

## COMPARATIVE STUDY OF DIESEL AND DIESEL-HYDROGEN DUAL FUEL USE IN RCCI ENGINE UNDER VARIOUS LOAD CONDITIONS

Mustafa Berat Gördük<sup>1</sup>, Usame Demir<sup>2</sup>, Mustafa Deniz Altinkurt<sup>3</sup>

<sup>1</sup>Bilecik Şeyh Edebali University, Mechanical Engineering Department, Bilecik, Turkey

<sup>2</sup>Bilecik Şeyh Edebali University, Mechanical Engineering Department, Bilecik, Turkey

<sup>3</sup>Kocaeli University, Automotive Engineering Department, Kocaeli, Turkey

<sup>1</sup> Corresponding Author: Mustafa Berat Gördük, musberat@gmail.com

### ABSTRACT

The aim of this study to investigate the effects of using hydrogen and diesel fuels on combustion characteristics and emissions in a Reactively Controlled Compression Ignition (RCCI) engine. RCCI technology optimizes the combustion process by exploiting the differences in reactivity of the two different fuels. This improves engine performance and reduces emissions. The study will examine the potential benefits of using alternative fuels such as hydrogen in combination with diesel fuel in RCCI engines with the aid of CFD analysis. The main reason for studying hydrogen is that hydrogen has the most research in the literature and it has a wide flammability range, high flame speed, high diffusivity, zero carbon, sulphur content. Replacing part of the diesel fuel reduces the total carbon content and HC emissions in RCCI mode, while increased engine load increases HC and NO<sub>x</sub> emissions. A low engine load may be more advantageous for H<sub>2</sub>-diesel RCCI combustion, as HC emissions are reduced more than a slight increase in NO<sub>x</sub> emissions. The study reveals that diesel-hydrogen dual fuel systems can be an environmentally friendly alternative to diesel engines if supported by appropriate engine control strategies and emission control technologies. The results highlight the need for further research and optimization in energy efficiency and emission management.

**Keywords:** Reactively Controlled Compression Ignition, RCCI engine, combustion characteristics

### 1. INTRODUCTION

Environmental concerns and increasing demands for fuel efficiency are transforming the automotive industry[1]. While environmentally friendly technologies such as hybrid, electric and hydrogen fuel cell vehicles are gaining prominence, internal combustion engines (ICEs) still have a significant share in the automotive market[2]. In the future, ICEs are expected to continue to play an important role in a sustainable automotive industry[3]. Therefore, it is vital to improve the efficiency of existing ICEs[4]. Technological advances will enable ICEs to improve their environmental performance while maintaining cost-effectiveness and driving pleasure[5]. Environmental regulations are forcing car manufacturers to develop vehicles with lower emissions[6,7]. This increases the popularity of hybrid and electric vehicles and accelerates technological advances in ICE efficiency[8]. However, ICEs will continue to be an important player in the automobile market in the coming years as they have advantages in terms

of cost effectiveness, range and fuel infrastructure. They will also continue to be the most suitable option for heavy-duty vehicles and long-distance driving.

Low temperature combustion (LTC) strategies are being developed to improve the efficiency of diesel engines and at the same time reduce NO<sub>x</sub> and PM emissions. LTC injects fuel at an earlier stage, creating a homogenous and lean mixture[9]. This allows enough time for the fuel and air to premix and lowers the combustion temperature. The application of LTC leads to combustion at lower temperatures, which reduces heat loss through the cylinder wall. This improves thermal efficiency and reduces NO<sub>x</sub> emissions[10]. The application of LTC to diesel engines can provide the following benefits: (Improved thermal efficiency, reduced NO<sub>x</sub> emissions, and reduced PM emissions). Research is ongoing to further develop LTC technology and further improve the environmental performance of diesel engines. However, some disadvantages of LTC should also be taken into account, e.g. cold starting difficulties, increased carbon monoxide (CO) emissions, and higher hydrocarbon (HC) emissions[11]. Overall, LTC has significant potential to improve the efficiency and environmental performance of diesel engines. However, its disadvantages also need to be taken into account and further research is needed to overcome them[12].

LTC strategies are new combustion methods developed to improve the efficiency of diesel engines while reducing their emissions. These strategies can be divided into three main categories:

- Homogeneous Charge Compression Ignition (HCCI): HCCI injects fuel at an early stage, allowing enough time for the fuel to mix homogeneously with air. This mixture is then compressed and ignites spontaneously. The advantage of HCCI is that the low combustion temperature prevents the formation of NO<sub>x</sub> and PM. However, the ignition timing is difficult [13]
- Pre-mixed Charge Compression Ignition (PCCI): PCCI premixes the fuel by injecting it during the compression process. This allows for higher load conditions than HCCI. However, it has limitations under full load conditions[14].
- Reactivity Controlled Compression Ignition (RCCI): RCCI is a hybrid engine that combines the characteristics of diesel and petrol engines. They use a high compression ratio like diesel engines, but provide ignition by the heat of compression instead of a spark plug like petrol engines. RCCI provides flexible operation using two different fuels[15].

Hydrogen is seen as the fuel of the future due to its potential for zero carbon emissions. The use of hydrogen in RCCI engines is of interest due to the following advantages: The energy density of hydrogen is much higher than other fuels and resulting in high efficiency in RCCI engines [16]. Since only water is released as a result of hydrogen combustion and it is an environmentally friendly fuel, the low reactivity of hydrogen makes it an ideal fuel for RCCI engines and allows for a controlled combustion process[17]. Hosseini et al. [18] reviewed hydrogen utilization in dual-fuel diesel engines. They claimed that hydrogen blending with various gaseous fuels, adjusting engine design and control parameters and selecting an exhaust gas catalyst could improve hydrogen combustion. They stated that the main disadvantages of

using H<sub>2</sub> in diesel engines are knocking combustion and high NO<sub>x</sub> emissions and they must be controlled carefully.

Diesel is a widely used fuel in RCCI engines due to its high energy density and availability. The high reactivity of diesel is essential for efficient and controlled operation of RCCI engines. The use of diesel in RCCI engines provides the following benefits: The high energy content of diesel provides higher efficiency in RCCI engines, the high reactivity of diesel allows precise control of the combustion process and reducing emissions. The properties of diesel create optimum combustion conditions in RCCI engines.

The performance of RCCI engines is further enhanced when combined with low reactivity fuels such as diesel and hydrogen. Using these fuels together provides the following advantages: Low reactivity fuels offset the high reactivity of diesel and creating a more efficient combustion process, Low reactivity fuels help to reduce the emissions produced by diesel, Using diesel with low reactivity fuels provides RCCI engines with a wider fuel range.

Hydrogen is non-toxic, odorless, and renewable energy carrier. The combustion product of hydrogen is water, for this reason, researchers have been paid attention to it as an alternative fuel. The use of hydrogen as an additive to diesel fuel in RCCI engines has the potential to improve engine performance and emissions. Hydrogen's high flame propagation speed and clean burning properties improve combustion efficiency and reduce emissions. However, the high energy capacity of diesel fuel has a positive effect on efficiency.

Duan et al. [19] carried out a detailed analysis of hydrogen-diesel RCCI combustion in a lightduty diesel engine. They found much higher indicated thermal efficiency (ITE) using hydrogen compared to gasoline RCCI strategy. Besides, using double diesel injections, they further improved ITE and NO<sub>x</sub>. They improved combustion stability, ITE, maximum pressure rise rate (MPRR), soot and NO<sub>x</sub> emissions with higher H<sub>2</sub> premixed ratio. Gharehlar et al.[20] investigated H<sub>2</sub>-diesel RCCI low load performance by comparing with natural gas (NG)-diesel RCCI. They found a vast improvement in NG combustion by replacing it with H<sub>2</sub>. In addition, they found improvement in engine power and efficiency. By eliminating carbon containing NG fuel usage, they obtained lower CO<sub>2</sub>, methane, CO and formaldehyde emissions which are crucial to meet the latest emission regulations. Bakar et al. [21] experimentally investigated hydrogen ratio in dual fuel mode in a diesel engine at different engine speeds. They obtained improved engine performance and cyclic variations by using certain levels of hydrogen flow rates. Madhujit et al. [22] The use of hydrogen and diesel dual fuel in a single-cylinder, fourstroke, air-cooled diesel engine with hydrogen sprayed into the intake manifold resulted in improved thermal efficiency and reduced specific energy consumption. While CO, CO<sub>2</sub> and soot emissions decreased with increasing hydrogen content, NO<sub>x</sub> emissions increased. In addition, in-cylinder pressure and heat output rates also increased. Zhou et al. [23] Methane, hydrogen and methane-hydrogen mixtures were used in a four-cylinder, four-stroke, naturally aspirated diesel engine. At low loads, hydrogen addition reduced cylinder pressures and heat output ratios, while at high loads these values increased. At high loads, hydrogen increased thermal efficiency and reduced CO and HC emissions, but increased NO<sub>x</sub> emissions. Adding hydrogen at more than 30% of the total energy increased the heat output rate and decreased the ignition delay and combustion time. Pan et al. [24] Hydrogen was added to a two-stroke, turbocharged, intercooled, 12-cylinder diesel engine at different flow rates and it was observed

that hydrogen had no significant effect on CO<sub>2</sub>, NO<sub>x</sub> and soot emissions. Dhole et al. [25] The use of hydrogen in a four-stroke, four-cylinder, water-cooled, turbocharged, dual-fuel diesel engine increased thermal efficiency at high loads and decreased it at low loads. NO<sub>x</sub> emissions were reduced compared to diesel fuel at all loads. Zhenzhong et al. [17] With the use of hydrogen in a dual-fuel, six-cylinder, turbocharged diesel engine, cylinder pressures and heat output rate initially increased and then decreased due to the increase in the amount of hydrogen. NO emissions increased while soot emissions decreased.

Hydrogen, the main carbon-free fuel, can be produced from clean energy sources that significantly reduce CO<sub>2</sub> emissions and therefore has a promising application. Research on hydrogen as an alternative energy source has been conducted for many years, but there are still some challenges in promoting its application due to the limitations of its physicochemical properties. For example, the storage and transportation of hydrogen is one of the bottlenecks in the development of hydrogen energy technology. At present, high-pressure hydrogen storage is one of the most widely used hydrogen storage methods in the world, but because the hydrogen density is very small, the hydrogen storage pressure required to obtain a certain volumetric energy density is very high, and the efficiency of hydrogen storage is very low[26]. At present, high-pressure hydrogen storage is one of the most commonly used hydrogen storage methods in the world, but due to the density of hydrogen is very small, the required hydrogen storage pressure is very high in order to achieve a certain volumetric energy density, and the efficiency of hydrogen storage is very low, if the storage pressure is 35 MPa, the temperature of 298 K, each kilogram of hydrogen needs to consume 2.2 kWh of electricity[27]. In addition, due to the low volumetric energy density of hydrogen, the dynamics of hydrogen internal combustion engine is worse than that of conventional internal combustion engine, and it has higher NO<sub>x</sub> emission and is very sensitive to the change of excess air coefficient, which poses a great challenge to the control of hydrogen internal combustion engine. In addition, hydrogen internal combustion engines have problems such as premature ignition, backfire, and power degradation, which limit the large-scale popularization of hydrogen internal combustion engines[28].

As can be seen in literature summary, using hydrogen in RCCI mode and in dual-fuel diesel engines can bring many advantages. More numerical studies should be performed to investigate the effects of hydrogen addition by replacing diesel fuel. Therefore, in this study, we compared conventional diesel and hydrogen-diesel RCCI combustion and emission characteristics using CFD analyses.

## **2. MATERIAL AND METHOD**

### **2.1. Experimental Engine Test System:**

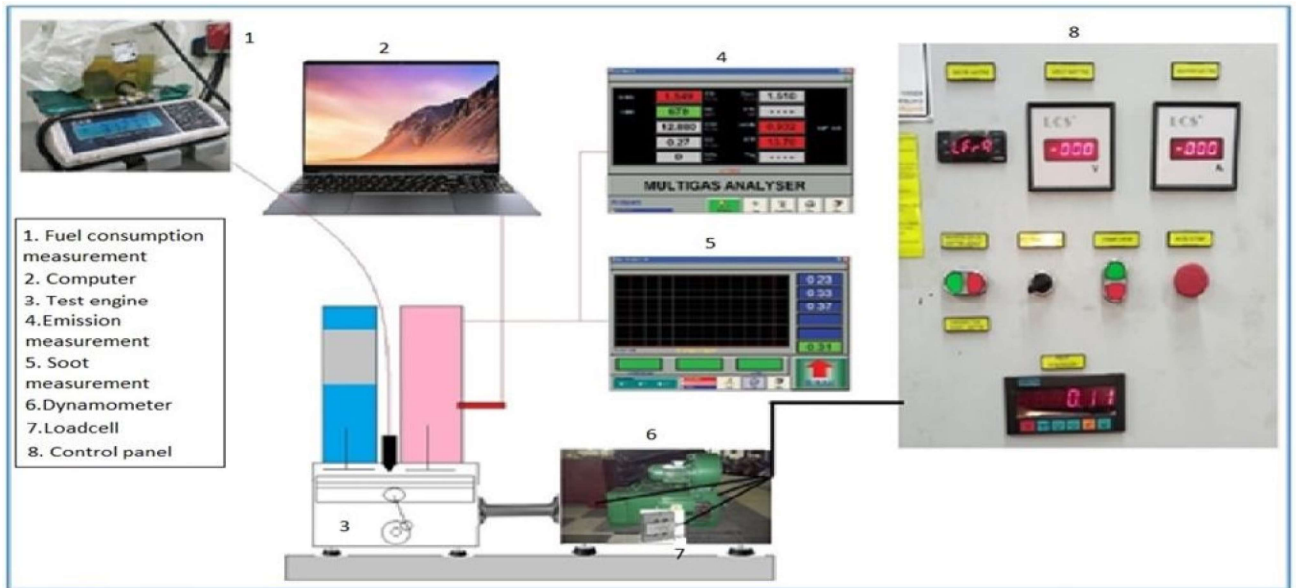
The experimental part of this study was carried out on a single cylinder, air cooled, 4-stroke direct injection diesel engine. The closed part of this engine's cycle (from IVC to EVO) was simulated in CFD software, which is between 40° after bottom dead center (aBDC) and 40° before bottom dead center (aBDC) of expansion stroke. The engine specifications are given in Table 1.

**Table 27.** Engine specifications

|                                  |                        |
|----------------------------------|------------------------|
| Engine Name                      | Lombardini 3 LD<br>510 |
| Stroke volume (cm <sup>3</sup> ) | 510                    |
| Diameter x Stroke (mm x mm)      | 85 x 90                |
| Connecting rod length (mm)       | 144.5                  |
| Compression ratio                | 17.5:1                 |
| Engine power [HP]                | 12                     |
| Maximum torque [Nm @1800 rpm]    | 32.85                  |
| Suction valve opening            | 16° bTDC               |
| Intake valve closure             | 40° aBDC               |
| Exhaust valve opening            | 40° bBDC               |
| Exhaust valve closure            | 16° aTDC               |

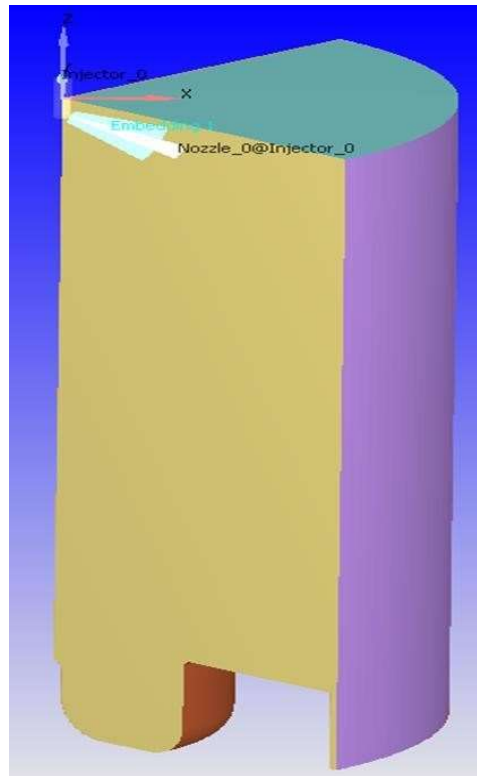
The experimental test system schematic is given in Figure 1 below. The engine tests were carried out at constant 1800 rpm and variable engine torque. For CFD analyses, low and high engine load experiments at 6.6 Nm and 23.1 Nm (corresponding to approximately 20% and 80% full load) were selected. The experimental test system is equipped with modern and precise measuring instruments to ensure high accuracy and repeatability. The tests were carried out on an internal combustion diesel engine. The engine is capable of running on hydrogen injection as well as standard diesel fuel. Hydrogen was injected into the intake manifold of the engine in a controlled manner, enabling dual-fueled operation. A series of sensors and analyzers were used for engine performance and emission measurements. Engine torque and speed were measured with a dynamometer, while emission analyses were performed with exhaust gas analyzers.

**Figure 1.** Experimental setup



## 2.2. Preparation of the CFD Model for Numerical Analyses:

In this study, CFD modelling and combustion analyses were performed in Converge 3.0 software. Since the number of injector holes is 4, a cylinder calculation volume of 1/4, i.e. 90°, was created. In order to create the mesh structure with the finite volume method, the base grid size was selected as 2.8 mm and three level AMR (adaptive mesh refinement) was applied according to the variation of in-cylinder velocity and temperature. Accordingly, when the velocity gradient exceeds 2.0 m/s and the temperature gradient exceeds 5 Kelvin, the cell size is reduced up to 0.35 mm to increase the calculation accuracy in the regions where spray atomisation and reactions take place. In addition to the AMR, 3 level mesh embedding was applied until the end of injection around the injector hole. Figure 2 below shows the calculation volume from the software and the diesel fuel spray as 3-D with boundaries having different colors. Besides, embedding applied around the spray is shown in Figure 2. In addition, used diesel injector specifications are given in Table 2.



**Figure 2.** Boundary conditions, embedding and fuel spray on 3-D engine geometry

**Table 2.** Diesel injector properties

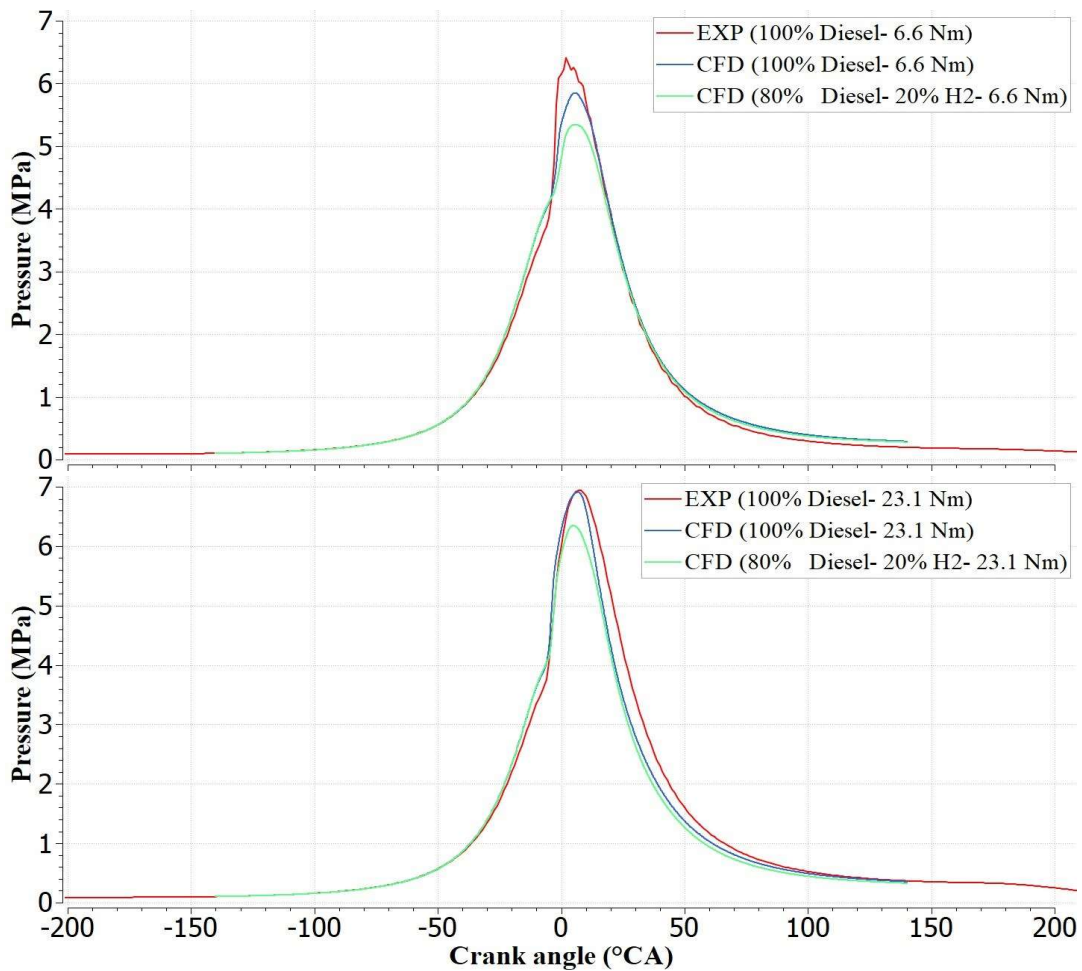
| Property               | Value   |
|------------------------|---------|
| Number of nozzle holes | 4       |
| Spray angle            | 126°    |
| Nozzle hole diameter   | 0.28 mm |
| Start of injection     | -15 °CA |
| Fuel temperature       | 330.15  |

During the CFD study, n-heptane was selected to represent diesel fuel. For the hydrogen-diesel RCCI combustion cases, the H<sub>2</sub> mass fraction was calculated according to the total energy input. Hydrogen energy input rate was determined as 20%. For the fuel break-up and atomization process, KH-RT model was selected for the primary and secondary break-up mechanisms. The break-up time constants of the KH and RT model were selected as 7 and 1, respectively. The nozzle discharge coefficient was selected as 0.7. Frossling model was used for fuel droplet

evaporation. The RNG (re-normalisation group)  $k$ - $\epsilon$  model, one of the most suitable RANS models for ICE simulations, was selected as the turbulence model.  $\text{NO}_x$  and soot emission formation models were used as emission formation models. Extended Zeldovich mechanism was used for  $\text{NO}_x$  emission modelling and Hiroyasu-NSC model is used for soot emissions.

### 3. RESULTS AND DISCUSSION

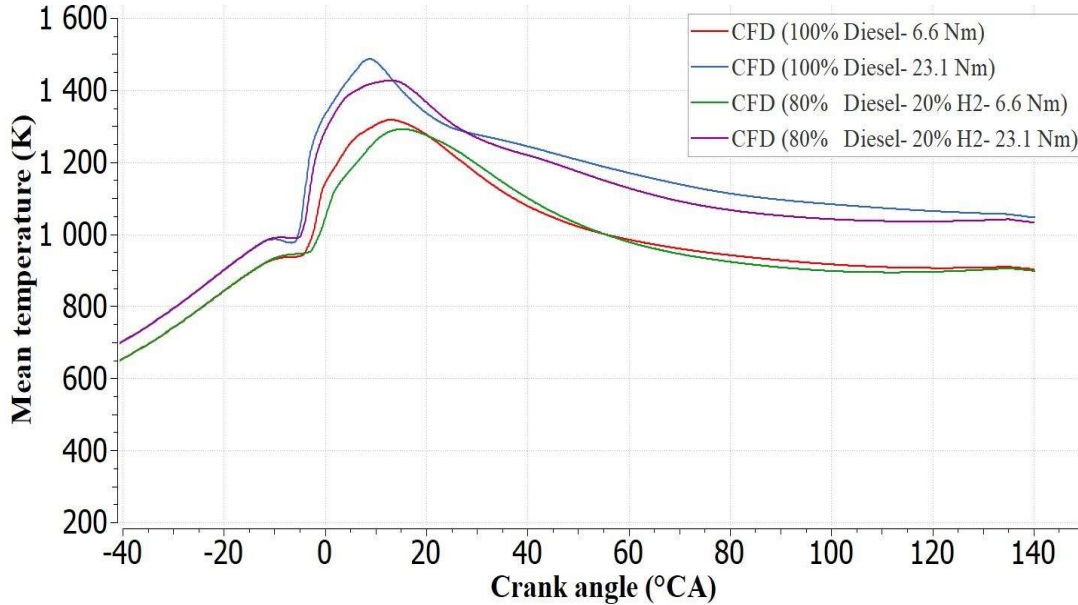
In this section, the results of the experimental study and CFD analyses are compared. Firstly, cylinder gas pressure data of diesel experiments was compared with CFD analyses. Then, CFD simulation data of diesel and diesel-hydrogen RCCI combustion cases were evaluated based on the results of in-cylinder mean temperature,  $\text{NO}_x$  and HC emissions.



**Figure 3.** Cylinder gas pressure comparison (diesel and  $\text{H}_2$ -diesel RCCI)

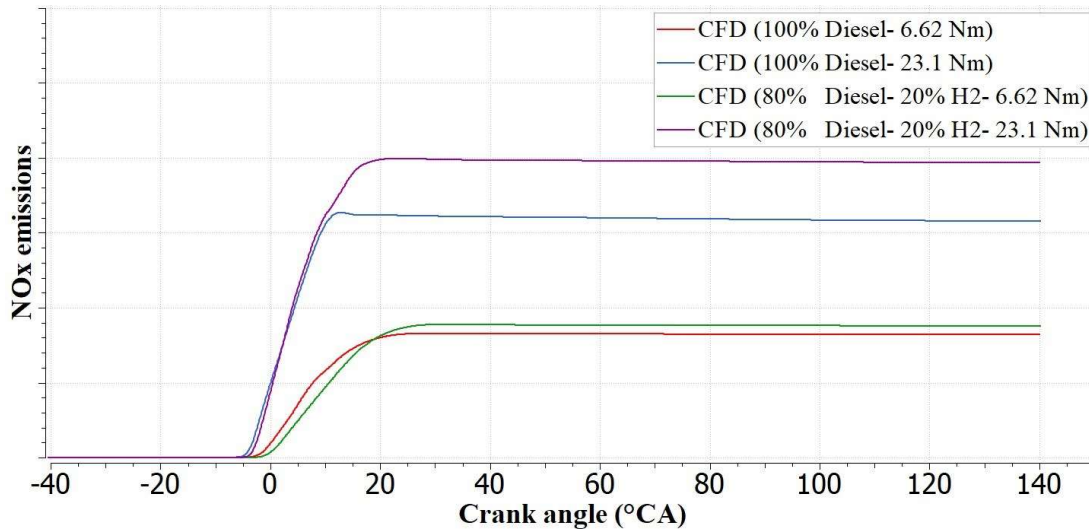
Experimental cylinder gas pressure graphs obtained with 100% diesel usage are compared with CFD analyses in Figure 3. Besides, CFD results of  $\text{H}_2$ -diesel RCCI mode are also depicted in Figure 3. In  $\text{H}_2$ -diesel mode, 20% of the total energy content of diesel fuel was replaced with hydrogen fuel. The experimental data coming from the cylinder pressure sensor are filtered to reduce noise. As can be seen in the Figure 3. CFD simulations have largely captured the diesel

mode experimental data. At 80% engine load, it is seen that the maximum cylinder pressure ( $P_{\max}$ ) values increase with increasing fuel amount and move slightly away from the TDC. Looking at the pressure data, it is seen that the hydrogen addition decreases the  $P_{\max}$  values. The reasons for this can be explained by the decrease in the amount of diesel fuel at constant energy input conditions, which reduces the intensity of diffusion combustion, and the high stoichiometric air-fuel ratio of  $H_2$ .



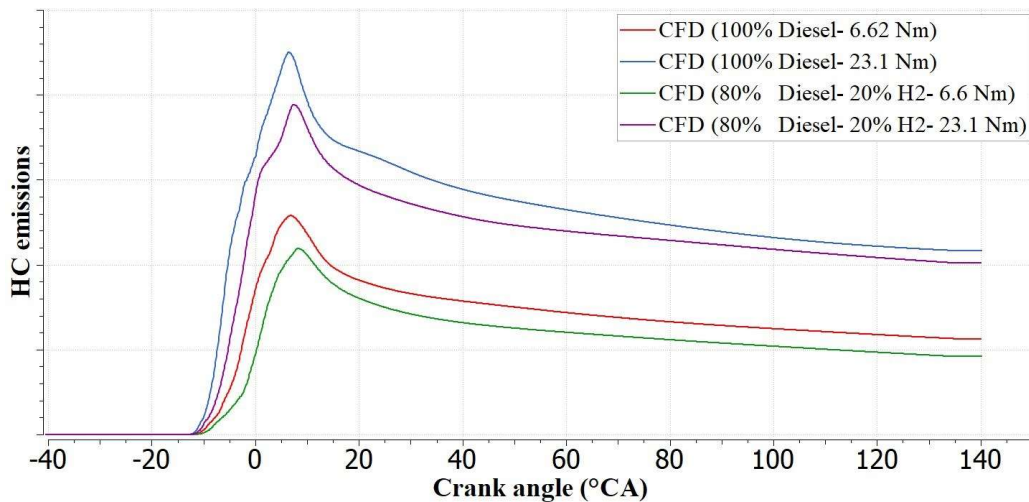
**Figure 4.** Comparison of cylinder mean temperatures (CFD results)

In Figure 4, the average in-cylinder temperature values obtained from CFD analyses are plotted against the crank angle. As expected, for the higher load case (23.1 Nm), more heat energy was released due to the increase in fuel amount and this caused the average temperature values to increase. The noteworthy point here is that the average temperatures decrease slightly in the  $H_2$ -diesel RCCI combustion mode compared to the diesel mode. Hydrogen is a fuel with high potential to cause increased combustion temperatures due to its high laminar flame speed and high energy content. However, the effective parameter here is the decrease in the local equivalence ratio. The high diffusivity of  $H_2$  in the gas phase allows it to be taken into the cylinder by mixing faster with the air and the decreasing amount of diesel reduces the rich mixture zones and reduces the combustion temperatures [29]. In addition, the higher calorific value of hydrogen means a smaller amount of fuel required for constant energy input, resulting in a leaner overall mixture and lower average temperatures.



**Figure 5.** Comparison of in-cylinder  $\text{NO}_x$  emissions for CFD cases

In Figure 5, the variation of  $\text{NO}_x$  emissions with crank angle is compared for diesel and  $\text{H}_2$ diesel RCCI modes at two different loads. It is known that  $\text{NO}_x$  emissions occur at high flame temperatures (1800 K and above) and in the presence of sufficient oxygen [30]. Therefore, for the high load (23.1 Nm) cases,  $\text{NO}_x$  emissions increased in parallel with increasing in-cylinder pressure and temperature. In addition, the high flame speed and flammability range of  $\text{H}_2$  might have caused  $\text{NO}_x$  emissions to increase slightly.



**Figure 6.** Comparison of HC emissions from CFD analyses

Figure 6 shows the variation of HC emissions depending on the crank angle. In the higher load mode, the increase in the amount of fuel and rich mixture regions leads to an increase in HC emissions. In addition, as expected, for the  $\text{H}_2$ -diesel RCCI mode, the replacement of carbonfree  $\text{H}_2$  fuel with carbon-containing diesel fuel in the  $\text{H}_2$ -diesel RCCI mode resulted in a decrease in HC emissions.

#### 4. CONCLUSIONS

In this study, we analyzed hydrogen-diesel RCCI combustion numerically by using CFD method and compared with conventional diesel combustion at low and high engine load. First, diesel engine experiments were modelled and simulated in CFD software. Then, H<sub>2</sub>-diesel CFD cases were created by replacing 20% of diesel's energy content with H<sub>2</sub> fuel which is taken into intake port. Following were deduced from the study:

- Hydrogen addition decreased  $P_{max}$  values and maximum cylinder mean temperature values. However, NO<sub>x</sub> emissions increased when using H<sub>2</sub> fuel in H<sub>2</sub>-diesel RCCI mode, especially in higher load case.
- Replacing some of diesel fuel decreased the overall carbon content and HC emissions in RCCI mode, compared to conventional diesel mode.
- Increased engine load increased HC and NO<sub>x</sub> emissions in both combustion mode. Low engine load can be more suitable for H<sub>2</sub>-diesel RCCI combustion, since HC emissions decrease proportionally more with a slight increase in NO<sub>x</sub> emissions.

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