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Experimental validation of the combustion properties of NB10 biodiesel in diesel engines with CFD analysis

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Abstract:

The paper studies the combustion properties of the Neem NB-10 biodiesel engine through CFD analysis and validates the same experimentally. Initially the tests were carried out for Compression Ratios (CRs) 12:1, 15:1 & 17:1 at varied loads for different blends viz., NB-10, NB-15, NB-20, and NB-25 using variable compression ratio, 4-Stroke CI engine. At maximum load (80%), NB-10 exhibits better performance and emission characteristics compared to other biodiesel blends. CFD simulations were performed with 120° sector geometry for the period when both inlet and outlet valves are closed. ANSYS Fluent 15.0 software was utilized to consider the impact of compression ratio on the peak pressure, temperature, rate of heat release (HRR), and delay in the ignition during the combustion. There was a strong correlation between experimental & CFD simulation results.

Keywords: Neem blended biodiesel, combustion characteristics, CFD simulation, Pressure vs. Crank angle (P-Ө) diagram, maximum pressure, rate of heat release (HRR), and delay in ignition.

Nomenclature

CCs	Combustion characteristics	CA	Crank angle
CI	Compression Ignition	BTDC	Before top dead center
CRs	Compression ratios	ATDC	After top dead center
IC	Internal combustion	VCR	Variable compression ratio
CFD	Computational Fluid Dynamics	ABDC	After bottom dead center
NOx	Oxides of Nitrogen	BBDC	Before bottom dead center
NOP	Nozzle opening pressure	EVO	Exhaust Valve open
TDC	Top dead center	IVC	Inlet valve close
NB10	10% Neem by volume blended to diesel fuel	HRR	Heat release rate

1 Introduction

Today, all production operations, as well as modern human life in general, require energy. It could be derived and used from a range of traditional and nontraditional energy sources [1]. The fast exhaustion of these energy sources is related with current energy demand. Fossil fills are assessed to be accessible until 2040. Experts' suggestions, blending diesel with natural oils is utilized as an alternative fuel to decrease the issue of financial debilitating, raising costs, worldwide climate change and anticipated fossil fuel shortfalls.

1.1 Biodiesel

Biofuels are vaporous or fluid fuels determined from biomass and utilized rather than diesel, gasoline or other fossil fuels for vehicles, stationary and convenient energy conversion devices. Biodiesel is a liquid fuel generated from biomass that may be used in normal diesel engines without requiring any modifications [2]. The modern world is facing two crises: the depletion of fossil fuels and the destruction of the environment. Thus, some researchers also consider organic material as one such source other than fossil fuels as fuel. Several attempts have been made to utilize edible and inedible oils in auto-ignition engines for different purposes. However, developing countries cannot afford to buy edible oil because they can hardly use food as an energy source. However, non-edible oils can be strategically secured and can form the basis of a self-sufficient agricultural platform that could breathe new life into rural materials. Organic matter is stronger than oil, which means it can be developed and delivered with a less negative affect on our biological system [3]. Biodiesel is renewable, safe, environmentally friendly, non-toxic, sulfur-free and reduces the level of serious air pollutants. The Indian government unveiled its "National Biofuel Policy" on September 12, 2008 and the biodiesel mixing program was considering mandatory biodiesel initiatives. As a result of these policies, population growth and increased energy demand, biodiesels may become a significant market in India. The goal is to use the facilities to meet 20% of India's diesel fuel needs. [2].

1.2 NEEM :

Neem (Azadirachta Indica) may be a tree of the Melaisi-akaju family. It grows in nearly all sorts of salt and alkaline soils. The seeds are gathered, dried and smashed to extricate the oil. Seeds contain 45% oil, which opens up extraordinary openings for the generation of biodiesel. The oil is more often light brown in colour, bitter in taste and has an extremely impressive smell. Neem has remarkable properties: viscosity 5.3 (JV) at 40 degrees Celsius, calorific value of 39.1 MJ/kg, density of 15 degrees Celsius 0.78 (g/cm3) and cetane number 46. The oil has surprisingly high stability at room temperature. Low cost, ease of use, availability and excellent diesel solubility were good choices as an alternative to fossil fuels used in AI engines. The aim of this study is to explore aspects related to the development of CFD modeling of performance and combustion characteristics of 10% Neem, mixed with 90% diesel fuel, to avoid experiments to save time and money [5], [6].

1.3 Combustion in CI engines :

Fuel combustion in the internal combustion engine is expected to take place in four phases, such as ignition delay/pre-burning period, the uncontrolled/rapid combustion period, the controlled combustion period and the post-combustion period. These four combustion phases in an internal combustion engine depend on the angle of rotation of the crankshaft, in which the inlet and outlet valves open and close, as well as on the fuel injection and its duration.

The pressure measured in the cylinder at each angle of rotation of the crank shaft of the engine is a highly essential and easily quantifiable characteristic for understanding the combustion process of engine fuel. Many variables, such as increasing the volume of the combustion chamber, heat transmission to the walls, and mass loss, affect this pressure curve. As a result, distinguishing the effects of volume change, mass loss and heat transfer is crucial for a thorough knowledge of combustion processes. This can be done by computing the heat release rate, which has the advantage of allowing combustion rates such as ignition and combustion time to be determined. The process of heat transfer and loss of mass at cylinder pressure as a function of the angle of the crank shaft (the volume of the cylinder) is called the heat release analysis [3].

1.4 Computational Fluid Dynamics (CFD) analysis :

To offer a qualitative and quantitative forecast of fluid flows, CFD employs mathematical modelling, numerical methods, discretization and solution techniques, software embedded in solvers, and pre and post processing programmes.

Engineers and scientists can utilize computer simulations to conduct numerical experiments in a virtual flow lab utilizing CFD. Flow models are complex, expensive, and hard to explore using traditional experimental approaches [20].

The researchers have made various observations in their studies. Some basic observations from the free literature include the fact that he thermal efficiency of a biodiesel engine is slightly lower than that of a diesel engine, and biodiesel can be used in conventional diesel engines without any changes in the equipment adjustments. When compared to pure diesel, all biodiesel uses less fuel and emits less hazardous emissions. Several studies have shown that the characteristics of mixed biodiesel combustion are highly controversial. Because the combustion process is controlled by kinetic reactions and mixing properties, direct management of the ignition angle and combustion rate in a wide variety of engine speeds, loads, and compression ratios is difficult. Further research is therefore needed to understand the phenomenon of fuel combustion and the characteristics of engine exhausts running on different biodiesel mixtures and at different compression ratios. Further research is therefore needed to understand the characteristics of fuel combustion and engine emissions from different biodiesel mixtures and different compression ratios It was observed from the literature survey, limited studies were reported on CFD combustion analysis for CI engine fueled with biodiesel blends as fuel at various compression ratios at full load conditions.

2 Testing Procedure :

The University of Agricultural Sciences, Gandhi KRISHI Vignyana Kendra, Bangalore, India, provided various blends of transesterified neem biodiesels and Sneha Test House in Bangalore, India, tested their basic qualities such as calorific value, kinematic viscosity, flame and ignition point, and density. Table 1 lists the attributes of various neem biodiesel blends that were investigated.

Table 1: Attributes of the different blends of neem biodiesel

Properties	Diesel	Neem biodiesel			
		NB-10	NB-15	NB-20	NB-25
Total Heat Value	44800	41533	40946	40361	39775
Density kg/m^3	840	841	844	846	850
Viscosity (Kinematic -	4	3.78	3.81	3.85	4.96
Flash Point ^{o}C	61	57	59	62	65
Fire Point ^{o}C	65	67	71	74	78

2.1 Experimental setup :

An experimental setup was used in this study to analyse the engine's performance characteristics (PCs) and combustion characteristics (CCs) at different CRs of 12:1, 15:1, and 17:1 respectively. The tests were carried on a single-cylinder, water-cooled, four-stroke diesel engine with a displacement of 553 cubic centimetres, a speed of 1,500 revolutions per minute, and a power output of 3.75 kW. An eddy current dynamometer is attached to the motor. It also has a fuel system, lubrication system, and several sensors and gauges for measuring load, air and fuel flow, and exhaust temperature that are all incorporated into the data collecting system. The arrangement allows for the evaluation of the engine's thermal properties and emission components. The thermocouples have been placed in the proper locations. Peak pressure, maximum heat release rate, and ignition delay in fuel combustion are the performance parameters, whereas BP, SFC, and exhaust temperature are the combustion characteristics parameters. Also included is an exhaust gas analyser. The exhaust gas analyzer measures exhaust components such as CO, HC, and NOx. The conceptual depiction of the test facility is shown in Fig. 1, and the actual test facility is shown in Fig. 2 [5], [6], [7].

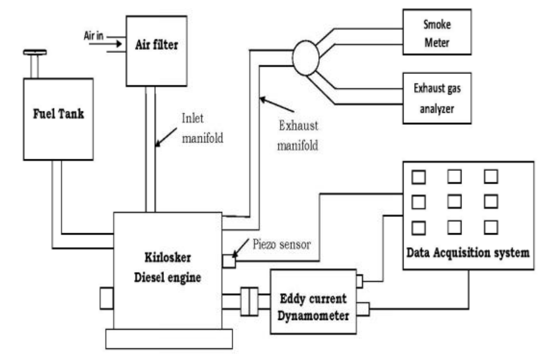

Figure 1: Schematic diagram of the experimental setup.

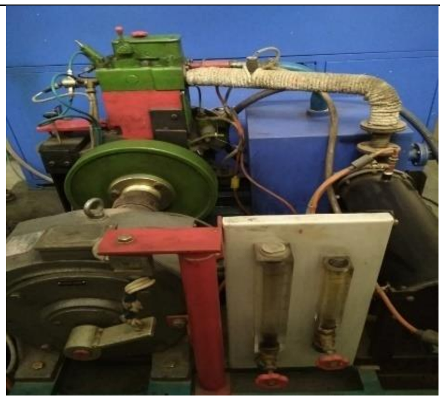

Fig.2. shows the actual experimental setup

The engine operation tests were carried out and compared successively with diesel and biodiesel mixtures. The tests were repeated three times and the average values of the measured values were recorded. Each time the proportion of biodiesel or mixture changes, the engine is operated with diesel for a few minutes to flush the fuel lines [14], [15].

2.2 Performance characteristics evaluation :

Performance and emission analysis experiments were carried out on an internal combustion engine powered by various mixtures (NB-10, NB-15, NB-20 and NB-25) of Neem biodiesel. For a fuel consumption of 10 cm^3 the time was taken, the speed and torque were recorded and the corresponding power parameters such as BP, mechanical efficiency, BSFC, BTE, ITE were calculated. The exhaust emissions analyzed include CO, CO_2, NO_x and unburned hydrocarbons [8]. However at maximum load (80%), as shown in Table 2, NB10 outperforms all other biodiesel blends in terms of performance and emissions. Although several research have been completed under constant CR, a very few studies on combustion analysis in VCRs using Neem biodiesel as a fuel. As a result, NB10 was chosen for future research [8], [9], [10].

Table 2: Performance and emission characteristics of various neem biodiesel blends at various compression ratios.

	BP in kW			BSFC in kg-kW/hr.			BTE in %		
CR	12:	15:1	17:1	12:1	15:1	17:1	12:1	15:1	17:1
NB10	2.2	2.41	2.64	0.40	0.38	0.31	21.74	23.03	27.89
NB15	1.1	2.3	2.30	0.64	0.41	0.29	13.83	21.43	30.16
NB20	1.4	2.45	2.39	0.65	0.37	0.33	13.72	23.88	26.66
NB25	1.5	1.63	2.14	0.59	0.47	0.39	15.45	19.22	23.41

	CO in %			CO_2 in %			HC in ppm			NOx in ppm		
CR	12:1	15:1	17:	12:1	15:1	17:	12:1	15:1	17:	12:1	15:	17:
NB 10	15.74	0.601	0.2	5.7	13.98	3.1	17.08	21.0	13.	1405	68	47
NB 15	14.5	4.29	9.4	5.0	10.44	3.3	11.69	12.7	16.	1388.4	95	57
NB 20	13.2	7.98	9.5	4.2	6.89	3.4	27.92	18.63	19.	1371.9	12	66
NB 25	11.67	11.95	9.6	3.4	3.46	3.5	29.26	27.75	19.	1472	13	76

2.3 Combustion characteristics evaluation :

The process of combustion of fuel in the engine is the measurement of pressure in the cylinder at each crank angle of the engine. However, the history of pressure is affected by numerous variables, such as the change in the combustion chamber volume, the heat exchange with the walls and the mass of fluid flow. As a result, separating the impacts of heat transfer, mass loss and volume change is required for a comprehensive understanding of combustion events. Calculating the HRR speed has the advantage of identifying indicators of combustion such as ignition duration, combustion duration, HRR speed, and crank shaft angle position [11], [12]. Combustion is the process of burning fuel in the presence of oxygen to produce heat. This may be characterized (i) by the heat release rate (ii) by the delay of the ignition.

Heat release rate calculations :

The in-cylinder pressure and volume are the important parameter to analyze the combustion of fuel in CI engines and work producing process of the piston. During this process, heat is transferred to the walls of the combustion chamber, and the mass enters the crack zones and comes out of them between the piston, piston rings and the cylinder casing. The process of heat transfer and loss of mass at cylinder pressure relative to the angle of the crank shaft (cylinder volume) is called heat release analysis and is carried out within the framework of the first law of thermodynamics. The first law of the thermodynamic model of heat release is

$$\frac{dQ}{d\theta} = \frac{\gamma-1}{\gamma}\, p\, \frac{dV}{d\theta} + \frac{1}{\gamma-1}\, V\, \frac{dp}{d\theta}$$

Where

γ = Rate of specific heat (1.2 -1.4), P = Pressure inside the cylinder in bar, V = Volume of the cylinder in m^3, dp = Change of Pressure in bar, dv = Change of Volume in m^3.

The volume of the cylinder at any crank angle is given by

$$V_\theta = Vc + \frac{\pi d^2}{4}\left(\frac{l}{2}\right)(1 + Z - (Z^2 - Sin^2\theta)^{\frac{1}{2}} - Cos\theta)$$

Where

$Z = \frac{L}{l}$, d = Diameter of the cylinder in m, L = length of connecting rod in m, l = length of stroke in m, V_θ = Volume at any crank angle in m^3, V_C = Clearance Volume in m^3

Ignition delay (ID) :

The difference between the start of combustion (SOC) and the start of fuel injection (SOI) in relation to crank angle was used to compute the ignition delay. As discussed in section 2.2, NB10 has been considered for combustion analysis by experimental and CFD methods [13], [16].

CFD analysis process :

CFD analysis was carried out using ANSYS Fluent 15.0 Post-processing was carried out using ANSYS CFX is used for simulation and ANSYS CFX is used for post-processing of simulation results. Standard procedures which included the steps; formulation of the flow problem, geometric modeling considering a bowl type piston, flow domain modeling, establishing of boundary and initial conditions, grid generation using hexahedral elements, simulation and post-processing.

3. RESULTS AND DISCUSSION :

3.1 Pressure vs. Crank angle (P-Ɵ) Diagrams:

The comparison of P- Ɵ diagrams generated from experimental and CFD analyses for different CRs is shown in Fig.3 through Fig.6. The maximum pressure values from the experimental and CFD analyses for various CRs are shown in Fig.7.

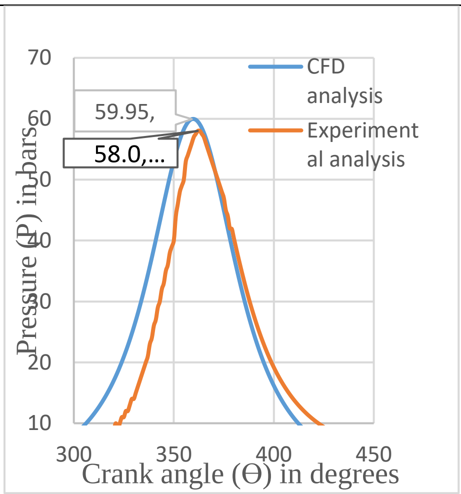

Fig.3: P- Ɵ diagram for neem B10 at CR 12:1

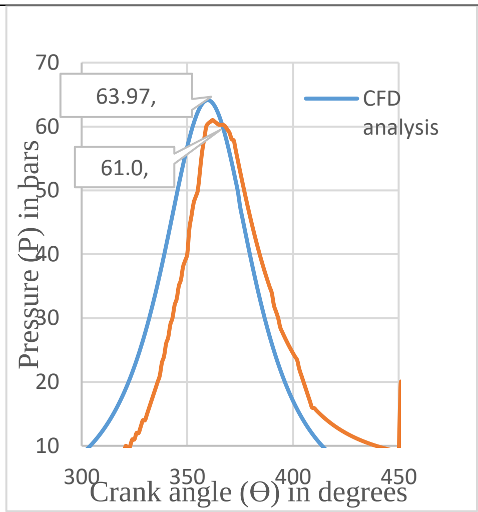

Fig.4: P- Ɵ diagram for neem B10 at CR 15:1

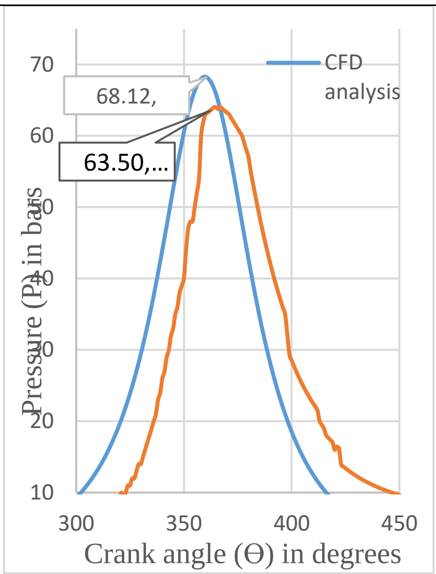

Fig.5: P- Θ diagram for neem B10 at CR 17:1

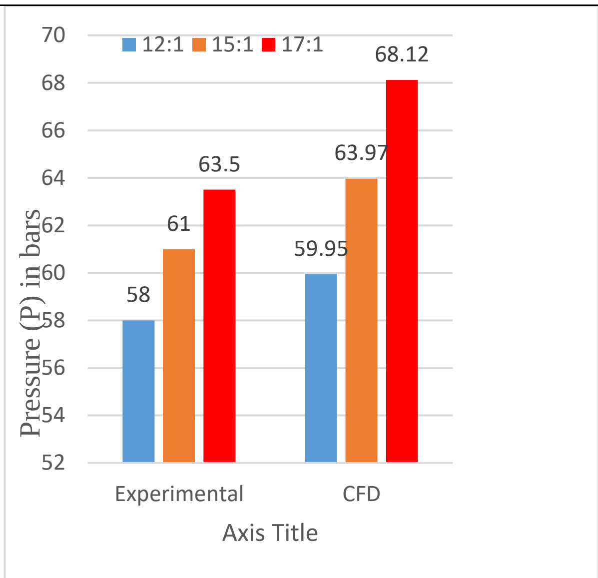

Fig.6: Peak Pressure (P) in bar for NB10 for different CRs

For Experimental and CFD study, the max pressure created in the cylinder at CR 12:1 is 58.0 (at crank angle 362°) and 59.95 (at crank angle 360.5°). Similarly, for experimental and CFD analysis, 61.0 (at crank angle 361°) and 63.97 (at crank angle 360.5°) bars at CR 15:1 and 63.5 (at crank angle 360°) and 68.12 (at crank angle 360.5°) bars at CR 17:1 were recorded. The results show that the peak pressure period of the combustion in CFD simulation remained the same as in experimental investigation. The results exhibit that in CFD simulation, the peak pressure period of the combustion remained the same and not changed as in experimental analysis. In a traditional engine, when the crank angle changes, the cylinder volume changes, causing the characteristics of biodiesel to change, resulting in distinct phases of combustion and ignition delays for each CR. The properties of biodiesel evolve linearly in a CFD simulation based on energy and mass conservation equations with initial boundary conditions. [17], [18].

With a rise in CR, the peak pressure created in the cylinder increases, but the ignition delay reduces. Biodiesel has a higher fuel-burning rate in the early stages of combustion due to its higher oxygen content, as well as a higher operating temperature in the fuel due to its higher CR, which brings the peak pressure closer to TDC. As a result, the ignition delay is reduced.

The correlation coefficient for the experimental and CFD results for the P- Θ diagram required for the validation result demonstrated a significant correlation between experimental and CFD results, with R2 values of 0.8998, 0.8216, and 0.7269 for CR 12:1, 15:1, and 17:1, respectively.. As a result, the CFD study is helpful in confirming the CI engine's CCs. According to the literature, only a few people have tried this type of CFD analysis before (using ANSYS 15.0). This could be a good model for future researchers to adopt.

3.2 Heat Release Rate analysis :

From Fig.7 to Fig.9, the HRR at a varied crank angle for different CRs for NB10 obtained from Experimental and CFD modelling are compared. The ignition delay for NB10 for various CRs is shown in Fig.10.

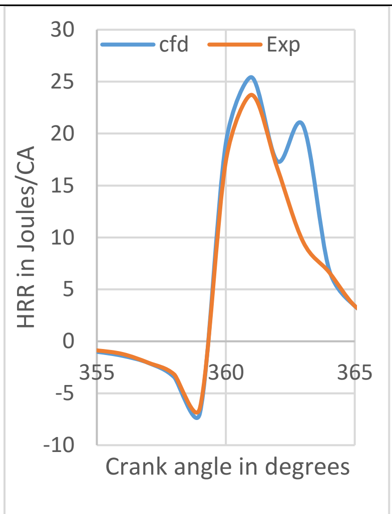

Fig.7: Comparison of HRR for NB10 at CR 12:1

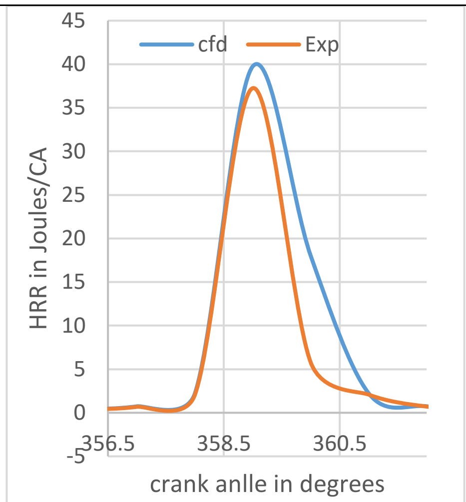

Fig.8: Comparison of HRR for NB10 at CR 15:1

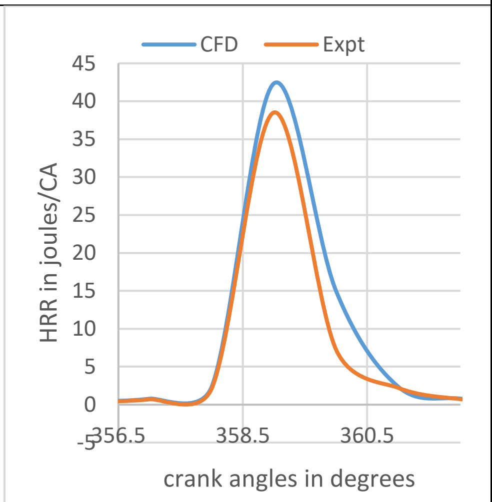

Fig.9: Comparison of HRR for NB10 at CR 17:1

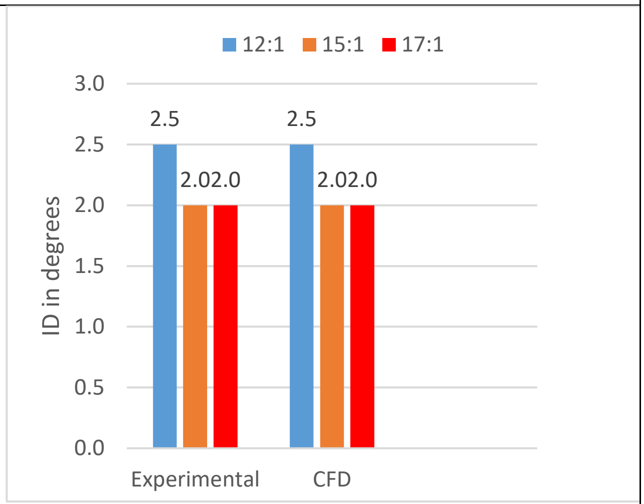

Fig.10: Ignition delay (ID) in degrees for NB10 for different CRs

For Experimental and CFD study, the HRR in the cylinder at CR 12:1 is 23.73 and 25.42 joules per crank angle, respectively. Similarly, for Experimental and CFD analyses, 37.25 and 39.76 joules at CR 15:1 and 38.51 and 42.34 joules at CR 17:1 were obtained.

In contrast, in all types of analysis, the ignition delay during the combustion of NB10 changed from 2.5° to 2° for various CRs from 12:1 to 17:1. HRR changes as a result of continuous fuel injection, heat addition from combustion, and heat loss from work and engine cooling [19], [20].

The correlation coefficient for experimental and CFD results for HRR necessary for validation revealed a significant connection between experimental and CFD results, with R2 values of 0.9368, 0.9237, and 0.9753 for CR 12:1, 15:1, and 17:1 respectively. As a result, CFD study is useful for validating IC engine Combustion Characteristics.

4. Conclusion

- The results show that the peak pressure period of the combustion in the CFD simulation stayed the same and not changed as in the experiment. In a traditional engine, when the crank angle changes, the cylinder volume changes, causing the characteristics of biodiesel to change, resulting in distinct phases of combustion and variable ignition delays for each CR. The properties of biodiesel evolve linearly in a CFD simulation based on energy and mass conservation equations with initial boundary conditions.

- It is worth noting that the experimental and CFD findings obtained for peak pressure have R2 values of 0.8998, 0.8216, and 0.7269 for CR 12:1, 15:1, and 17:1, respectively. As the compression ratio rises, the ignition delay lowers. For both experimental study and CFD, the minimal delay period for a full load at 17:1 compression was recorded.
- It has also been demonstrated that CFD modelling and analysis can be an effective tool for analyzing the combustion of CI engines under various operating situations, such as varying compression ratio.

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