dead center. Figure 2 shows the variation of mass fraction burned graph (combustion duration) with crank angle at the compression ratio of 18 and 12 kg of loading condition.

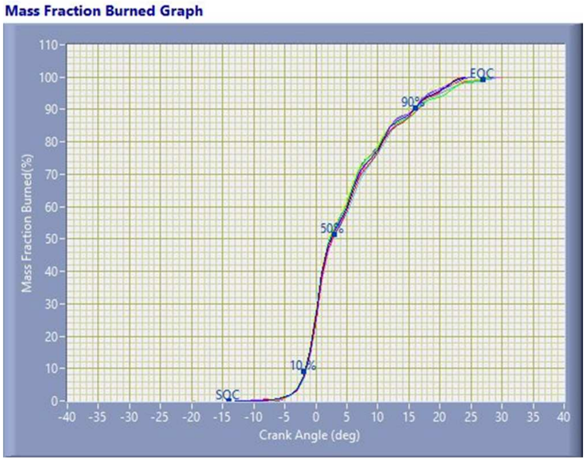

Fig 2: Mass fraction of fuel burned (combustion duration) variation with crank angle for hydrogen fuelled engine at compression ratio of 18 and 12 kg of load.

C. Mean gas temperature

Figure 3 shows the variation of the mean gas temperature inside the cylinder versus the crank angle at the compression ratio of 18 and 12 kg of load. The temperature inside the cylinder increases just after the combustion initiated by diesel as pilot ignition source by compression process and rapid burning of hydrogen increases the temperature in the cylinder. As the CR increases, the maximum values of mean gas temperature decrease due to more area available for burning gas to travel and more area available for heat release. The experimental results report that at the compression ratio of 18 and 12 kg of engine load, the mean gas temperature was 1310 °C.

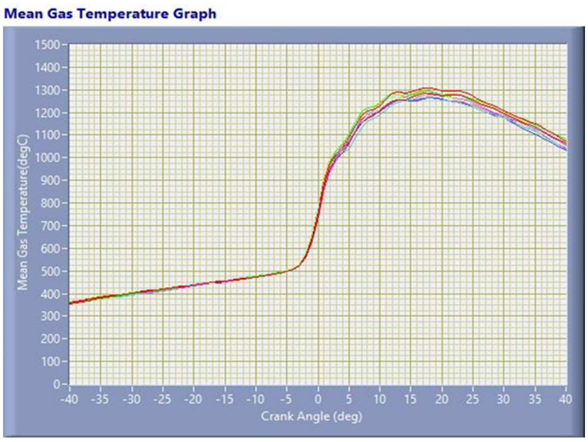

Fig 3: Mean gas temperature variation with crank angle for hydrogen fuelled engine at compression ratio of 18 and 12 kg of load

D. Neat heat release

The combustion for hydrogen start at the crank angle about 10 degree before top dead center. The experimental results reports the maximum value of Net Heat Release for hydrogen and 18 were 78.5 J/degree. The maximum NHR was observed 2° BTDC. Figure 4 shows the neat heat release variation with crank at the compression ratio of 18 and 12 kg of loading condition.

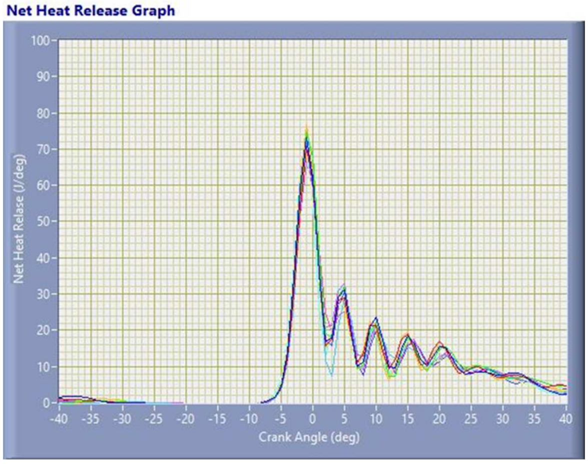

Fig 4: Net heat release variation with crank angle for hydrogen fuelled engine at a compression ratio of 18 and 12 kg load.

CONCLUSIONS

The experimental study of hydrogen fuelled CRDI dual fuel CI engine has been performed. The diesel is used as the secondary fuel to initiate the combustion cycle. The combustion analysis results have been observed and given below:

- The combustion duration of hydrogen as the primary fuel was observed at 16° after TDC at 12kg of engine load and 18 CR.
- The maximum pressure inside the cylinder was found at 68.2 bar at the 12 kg engine load and 18 CR.
- The mean gas temperature inside the combustion chamber was observed at 1310 °C at 18 and 12 kg of engine load compression.
- The neat heat release during the combustion was observed at 78.5 J/degree at the 12 kg engine load and 18 CR.

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