Experimental Combustion Characteristics, Nanoparticles and Soot-NO_x trade off in a Common-Rail HSDI Diesel Engine running on ULSD and HFO Fuels

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ABSTRACT

The flow distribution This study investigates the combustion characteristics, nanoparticles and soot-NOx trade off from a high speed direct injection (HSDI) diesel engine fueled with ultra-low sulfur diesel (ULSD) and heavy fuel oil (HFO) and run at a constant speed (1500 rpm) with single injection strategy at constant fuel injection pressure (1200 bar) and varying fuel injection timings (-12,-9,-6,-3,0) ATDC , for two loads(2.5 and 5 bars) BMEP . In-cylinder pressure was measured and analyzed using (LABVIWE) program. Calculation program specially written in (MATLAB) software was used to extract the apparent heat release rate. Gases emission measurements included; NOx, CO, THC and smoke number (SN). An electrostatic mobility spectrometer (EMS) was used in this experiment to obtain the exhaust soot particle number size distribution. The results showed that ULSD generate higher NOx due to higher combustion temperature, while, HFO generate higher soot due to sulphur content. The mass particle size distribution of HFO has a unimodal shape with two maxima points, one in the nucleation mode at diameter around 11nm and another one in the accumulation mode at diameter around 123 nm. The nucleation and accumulation CCN of HFO was higher than of USLD fuel at low and high loads, the difference is particularly obvious at accumulation mode.

Keywords: *The author shall provide up to 5 keywords (in alphabetical order) to help identify the major topics of the paper.*

INTRODUCTION

Heavy fuel oil (HFO) is a residue from the crude oil refining process and as such is the dregs of the process. It is so viscous that it has to be heated with a special heating system before use and it contains relatively high amounts of pollutants, particularly sulphur, which forms sulfur dioxide upon combustion [1]. Heavy fuel oil is used in marine main diesel engines, power plants and large diesel engines which are used for power generation. The fuel quality of HFO is quite important for smoke formation [2]. Higher sulphur, lower cetane number (CN) and higher fuel density give more smoke; aromatics and volatility have a slight increasing of smoke. Reducing fuel density lowers NOx and PM, but increases HC and CO [3].

Sulphur is one of the most important fuel characteristic to address in order to reduce emissions from diesel engines[4], contributing directly to PM emissions. Diesel fuel typically contains from 0.1 to several wt-% sulphur [1]. Sulphur is also known to interfere with several diesel combustion and emission control strategies. High levels of sulphur in diesel fuel exclude the use of the most effective PM and NOx control technologies [5]. In the exhaust from diesel engines, PM primarily consists of agglomerate carbon particles, soluble organic fraction (SOF) that can condense on the surface of the carbon particles or nucleate to form new very small particle during the dilution and cooling process, lesser amounts of sulfate compounds, and other species [5-7]. The particle size distributions are generally lognormal in form and may include three modes denoted as nucleation, accumulation and coarse modes.

Sarvi et. al.[1] compared the emission of burning heavy fuel (HFO) and light fuel (LFO) oils. PM emissions are more than three times higher with HFO than with LFO and appear to decrease with the load except for HFO during the generator mode where an increase of PM emissions with the load is seen.

Nabi et.al.[8] studied diesel particulate matter emissions, with special interest in fine particles from the combustion of two base fuels. The base fuels selected were diesel fuel and marine gas oil (MGO). The results showed that the fine particle number emissions were higher with MGO compared to diesel fuel. It was observed that the fine particle number emissions with the two base fuels were quantitatively different but qualitatively similar. The gravimetric (mass basis) measurement also showed higher total particulate matter emissions with the MGO.

The aim of this investigation was to study the combustion characteristics, nanoparticles and soot-NOx trade off from a high speed direct injection (HSDI) diesel engine fueled with ultra-low sulfur diesel (ULSD) and heavy fuel oil (HFO) and run at a constant speed (1500 rpm) with single injection strategy at constant fuel injection pressure (1200 bar) and varying fuel injection timings (-12,-9,-6,-3,0) ATDC , for two loads(2.5 and 5 bars) BMEP .

EXPERIMENTAL SETUP

Experiments were carried out in a 2.0 lt, 4 cylinders, 16 valves, and compression ratio18.2, direct Injection Ford's Duratorq (Puma) Euro3 diesel engine. Instrumentation enables the measurement of in-cylinder pressure and exhaust gas emissions under steady-state engine operating conditions. The in-cylinder pressures were measured using a Kistler pressure transducer fitted into the first cylinder of the engine. The signal from pressure transducer was amplified by the charge amplified and then recorded by the (LabView) software in conjunction with the shaft encoder. In-cylinder pressure data were collected over 100 engine cycles per measurement, and the measurement was repeated 5 times for each point in the experimental matrix .These data were averaged from 100 cycles. A common rail fuel injection system with six holes injector of 0.154 mm in diameter, and a spray-hole angle of 1540 was used in this investigation.

The gaseous exhaust emissions were acquired using a Horiba-Mexa 7170DEGR gas analyzer. The engine exhaust smoke emissions were measured using the AVL – 415 smoke meter. An electrostatic mobility spectrometer (EMS) was used in this experiment to obtain the exhaust soot particle number size distribution. The EMS consists of a differential mobility analyzer (DMA) coupled to a Faraday cup electrometer (FCE), a neutralizer and a dilution probe where exhaust soot particles are simultaneously diluted and heated up. The DMA used in this work is approximately 600 mm long and it is capable of measuring particle mobility diameters in the range from 5 nm to 700 nm. Dilution ratio was kept constant at 31.5.

The data obtained from the experiments conducted were collected from using the instrumentation automation software package LabView. Data batches collected were migrated to Matlab in order to process the data to obtain related values for peak pressure and the accompanying angle at which peak pressure occurred, the angle between start of combustion (SOC) and peak pressure, and to estimate the apparent heat release rate (AHRR). The mathematical processing was carried out using an elementary methodology employing the conventional first law heat release model, assuming a constant specific heat ratio of 1.35 without any accompanying modeling of heat transfer or crevice effects.

RESULTS AND DISCUSSIONS

A . Combustion characteristics

Figure (1) shows the comparison of the in-cylinder pressure with crank angle at both high and low loads (80 N.m= 5 bar BMEP & 40N.m=2.5 bar BMEP) and injection timing (-9 ATDC) for HFO and USLD fuels. It can be clearly note that the ULSD pressure curve rises earlier for both loads, but they are advanced to a slightly greater degree under the high load. This confirmation is supported by the heat release plots depicted in Figure (2) which shows the same trend, this advancement is due to the difference in ignition delay of fuels, ignition delay of HFO was always longer than that of ULSD. The longer ID of HFO is due to physicochemical properties of heavy components, the ignition delay depends on the nature of the volatiles in the heavy fuel oil and on the decomposition of the asphaltene to volatile molecules of lower molecular weight during the pre-ignition stage [4].

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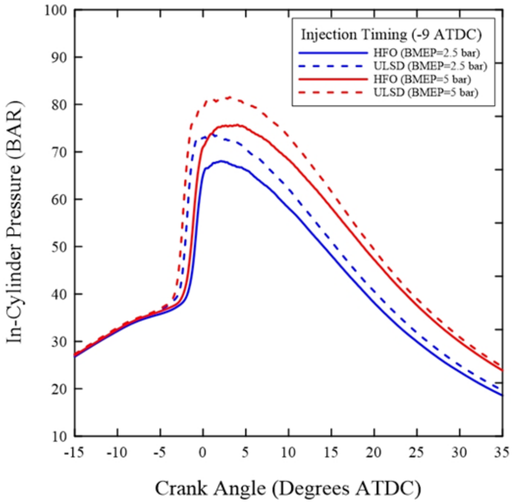

Figure.(1) In-cylinder pressure for ULSD & HFO

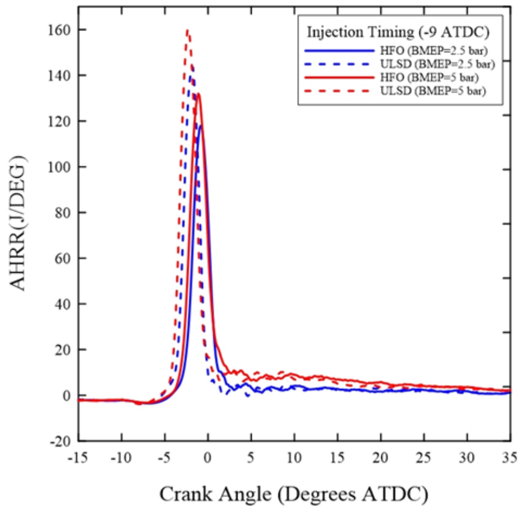

Figure.(2) apparent heat release rate for ULSD & HFO

B. Emission characteristics

Smoke Number

Figure (3) shows that the smoke emission of HFO was higher than of USLD fuel at low and high loads, the difference is particularly obvious at high engine load. The fuel quality of ULSD and HFO is quite important for smoke formation [1]. For HFO , higher sulphur, lower cetane number and higher fuel density give more smoke; also, aromatics and volatility have a slight increasing affect; and oxygenate have a slight decreasing effect. Diesel engine exhaust contains sulphur dioxide (SO_2) formed during the combustion of sulphur from diesel fuel and lubricating oil. A fraction of this SO2 is oxidized in the exhaust to form SO_3, which rapidly hydrates to form sulphate (typically 1–2% of fuel sulphur) and is emitted as particulate matter (thus contributing to total PM) [1]. The degree of conversion depends to a large extent on the exhaust temperature and the presence of catalytically active species. Lowering the sulphur in fuel lowers the SOx fraction of PM thus lowering the overall mass of PM emitted. Soot formation studies have shown [9] that diesel combustion soot is formed in the fuel-rich zone. Decreasing the fraction of the higher boiling point components in the fuels linearly reduces particulate emissions. This indicates that fuel properties which determine fuel atomization or mixture formation are also important factors for formation of particulate emissions. It has been shown that nitrogen species compete with sulphur compounds to be adsorbed by diesel particulate matter (PM) before being emitted to the atmosphere [5]. Diesel particulates consist of many agglomerated primary (size ~0.01–0.1 nm) particles (spherules) [6], formed by a complex series of chemical and physical processes from combustion in over-rich (lack of air) mixtures in diesel engines. This usually occurs at high speed or high load of the engine. Furthermore, retarding the injection timing produces more heat in the premixed phase , thus it can be suggested that soot emissions could be lower at late fuel injection timing as shown in figures (3) . Higher injection pressure leads to smokeless emissions at low load with ULSD due to better fuel atomization and mixture formation at high injection pressure.

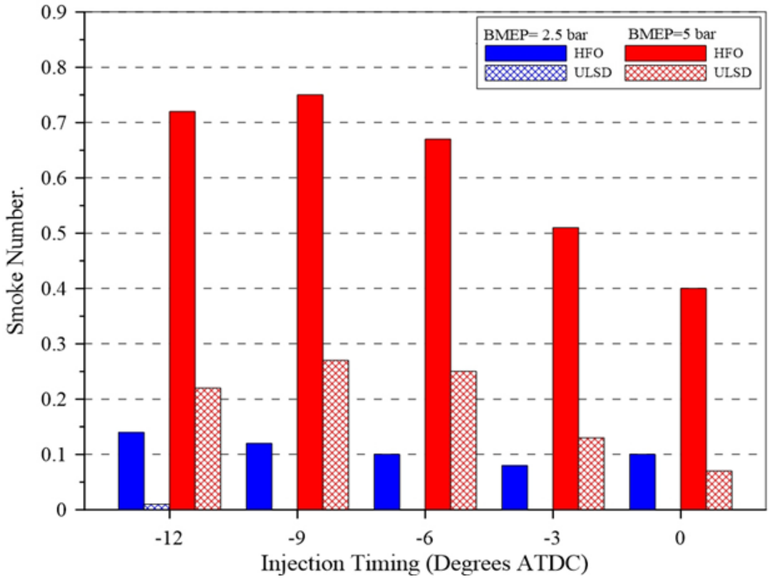

Figure 3: smoke number under high and low load for both types of fuels

Nitrogen oxides

Figure (4) shows the variation of the nitrogen oxides emissions NOx with injection timing at low and high loads for both types of fuels. Higher NOx formation is normally related to a larger premixed combustion process portion with ULSD, which is less with HFO. Nitrogen oxide emissions depend strongly on the maximum local conditions of temperature of combustion composition (Zeldowich mechanism), which means that it also depends on air excess (NOx formation rates are highest in the close-to-stoichiometric region). The retarded injection timing significantly reduces the NOx emissions because of the low in-cylinder temperature resulting from the shift of the combustion into the expansion stroke. As the big difference of NO_x emissions between high and low-load due to the difference of temperature in combustion chamber
Techniques to control NO_x formation are mainly linked to a reduction in combustion temperature during this phase of combustion. Unfortunately, a reduction in combustion temperature also leads to an increase in soot emissions. The reduction in soot leads to a reduction in soot radiative heat losses; soot radiative heat losses have been identified as a significant cause of NOx reduction when operating on traditional petrodiesel, due to the associated temperature reduction [10]. Since in-cylinder soot quantities are lower when fuelling with ULSD, the magnitude of this temperature reduction may decline, leading to increased temperatures and higher NO_x emissions [11]. In addition to increased thermal NO_x due to a reduction in radiative heat losses, it has also been hypothesized that a reduction in soot formation may be chemically associated with increased NO_x formation via the prompt NO mechanism [12,13].

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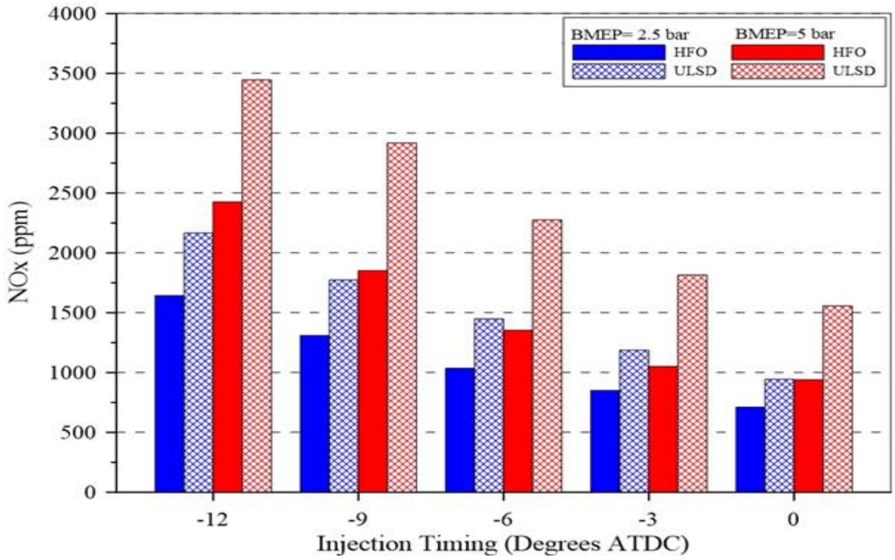

Figure 4: NOx emissions under high and low load for both types of fuels

B. Particles Number Size Distribution

The particle number size distribution for USLD and HFO at low load is shown in figure (5). The mass particle size distribution of HFO has a unimodal shape with two maxima points, one in the nucleation mode at diameter around 11nm and another one in the accumulation mode at diameter around 123 nm.

The figure shows that the particle number size distribution of HFO was higher than of USLD fuel, the obvious difference is due to fuel quality, where ,HFO has higher sulphur, lower cetane number , higher aromatics and higher fuel density give more PM.

Sulphur concentration is about 100 times higher in HFO than in ULSD for the fuels used here, so the nuclei-mode particles consist of sulfate have dominant effect in this part of study, which is mainly converted to sulphur dioxide upon combustion while a portion of w20% of the sulphur is converted to sulphate which is present as a minor constituent in the particulate matter [14].

It is generally accepted that fuel higher in sulphur, fuel density and fuel final boiling point (FBP) increase PM emissions[1].

The same trend can be seen at high load as shown in figure (6). The particle number size peak at the nucleation mode was at diameter around 13nm and another peak in the accumulation mode was at diameter around 151 nm.

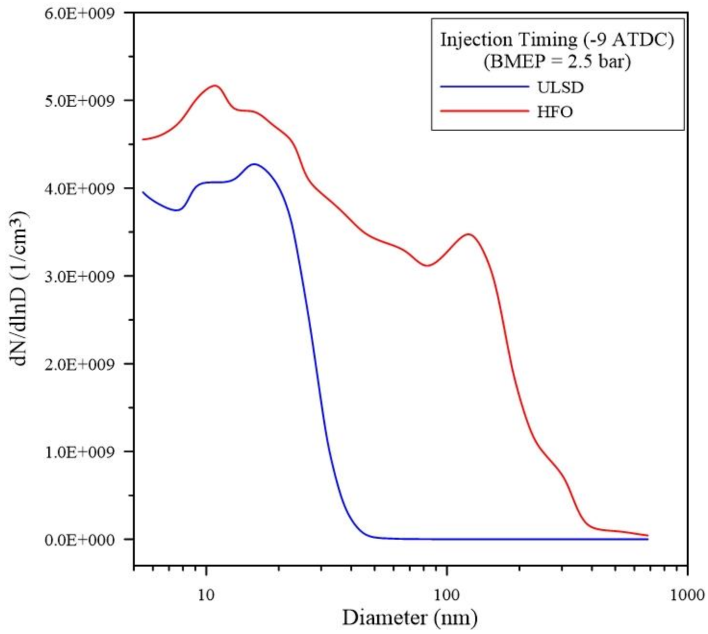

Figure 5: particulate number concentration and size distribution for HFO and ULSD at low load

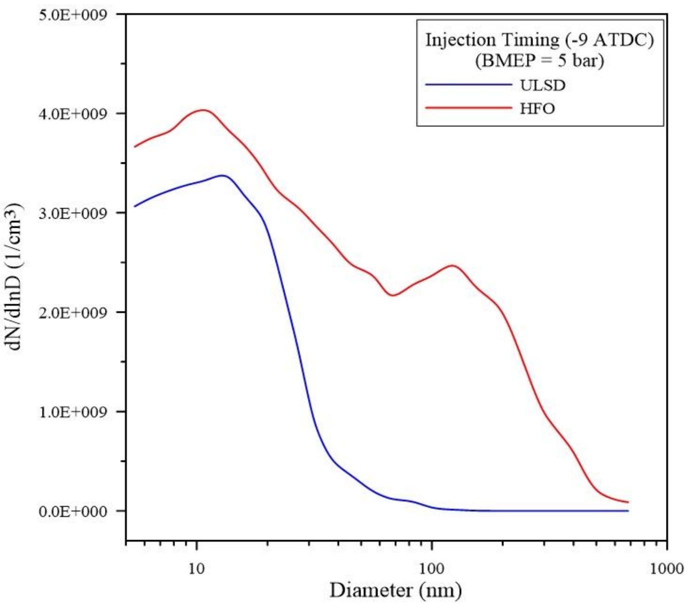

Figure 6: particulate number concentration and size distribution for HFO and ULSD at high load

C. The Cumulative Concentration Number

Figure (7) shows the cumulative concentration number (CCN) in the nucleation and accumulation mode of both types of fuel at low and high loads. The nucleation CCN of HFO was higher than of USLD fuel at low and high loads, the difference is particularly obvious at accumulation mode. ULSD fuel contains less ash, less sulphur and lower fractions of HC and aromatics than HFO fuel, thus making the vaporisation and burning of the ULSD easier. Thus the better fuel quality of the ULSD than HFO fuel oil is a more decisive factor for PM emission concentration than other factors.

In addition, HFO contains a number of minerals and metals that can play an important role in the formation of particulate matter, such as vanadium, calcium, magnesium, silicon, zinc, nickel, iron, and aluminum [3].

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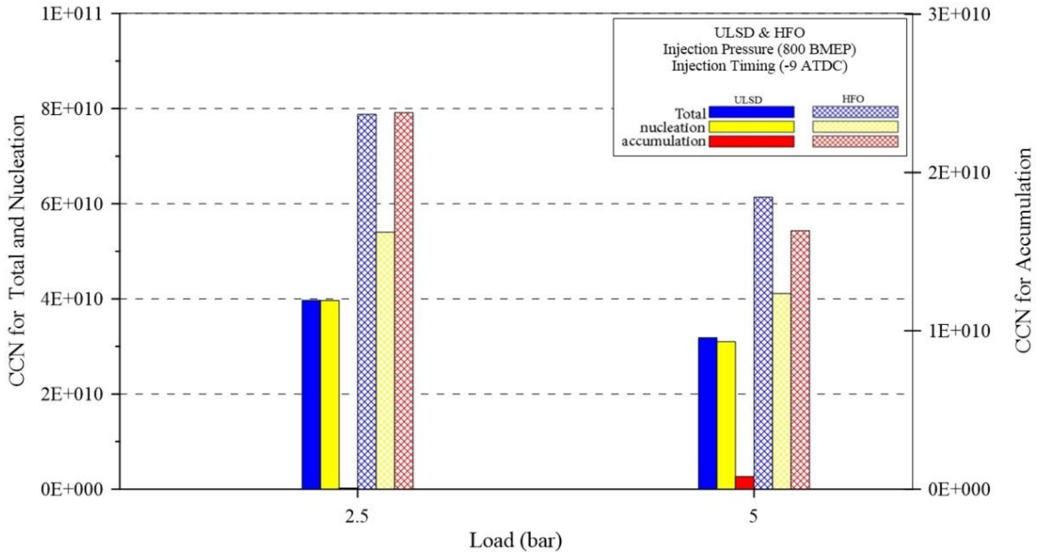

Figure 7: the cumulative concentration number (CCN) for total and nucleation& accumulation mode for HFO and ULSD

Conclusions

1. The ULSD pressure curve rises earlier for both loads, but they are advanced to a slightly greater degree under the high load. The value of the maximum pressure decrease with the retardation of the injection timing to TDC .
2. The peaks of in-cylinder pressure are mostly higher for ULSD. This is due to the advancement of start of combustion with ULSD.
3. The smoke emission of HFO was higher than of USLD fuel at low and high loads due to higher sulphur content, lower cetane number and higher fuel density.
4. Higher NOx formation is normally related to a larger premixed combustion process portion with ULSD, which is less with HFO.
5. The mass particle size distribution of HFO has a unimodal shape with two maximum points, one in the nucleation mode and another one in the accumulation mode, while the particle number size distribution of ULSD shows unimodal log-normal distribution with one maximum point in the nucleation mode.
6. The nucleation and accumulation CCN of HFO was higher than of USLD fuel at low and high loads, the difference is particularly obvious at accumulation mode

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