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Impact of Compressed Natural Gas on CRDI Engine with Waste Plastic Oil Blend

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Abstract: *This experimental study aims to investigate the impact of compressed natural gas (CNG) on a CRDI (Common Rail Direct Injection) engine operating with a selected waste plastic oil blend. The growing concern for environmental sustainability and the need for alternative fuels have led to increased interest in utilizing waste plastic oil as a potential fuel source. In this research, the focus is on evaluating the performance and emissions profile of a CRDI engine when using a blend of waste plastic oil and CNG. Experimental tests are conducted on the CRDI engine to find out the impact of waste plastic oil blend WPO20D80 (20% of waste plastic oil, 80% of Diesel fuel) with different flow rates of CNG (10%, 20% and 30%). Parameters such as brake power, brake specific fuel consumption, emissions of pollutants (such as NOx, CO, HC), combustion characteristics (such as heat release rate and cylinder pressure), and overall engine performance are measured and analysed. The results compared with those of conventional diesel fuel operation.*

Key Words: *CRDI engine, CNG, waste plastic oil, performance.*

1. INTRODUCTION:

In today's world, the transportation and power generation sectors heavily rely on CI engines due to their remarkable fuel efficiency and reduced exhaust emissions of carbon monoxide (CO) and unburned hydrocarbons (UHC) [1]. However, it is important to acknowledge that these compression ignition (CI) engines also pose significant environmental risks as they can generate elevated levels of nitrogen oxides (NOx) and particulate matter [2-5]. The emission regulatory organizations in various countries have imposed stringent guidelines due to the emissions mentioned above. To tackle these concerns, engineers and researchers have been compelled to explore alternative fuels and novel combustion techniques to enhance engine performance and emission characteristics. Extensive literature has provided various emission reduction technologies aimed at decreasing exhaust emissions while simultaneously improving the performance of diesel engines [6-10]. The utilization of the dual fuel mode has emerged as a highly promising combustion method. This mode involves the simultaneous use of two distinct fuels. The primary fuel employed is a gaseous fuel, such as compressed natural gas (CNG), liquefied petroleum gas (LPG), or hydrogen, which possesses a high cetane number. On the other hand, the pilot fuel consists of a liquid fuel, namely diesel or biodiesel [11]. Ongoing modifications are being made to these engines to enable the co-combustion of fuels with varying reactivity. These modifications facilitate the simultaneous combustion of both liquid fuels, such as alcohols, and gaseous fuels, including compressed natural gas (CNG), liquefied natural gas (LNG), or hydrogen [12-14]. Dual-fuel engines that utilize gas as a fuel source incorporate a gas supply system, gas mixer, or injector. On the other hand, in liquid fuel engines, additional injectors are installed in the intake manifold. The redesign of the control system aims to account for the variations in the co-combustion process of different fuels compared to the reference fuel, primarily focusing on the ignition angle differences [15]. In today's world, plastics have become an indispensable commodity due to their exceptional versatility, extensive range of applications, and convenient manufacturing process. Plastics are primarily derived from petroleum products and are composed of lengthy hydrocarbon chains. Additionally, they are formulated with various additives, including coloring agents, anti-oxidants, and stabilizers [16-17]. Among the various fuel options, plastic oil generated through the pyrolysis process has gained significant attention due to its accessibility and environmental impact. Plastics have become an essential material in both industrial and household sectors, becoming virtually unavoidable. The demand for plastics continues to rise steadily, driven by their highly desirable characteristics and user-friendly nature. One significant concern associated with plastic oil is its higher density and viscosity in comparison to diesel. To mitigate these drawbacks, small amounts of oxygenated additives employed as combustion enhancers [18-21]. The impact of dual fuel combustion (specifically Diesel/hydrogen and Diesel/HHO gas) on the performance and emission characteristics of a dual fuel compression ignition (CI) engine was thoroughly examined. The investigation revealed that the introduction of alternative fuels resulted in a significant reduction in diesel consumption and emissions. Additionally, there was a simultaneous improvement in brake thermal efficiency (BTE) with the addition of 6 liters per minute (LPM) of HHO gas into the combustion chamber [22]. In order to enhance engine performance and decrease NOx emissions, a single-cylinder, 4-stroke, water-cooled, vertical diesel engine with a power output of 3.5 kW was selected for a dual fuel-based Reactivity Controlled Compression Ignition (RCCI) strategy. The RCCI strategy involved introducing approximately 10% of the total energy in the form of compressed natural gas (CNG) while blending different proportions (10%, 20%, and 30%) of non-edible seed oil biodiesel (NSOB) with conventional diesel. When compared to conventional diesel operation, the engine's performance with CNG supplementation exhibited subpar outcomes, resulting in an average decrease in Brake Thermal Efficiency (BTE) of 4.86% from the minimum load to the maximum load [23]. Enriched biogas (Bio-CNG) emits slightly more hydrocarbons (HC), carbon monoxide (CO), and nitrogen oxides (NOx) than compressed natural gas (CNG). Both enhanced biogas and CNG fuel usage remain unchanged. Enhanced biogas engines fulfil BS IV emission regulations. Compared to fossil CNG, renewable enhanced biogas performs similarly or better. Thus, enhanced biogas can fuel spark ignition automobiles [24-25]. Karabektas et al. [26] proposed a modification to the pilot fuel dose composition in a diesel-CNG dual-fuel engine by introducing diethyl ether (DEE) into the diesel fuel. The study focused on the combustion of diesel fuel alone, the co-combustion of diesel with 40% CNG, and the co-combustion of diesel and DEE with 40% CNG. The pilot-doses of DEE utilized were 5% and 10%.The findings revealed that the co-combustion of diesel fuel with CNG resulted in a decline in engine performance, particularly at low and medium loads. Additionally, this combination exhibited higher carbon monoxide (CO) and hydrocarbon (HC) emissions across all loads, while showcasing lower nitrogen oxides (NOx) emissions at high loads. However, the incorporation of DEE as an additive to the pilot dose demonstrated improvements in thermal efficiency and a reduction in specific energy consumption. Consequently, this led to decreased CO and NOx emissions. In the present work experimentation done on a single cylinder Automotive Dual fuel Diesel engine with waste plastic oil blend WPO20D80 at different flow rates of CNG (10%, 20% and 30%).

2. MATERIALS AND METHODS:

Preparation of Waste Plastic Oil

The Waste plastics are cannot be used as direct energy source, if they used directly, they burned and produces very harmful gases to the environment. In order to convert the raw waste plastic into useful energy source as fuel to use in diesel engines pyrolysis method was used. Pyrolysis is the thermal decomposition of biomass at high temperatures in an inert atmosphere. The main components for production WPO by using pyrolysis method are Reactor, heating coil, condenser, temperature controller and oil collector as shown in Figure 1.

Initially raw waste plastics were collected and crushed to small pieces and fed into the reactor chamber. The reactor is consisting of Nichrome wire heater where the temperatures were maintained between the ranges of 300°C to 500°C for period of 3 to 4 hours. PID controller is used to control the heating rate and temperature. At this high temperature, the waste plastic burned and evaporated. Then the evaporated waste plastic vapour supplied to the condenser where its get cooled. The condenser temperature is maintained at 25°C by circulating the cold water. Then the condensed plastic waste oil collected in the oil collector. In this pyrolysis process a weight of 75% liquid hydrocarbon (WPO), 5 to 10 % of residual coke and the rest is gas. The non-condensable gases were released into the environment, while the quality of the collected waste plastic oil (WPO) was poor. Approximately 2.09 kilograms of plastic waste feedstock were required to produce 1 kilogram of WPO. The process yielded WPO (50%), Pyro gas (40%), and char (10%). The energy input for converting waste plastic into products amounted to around 7.8 MJ/kg. The pyrolysis process had a duration of 90 minutes. The composition of the WPO was consistent with values reported in earlier research publications. As the oil used in this study was unprocessed, the WPO contained contaminants, dust, as well as low and high volatile hydrocarbon fractions. The WPO underwent filtration using a cloth filter followed by a micron filter, achieving a filtration efficiency of 99%.

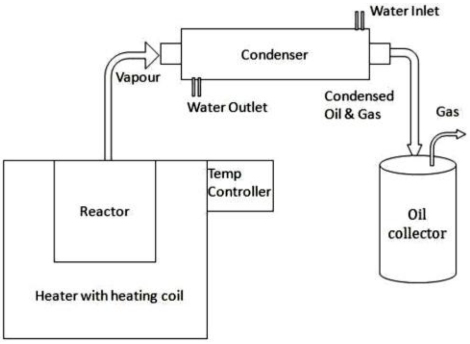

FIGURE 1: Schematic layout of production of WPO

Table 1. Properties of Test Fuel

Property	Waste Plastic Oil	Diesel
Density @ $30^{o}C$ in (g/cc)	0.8355	0.840
Ash content (%)	0.00023	0.045
Gross calorific value (kJ/kg)	44,340	46,500
Kinematic viscosity, cst @ $40^{o}C$	2.52	2.0
Cetane number	51	55
Flash point (^{o}C)	42	50
Fire point (^{o}C)	45	56

Table 2. Properties of CNG.

Property	CNG
Boiling point (K@1 atm)	147
Density (kg/m3@1atm 15°C)	0.77
Flash point	124
Octane number	130
Flammability limit range Flame speed (cm/s)	5.0–15.0 33
Net energy content (MJ/kg)	49.5
Auto ignition temperature (k)	923
Combustion energy (kJ/m3)	24.6
Stoichiometric air fuel ratio	17

Experimental Setup:

The experimental setup utilized in this study involved Mahendra & Mahendra's JEETO CRDi vehicle research engine. This test engine is a water-cooled, single-cylinder, four-stroke, direct injection (DI) compression ignition diesel engine. Detailed information about the research engine found in Table 1. The schematic representation of the engine setup depicted in Figure 2. To control the engine setup, an open Electronic Control Unit (ECU) was employed. The open ECU played a crucial role in sensor data evaluation, fuel mass calculation, injection time control, fuel pressure regulation (up to 1000 bar), and identification of top dead centers (TDCs) in the engine, main relay control, engine speed control, and communication. The ECU was calibrated using dedicated software for PCs, which allowed for precise adjustments and fine-tuning. Additionally, the software facilitated data collection during engine operation, enabling thorough analysis. To establish communication between the open ECU(MCS1-i7 model) and the data acquisition system, a Kvaser Leaf Light V2 type CAN cable was employed. This connection enabled seamless data transfer and synchronization between the ECU and the data gathering system. The engine's performance was controlled and monitored through the implementation of an open ECU, which facilitated precise calibration and data collection for comprehensive analysis. The cylinder head of the engine was equipped with a PCB113A22 model piezo-electric pressure transducer from PCB Piezotronics. This pressure sensor had a range of 0-344 bar and was connected to a charge amplifier to ensure accurate measurement of cylinder pressure. The AUTONICS model E5OS8 rotary encoder was utilized to measure the crank angle. Rotary encoders are capable of continuously tracking the position of the crankshaft by converting rotational motion into electrical pulses. By analyzing the output pulses of the encoder, the data acquisition system accurately calculated engine speed and top dead center (TDC) positions. For data collection and analysis, an engine scan software based on LabVIEW was employed. This software facilitated the collection and analysis of various parameters such as airflow, fuel consumption, and in-cylinder pressure. To detect fuel usage, a pressure-based fuel flow sensor was employed, which utilized a pressure transmitter from the Dawyer 628 series. The fuel flow sensor was controlled by a UnflowDAN14Z solenoid valve, which was normally open but could be closed by the engine scan software for a specific duration (30 or 60 seconds) to interrupt fuel supply from the tank.The intake airflow rate was measured using an HFM Type T-MAF sensor.

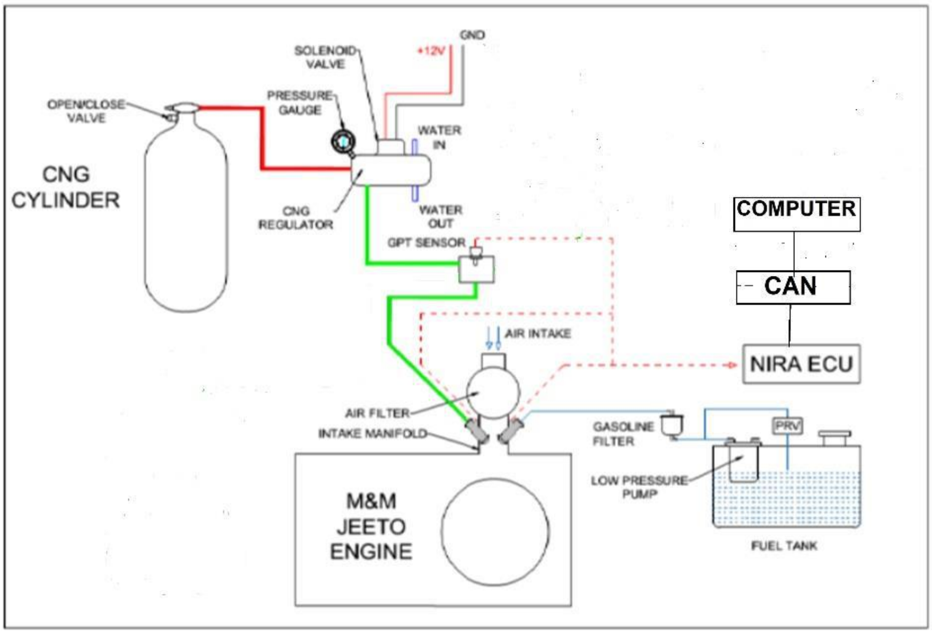

FIGURE 2: Line Diagram of Experimental setup

Table 3. The research engine specifications

Description	Specifications
Make	Mahendra and Mahendra
No.of Cylinders	1
Engine capacity (cc)	625
Number of strokes	4
Compression Ratio	18:1
Bore (mm)	93.0 to 93.018
Stroke length (mm)	92
Application	Automotive (Multi speed)
Ignition	Compression Ignition
Nozzle diameter and holes	0.145 mm and 6 holes
Max. Power @RPM	9HP @ 3000 RPM
Max. Torque @RPM	30NM @ 1800 RPM
Cooling	Water Cooled
Number of Valves	2

Table 4. Emissions analyzer specifications

Name of the analyzer	Measuring Range	Precision	Resolution
AVL Analyzer	0-100 HSU	1 HSU	1 HSU
Netel Chromatograph NOx analyzer	0-5000 ppm	5 ppm	5 ppm

This sensor employed the hot film principle to calculate the engine's intake airflow in kilograms per hour. It provided a digital output for airflow measurement and also included an in-built NTC-based ambient air temperature sensor, allowing the ECU's software to record this value. To measure the exhaust emissions, an AVL gas analyzer was utilized. The gas analyser's specifications are detailed in Table 4, which provides information on its capabilities and features.

3. RESULTS AND DISCUSSIONS:

An experimental comparison done on CRDI Diesel engine with selected waste plastic oil blend WPO20D80 with different ratios of CNG as it shows best performance among the blends. The following performance & emissions parameters were evaluated and discussed below.

4. PERFORMANCE PARAMETERS:

Brake Thermal Efficiency:

The combustion quality of an engine is reflected by its brake thermal efficiency (BTE), as illustrated in Figure 3, depicting the relationship between BTE and brake power (BP). Under low load conditions, the conventional diesel engine exhibited a higher BTE compared to the dual-fuel engine. This disparity in BTE was attributed to two factors: the elevated self-ignition temperature of CNG and the deficient flame propagation characteristics of the lean CNG-air mixture in the dual-fuel engine. As the load increased, the fuel-air mixture gradually shifted towards a richer composition, resulting in elevated temperatures within the mixture and the engine cylinder. This, in turn, decreased the ignition delay of both the primary and pilot fuels, contributing to an enhancement in BTE.

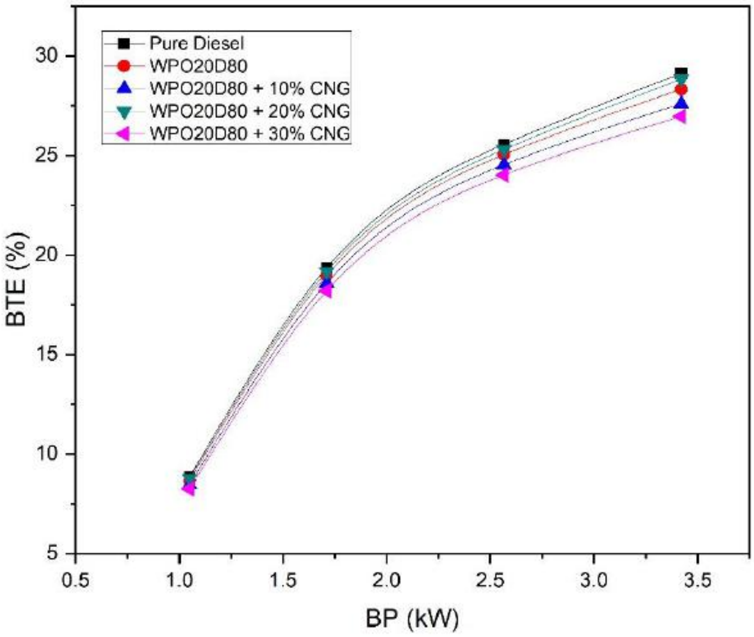

FIGURE 3: variation of BP vs BTE

Brake Specific Fuel Consumptio:

The brake specific energy consumption (BSEC) of an engine represents the ratio of the total energy consumed to the engine's brake power. Figure 4 depicts the variation of total BSEC with brake power (BP). To compare the conventional diesel engine and the dual fuel engine, the total mass of fuel consumed during operation was converted into total energy for each loading condition. It was observed that, at low and intermediate loads, the conventional diesel engine exhibited a higher total BSEC compared to the dual fuel engine. This difference was primarily attributed to the suboptimal utilization of gaseous fuel in the dual fuel engine at low loads. However, as the load increased and the calorific value of CNG improved, the fuel utilization in the dual fuel engine also improved, leading to an enhancement in the total BSEC. Interestingly, at high load conditions, the total BSEC of the dual fuel engine surpassed that of the conventional diesel engine.

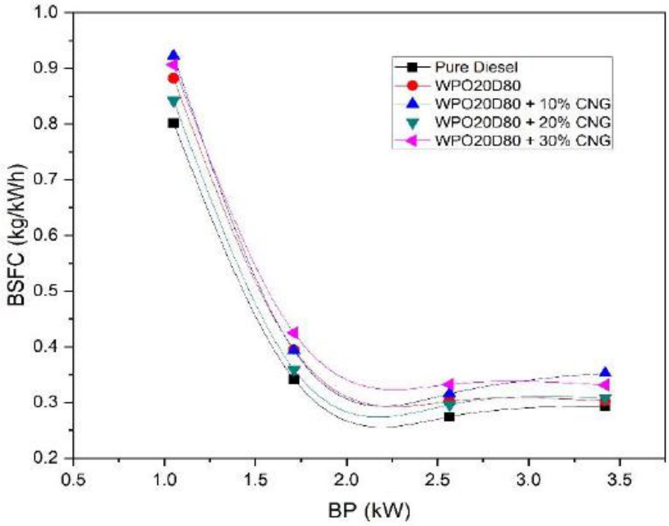

FIGURE 4: variation of BP vs BSFC

5. EMISSION CHARACTERISTICS:

Carbon Monoxide:

The presence of carbon monoxide (CO) emissions indicates inadequate and incomplete combustion in the dual fuel engine, primarily caused by lower in-cylinder temperatures and limited oxygen availability. Figure 8 displays the relationship between CO emissions and load for all operating modes. In general, the dual fuel engine exhibited higher CO emissions compared to the conventional diesel engine across various loads, except at full load. This disparity can be attributed to the challenges faced in achieving efficient combustion of gaseous fuel due to the dilute CNG-air mixture and low in-cylinder temperatures. However, as the load increased, the rate of CO emissions from the dual fuel engine decreased, indicating improved combustion efficiency.

Hydrocarbons (HC):

Figure 8 depicts the variation of Brake Power and Hydrocarbons. The presence of unburned hydrocarbons in the exhaust gas indicates incomplete combustion and serves as a crucial indicator of combustion inefficiency. Previous investigations have shown that at lower loads, there is a higher concentration of unburned hydrocarbons due to inadequate fuel distribution and lower in-cylinder temperatures. from the figure it can be observed that the HC emissions are more in the combination of WPO20D80 + 30% CNG. The higher viscosity of the fuel blend poses limitations on achieving thorough mixing, leading to the formation of localized areas with both rich and lean mixtures. In these regions, the lean mixtures lack sufficient richness to ignite, while the fuel-rich areas lack adequate oxygen to completely burn the fuel. Additionally, the unsaturated aromatic compounds present in the blend exhibit resistance to decomposition during the combustion process.

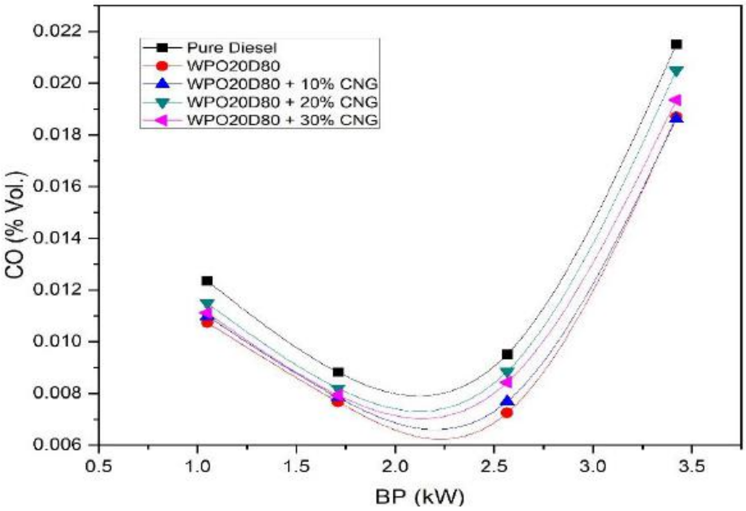

FIGURE 7: variation of BP vs CO

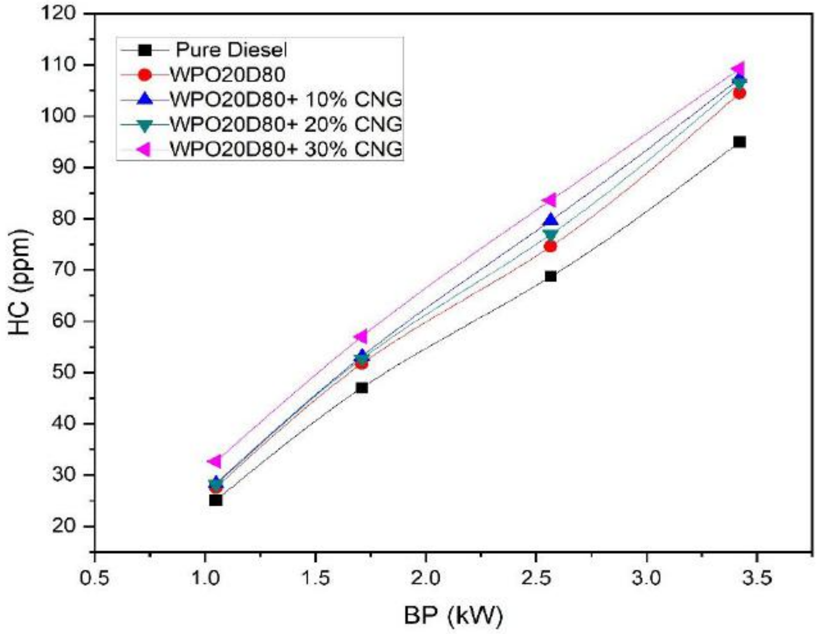

FIGURE 8: variation of BP vs HC

Nitrogen Oxides (NOx):

Figure 6a illustrates the impact of using CNG gas on the emission of nitrogen oxides. Nitrogen oxide emissions from a piston engine mainly consist of nitric oxide (NO) and nitrogen dioxide (NOx).The formation of nitric oxide in the engine is a direct result of the reaction between nitrogen (N2) and oxygen (O2) during the combustion process in the engine cylinder, under the favorable conditions present. While NO is primarily produced during combustion, NOx is formed through the oxidation of nitric oxide in the atmospheric air. The concentration of NOx in the exhaust gas is significantly lower than that of NO. Increasing the proportion of CNG co-combusted with diesel fuel leads to higher emissions of nitric oxide. The highest recorded NO emission value, reaching 242 parts per million (ppm), was observed when using WPO20D80 + 30% CNG. This increase in nitric oxide emissions resulted from intensified combustion during the kinetic phase and an increased rate of heat release, facilitated by the co-combustion of CNG gas with diesel fuel. However, once the CNG gas proportion exceeded 30%, the rise in nitrogen oxide emissions was attributed to an excess availability of oxygen in the engine cylinder, which remained unused during the prolonged combustion process. Furthermore, the presence of nitrogen-rich CNG gas led to an increased concentration of nitrogen in the engine cylinder and the exhaust gas.

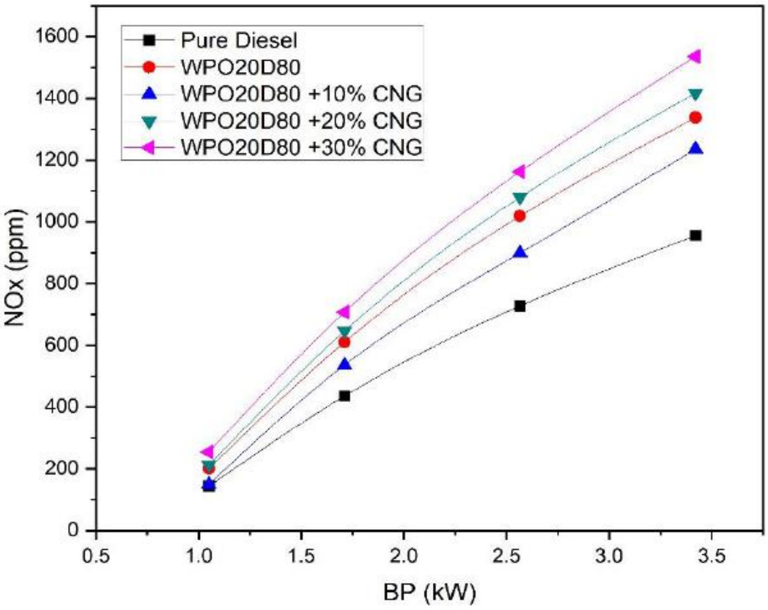

FIGURE 9: variation of BP vs NOx

6. CONCLUSIONS:

The experimental tests conducted on the CRDI engine involved the use of a specific blend, WPO20D80 (20% waste plastic oil and 80% diesel fuel), with varying flow rates of CNG (10%, 20%, and 30%). Several parameters, including brake power, brake specific fuel consumption, emissions of pollutants (NOx, CO, HC), combustion characteristics (heat release rate, cylinder pressure), and overall engine performance, were measured and analysed. The results of the study indicated that the utilization of the WPO20D80 blend with CNG as an alternative fuel in the CRDI engine had a significant impact on engine performance and emissions. In terms of engine performance, the brake power and brake specific fuel consumption were evaluated, and it was found that the blend of waste plastic oil and CNG had a positive effect on brake power, while reducing the brake specific fuel consumption compared to conventional diesel fuel. Regarding emissions, the study focused on the pollutants NOx, CO, and HC. The results demonstrated that the use of the WPO20D80 blend with CNG led to lower emissions of these pollutants compared to conventional diesel fuel. This reduction in emissions can be attributed to the properties of waste plastic oil, which has a lower carbon content and a higher hydrogen-to-carbon ratio compared to diesel fuel.

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