Running Test Results of Burning Low-sulfur and High-aromatic Distillate Fuel in High-speed Diesel Engine *

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Light Cycle Oil (LCO), a highly aromatic distillate which is a by-product of from the FCC process in oil refining, can be suggested as a possible low sulfur fuel for marine engines in the near future. Therefore experimental investigation of the influence of LCO on the overall combustion characteristics is necessary in order to elaborate the feasibility of LCO as a low sulfur fuel.

Experiments have been carried out on a four-cylinder high speed diesel engine. LCO has been blended with gas oil (GO) at varying percentages of 40% to 80%. A highly accurate PM measurement has been achieved using a dilution tunnel.

1. Introduction

New regulations of the International Maritime Organization (IMO), introducing drastic reductions in fuel sulfur content, allow 0.1% sulfur in fuels used in emission control areas (ECA), starting from 2015. Together with the worldwide situation of decreasing fuel resources the introduction of alternative fuels complying with future regulations displays an important research these days.

Light Cycle Oil (LCO), a distillate from the FCC process in refining, represents such a possible alternative marine fuel. The main properties of LCO show low viscosity, low sulfur content yet high content of aromatic hydrocarbons. The high aromaticity of LCO, up to 80%, results in a strong deterioration of the ignition and combustion properties of the fuel. This negative influence was also reported by Takasaki et al. [1], blending heavy residue with FCC product fractions. Another approach was chosen by Struckmeier et al. [2] introducing LCO as a possible fuel for large diesel HCCI, by taking advantage of the long ignition delay of LCO to promote mixture formation. Yet further experimental investigation of the effects and influence of LCO on the overall combustion characteristics is necessary in order to elaborate the feasibility of LCO as a low sulfur fuel.

Experiments have been carried out on a four-cylinder high speed diesel engine (2400rpm) with 110mm in bore and 125mm in stroke. The effective mean indicated pressure is 1.08MPa with a total power output of 103kW. In order to investigate the effects of LCO on the overall combustion characteristics, it has been blended to gas oil (GO) with a varying percentage of 40% to 80%. The experiments cover a condition range from 10% over 25% and 50% to 75% load. Further the pollutant emissions such as NO_x and PM have been measured. A high grade of accuracy in the PM measurement has been realized using dilution tunnel measurements.

2. Properties of LCO

Figure 1 shows a schematic sketch of the Fluid Catalytic Cracking (FCC) process in oil refining. In order to promote the production of light fractions such as gas oil (GO) and gasoline, light hydrocarbons (paraffins) are cracked from the base. The remaining fraction is Light Cycle Oil (LCO) or cracked gas oil which is composed of high aromatic compounds (70-80%), containing mainly one and two ring aromatics. A general overview of the physical and chemical properties of LCO is given in Table 1.

Fig. 1 FCC process and LCO

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Table 1 Properties of LCO

Characteristic	Unit	MDO	NFU-LCO	KU-LCO
Density@15°C	g/cm ³	0.867	0.925	0.934
Sulfur	% m/m	0.53	0.26	0.18
Viscosity@50°C	°C	2.35	2.71	2.45
Flash point	°C	71	87	81
Ash	% m/m	0.001>	0.001>	0.001>
Distillation (10% point)	°C	228	234	233
Distillation (50% point)	°C	281	284	278
Distillation (90% point)	°C	330	357	346
Cetane Index (ISO4264)		46	27	23
Higher Calorific Value	MJ/kg	45.1	44.3	44.2
Lower Calorific Value	MJ/kg	42.4	41.7	41.6
Saturated content	volume%	57	24	22
Olefin content	volume%	1	11	7
Aromatic content%	volume%	42	65	71

*NFU-LCO is for the running test using the high-speed engine.

KU-LCO is for the visual study using the VCVCC

The properties of two different types of LCO (NFU-LCO and KU-LCO) have been compared to those of Marine Diesel Oil (MDO), commonly used in marine vessels. The main characteristics of LCO can be summarized as followed: High density, yet low viscosity with low sulfur content. The low sulfur content is guaranteed due to the desulfurization process prior to the catalytic cracking. The high density of LCO compared to MDO mainly results from the high grade of aromaticity in the fuel, which can reach up to 80%. Yet, the number of fused benzene rings is usually quite low (1 or 2 rings), keeping the viscosity low and comparable to that of MDO. From the data obtained from the distillation of the fuel samples, we can assume the similarities in evaporation behavior of LCO and MDO. Further, Table 1 indicates a 2% (per unit mass) decrease regarding the net calorific value of LCO compared to MDO. Moreover, the chemical analysis reveals the high aromaticity of LCO of 65% and 71% together with lower content of saturated hydrocarbons. The calculated cetane index (CI), indicating the ignitability of a fuel, is significantly lower for LCO than for MDO. The limit of the CI value, assuring a safe burning, is currently around 35 and fuels with a lower cetane index are regarded as trouble inducing. Figure 2 shows results obtained from FCA (Fuel Combustion Analyzer) experiments for various fuel samples. The FCA is a well known device to investigate fuel combustion properties and the interested reader may be referred to [3] for further information about the experimental setting. Figure 2 displays the pressure rise rate (in proportion to the heat release rate under the constant volume condition) for gas oil as well as different LCO samples. It can be seen that LCO shows a significantly longer ignition delay than gas oil. Further Figure 2 implies that the combustion properties of recently taken LCO samples (within the last three years) differ greatly from those dated over a decade ago. This trend is mainly believed to be as a result from the

progress in oil refining with the aim of increasing the production of lighter fractions. The estimated cetane number (ECN) is experimentally investigated by the FCA and shows the same dependency as the previously mentioned cetane index (CI). In general ECN values less than 15 indicate trouble inducing fuels. During the last 13 years the ECN value of LCO dropped from 15.5 to 6, showing the deteriorating trend as well as possible quality differences of LCO on the market.

Fig. 2 FCA test result on LCO

Condition
 Air-pressure : 2.5MPa Air-temperature : 480 °C
 Ignition pressure : 80MPa Diameter of nozzle hole : 0.23mm

Fig. 3 Visualized flame of LCO-GO mixture in constant volume combustion chamber

In order to elaborate the combustion characteristics of gas oil blended with LCO, experiments in a visual constant volume combustion chamber have been carried out. Figure 3 shows typical flame images taken by a high speed camera for the combustion of GO, the LCO20 blend and the LCO50 blend. The chamber is charged with air of 2.5MPa and 480°C. The fuel is injected with an injection pressure of 80MPa through a single hole injector with a nozzle diameter of 0.23mm. More detailed information about the experimental device can be obtained from [1]. Figure 3 is pointing out the influence of LCO as a blending component of GO. The pure GO case shows shorter ignition delay resulting in a short flame lift-off length. By adding LCO, the ignition delay increases resulting in increased flame lift-off length as well as increased flame penetration.

3. Trial to burn LCO in a high speed engine

3.1 Experimental procedure

3.1.1 Test engine

Experiments have been carried out on a four-cylinder high speed diesel engine (2400rpm) with 110mm in bore and 125mm in stroke. The effective mean indicated pressure is 1.08MPa with a total power output of 103kW. In order to investigate the effects of LCO on the overall combustion characteristics, it has been blended to gas oil (GO) with a varying percentage of 40% to 80%. The experiments were carried out, covering a condition range from 10% over 25% and 50% to 75% load. The test engine is illustrated in Figure 4. Further specifications of the test engine are given in Table 2.

Fig.4 Photograph of experimental engine apparatus

Table 2 Principal specification of test engine

Engine Type	4-stroke DI Turbo-Charged	
Number of Cylinders	mm	4
Cylinder Bore	mm	110
Piston Stroke	mm	125
Compression Ratio		15
Maximum Power	kW	103
Engine Speed	rpm	2400
Maximum Pme	MPa	1.1
Fuel Injection Nozzle		5*0.32
Injection timing	BTDC	17°

3.1.2 PM measurement system

During the experiments the pollutant emissions such as NO_x and PM have been measured. A high grade of accuracy in the PM measurement has been realized using dilution tunnel measurements [4]. A detailed sketch of the measurement system is shown in Figure 5. The gas sample, taken from the exhaust gas port, is forwarded to the dilution tunnel. The exhaust gas is diluted with compressed fresh air of 25°C adjusted by a regulator and a flow meter (FM) as indicated in the figure. The particulate matter (PM) is extracted using prepared sample filters. The mass of PM is given by the

difference in weight of the filter before and after the experiments.

In order to get information about the composition of the PM, by means of dry soot and SOF (soluble organic fraction) content, the filter is washed using a solvent. The experimental setup of the Soxhlet extraction method is shown in Figure 6. The solvent washes out the SOF and the remaining components on the filter correspond to the amount of dry soot in the PM. The weight difference of the filter before and after the Soxhlet extraction method indicates the mass fractions of dry soot and SOF in the PM.

Fig. 5 PM measurement system (Dilution tunnel)

Fig. 6 Soxhlet extraction method

The authors believe that the exhaust gas of LCO combustion contains high mass fractions of SOF. Usually combustion with high PM emission is indicated by black smoke from the exhaust port, mainly composed of dry soot. The case of LCO combustion, however, shows high PM emissions with the appearance of clear exhaust gas, indicating a high content of SOF.

3.2 Test result

In order to investigate the effects of LCO on overall combustion characteristics, it has been blended to gas oil (GO) with a varying percentage of 40% to 80%. The experiments cover a condition range from 10% over 25% and 50% to 75% load. Further the pollutant emissions such as NO_x and PM have been measured as explained above.

Figure 7 shows the specific fuel consumption, BSFC (converted to lower calorific value of 42.7 MJ/kg) of different blending ratios of LCO to GO. In general, the specific fuel consumption increases with increasing LCO percentage in the fuel due to the deterioration of combustion. The cases for different loads from 10% to 75% show similar affection regarding the increase of BSFC. The addition of 60% LCO results in an increase of specific fuel consumption of about 4-5% at 10-25% load.

Figure 8 shows the relation between PM emission and LCO percentage in the fuel. In general PM emission is increasing with higher LCO percentage. Especially for low loads (10%, 25%), a drastic increase in PM emissions can be observed. With increasing LCO percentage in the blend the PM emission seems to increase exponentially for a LCO mass share of more than 50%.

Fig. 7 Change in BSFC with LCO %

Fig. 8 Change in PM emission with LCO %

Fig. 9 Change in SOF emission with LCO %

Fig. 10 Change in SOF percent in PM with LCO %

Fig. 11 Change in CO emission with LCO %

Fig. 12 Change in NOx emission with LCO %

The relation between emitted SOF (g/kWh) in the PM and the percentage of LCO in the fuel mixture, as shown in Figure 9, is similar to the general trend of increasing PM due to increasing LCO mass share and low load conditions. Figure 10 shows the percentage of SOF (mass %) in the PM in relation to the LCO fraction. It indicates high percentages of SOF in the PM of over 80% at low loads. Further SOF in the PM tends to increase with higher LCO content in the fuel mixture, due to increased aromaticity of the fuel. CO emissions (Figure 11) represent the combustion state and are an indicator for the completeness of the combustion process. As for the PM and SOF emissions, the relation between CO emissions and LCO mass share shows significant increase in emissions, particularly at low loads, with increasing LCO percentage. High mass shares of LCO in the fuel lead to a deterioration of combustion performance by means of completion of the combustion process at low load conditions.

The effects of LCO percentage on the NOx emissions are presented in Figure 12. For high load cases NOx emissions are increasing with higher LCO content. Due to the, for LCO combustion characteristic, high heat release rates during premixed combustion, the maximum flame temperatures are increased, resulting in higher NOx emissions. This influence is strengthened with increasing amount of LCO in the fuel mixture. At low loads NOx emissions seem to have a maximum in the range of 40% to 50% LCO mass share. Increasing the percentage of LCO in the fuel up to 40% results in increased NOx emissions due to the above mentioned reasons, whereas further increase in LCO percentage leads to a decrease of NOx emissions. The reason for the decreased NOx emission at low loads can be found in Figure 13. The figure shows the cylinder pressure over the crank angle at 25% load. The long ignition delay caused by the high percentage of LCO is shifting the combustion event to later timing in the expansion stroke. Therefore peak temperatures are reduced, resulting in decreased NOx emissions. This balance of two factors can be understood typically according to Figure 14, the change in heat release rate with LCO % (at 50 % load in this case).

Fig. 13 Change in cylinder pressure with LCO %
at 25% load Fig. 14 Change in heat release rate with LCO %
at 50 % load

4. Conclusion

In conclusion the effects of LCO on the overall combustion performance can be summarized as followed:

A clear increase in fuel consumption can be identified with ascending LCO percentage at low and high loads. Increasing percentage of LCO in the LCO-GO mixture leads to increased ignition delay and higher heat release in the early combustion stage. The increased aromaticity of the fuel with higher LCO mass shares leads to increased CO emissions indicating incomplete combustion at low loads. Consequently particulate matter emissions increase drastically at low load and with increasing LCO percentage. It could be reasoned that PM in the exhaust gas of high LCO blends contain a significant amount of SOF (soluble organic fraction) of over 80% at low loads, resulting in high emissions of unburned hydrocarbons. NOx emissions are increased with increasing load for LCO fractions up to 50%. Further increase in LCO fraction at low load conditions result in a shift of combustion into the expansion stroke and NOx emissions are decreased.

Abbreviations

CI: Cetane Index
ECN: Estimated Cetane Number
FCC: Fluid Catalytic Cracking
GO: Gas Oil
HCCI: Homogeneous Charge Compression Ignition
LCO: Light Cycle Oil
MDO: Marine Diesel Oil

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