CIMAC

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FUEL QUALITY GUIDE – IGNITION AND COMBUSTION

The International Council
on Combustion Engines

Conseil International des
Machines à Combustion

Contents

1 Scope

Current commercial residual fuel specifications cannot reliably predict the ignition and combustion characteristics of a fuel due to lack of a suitable test parameter. They cannot therefore protect fuel purchasers from receiving fuels that, whilst meeting all of the current specification parameters nevertheless do not perform satisfactorily in diesel engines. Such fuels can, in extreme cases, result in serious operational problems, engine damage and even total breakdown.

This document provides a short summary of the present status of knowledge on ignition and combustion performance issues and contains the following elements:

a) Outline of current routine and more detailed fuel test options
b) Guidance as to those zones of operation where ignition problems could be encountered with different engine types
c) Recommendations as to the precautionary measures that could be taken in order to reduce the adverse effects of using fuels with relatively poor ignition characteristics

2 Background

2.1 Engine Performance

Ignition and combustion performance are two linked but distinct aspects of engine operation. Although both ignition and combustion performance are dependent on the characteristics of the fuel, it must also be recognized that there are a wide range of other influencing factors including engine design, engine condition, engine settings, applied load, ambient conditions and fuel pre-treatment.

Ignition

- Ignition delay is the time that elapses from the start of fuel injection to the point at which combustion starts. A long ignition delay results in an accumulation of unburned fuel in the combustion chamber which, when ignition does occur, burns rapidly resulting in a steep rate of pressure rise that can cause diesel knock, irregular running and sometimes engine damage. (See Annex 3 for examples).

Combustion

- Poor combustion performance is normally characterized by an extended combustion period and/or poor rates of pressure increase and low p max resulting in incomplete combustion of the fuel. The resulting effects are increased levels of unburned fuel and soot that may be deposited in the combustion chamber, on the exhaust valves and in the turbocharger system, exhaust after treatment devices, waste heat recovery units and other exhaust system components. Extended combustion periods may also result in exposure of the cylinder liner to high temperatures which may disrupt the lubricating oil film, leading to increased wear rates and scuffing. Unburnt fuel droplets may also carry over impinging on the liner surfaces causing further risk of damage to the liner. (See Annex 3 for more details)

Laboratory research based on IP 541 has shown that for residual fuel oils there is not necessarily a good correlation between ignition properties and combustion properties (see figure 1). It is possible to formulate a fuel from various residues and cutter stock components where the resulting product has poor ignition properties and acceptable combustion properties, and vice versa. In some instances good ignition properties (i.e. short ignition delay) may be able to compensate for the unfavorable effects of poor combustion properties of a fuel, as long as the time span between ignition and main combustion of the main fuel charge is not too long resulting in a distinct 2-stage combustion process, however, in most cases, residual fuel oils with poor ignition performance also exhibit correspondingly poor combustion properties.

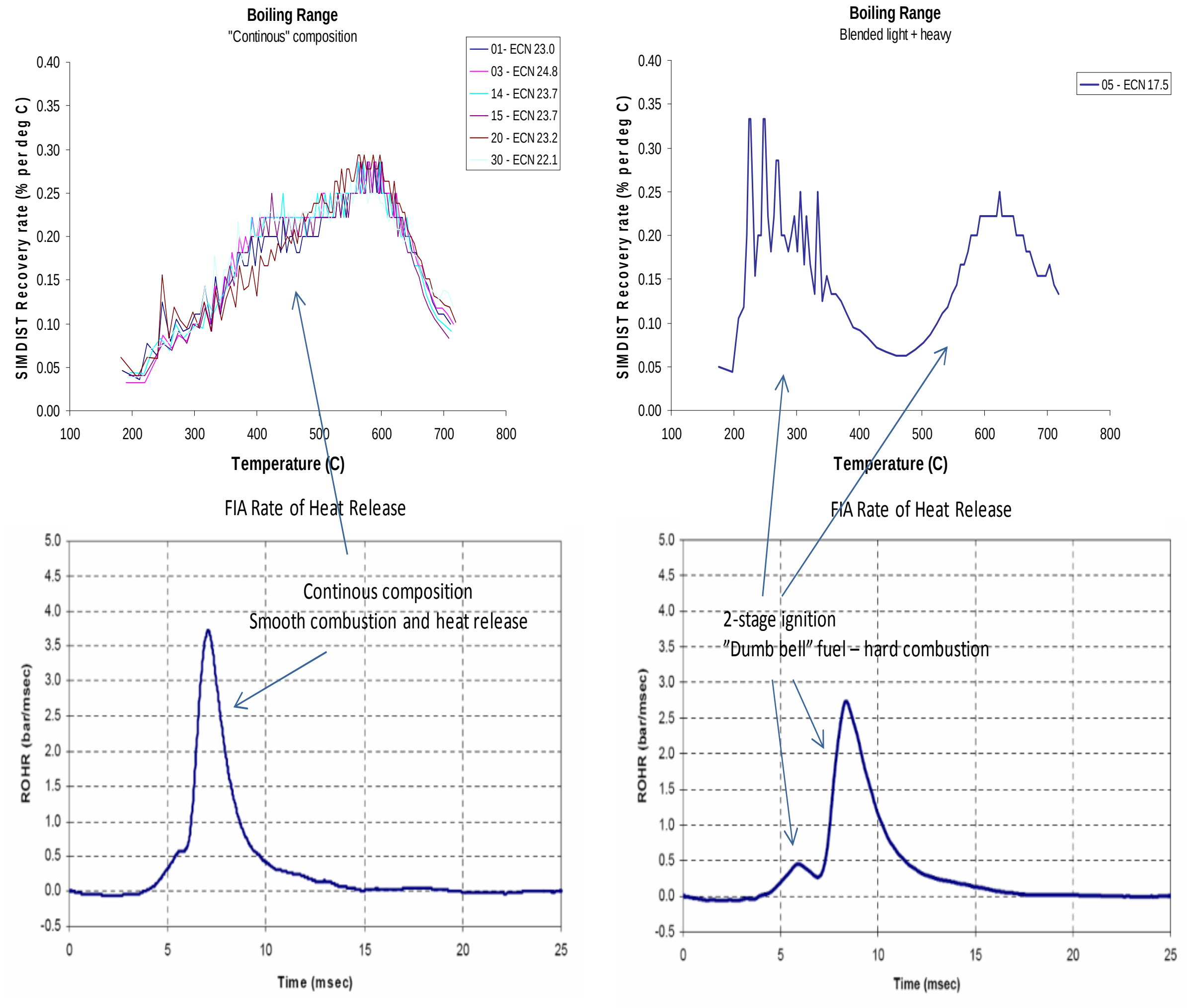

Figure 1: Example of two different compositions with different ignition and combustion properties. See Annex 2 for details of the terms used.

Various engine types and designs have different sensitivity to these parameters. There is evidence that suggests that high and medium-speed engines are more prone to experience operational difficulties due to poor ignition and combustion properties than low speed two stroke types. This is recognized by the OEM's (Original Equipment Manufacturers).

2.2 Ignition and Quality Assessment Methods

Determination of the ignition and the combustion characteristics of residual fuel oils in a simple and reliable manner have proved to be difficult and are subject to ongoing research and development.
CCAI (Calculated Carbon Aromaticity Index) was originally developed in the 1980's as an indicator of ignition performance. ISO 8217:2010[(1)], Specification of Marine Fuels includes CCAI limits in Table 2 of the standard but in this instance in order to avoid fuels with uncharacteristic density-viscosity relationships, which can lead to an extended ignition delay. Annex F of the standard provides additional information for suppliers and purchasers of residual fuel oils to agree on a more detailed assessment of ignition and combustion quality characteristics by the use of test method IP541/06 [2].

The CCAI parameter [3] is calculated from the density and viscosity values of a residual fuel oil. As such, CCAI provides a readily available, indication of the possible ignition performance of a fuel. It is recognized that over the years since its development the chemistry of residual fuel oil blends have become more complex and today, on occasions, fuels with similar densities and viscosities (i.e. similar CCAI's) may have significantly different ignition characteristics as may fuels of similar CCAI values but of different densities and viscosities. Consequently, fuels with an acceptable CCAI may exhibit poor ignition characteristics in some engines. Under some operating conditions maximum CCAI limits do not always provide adequate protection against the supply of residual fuel oils with poor ignition characteristics – the concern principally being in relation to those fuels with apparently acceptable CCAI values but which result in problems, or even engine damage, in service.

In an attempt to address both the ignition and combustion characteristics of a residual fuel a standard test method, IP 541/06, has been developed using a Constant Volume Combustion Chamber (CVCC) device which measures ignition and combustion parameters of a fuel under specific test conditions. Annex F of the test method enables an index called the Estimated Cetane Number (ECN) to be calculated from certain parameters measured during the test sequence.

Work is on-going to correlate this parameter with actual in-service experience, which of course is the final arbiter.

See also Annex 1 – CCAI and Annex 2 – IP 541/06 and other methods for more detailed descriptions.

3 Operational Reference Ranges for Ignition Properties - Estimated Cetane Number

The Estimated Cetane Number (ECN) is calculated from the ignition parameter *Main Combustion Delay* (MCD); high ECN means short MCD (favorable), low ECN means relatively longer MCD (less favorable). However, factors such as engine type, design, load and engine condition all play a role in affecting the ignition characteristics of the fuel being used and thus its impact on engine operation.

The ECN parameter is a measure of ignition quality derived from the cetane scale used to quantify the ignition characteristics of distillate fuels.

Figure 2 shows the recommended Operational Reference Ranges for the ECN parameter. Due to the various influencing factors, including engine sensitivity, on engine ignition performance it is not possible to give clear cut thresholds covering the grading of ignition performance and this is reflected in the gradual transition between the colour bands on the chart.

When considering whether an ECN value is acceptable it should be noted that ships and power stations typically use the same fuel in all their engines; hence, those engines with least tolerance of ignition quality issues set the limitation on this criteria, unless it is possible to run different fuels to particular sets of engines.

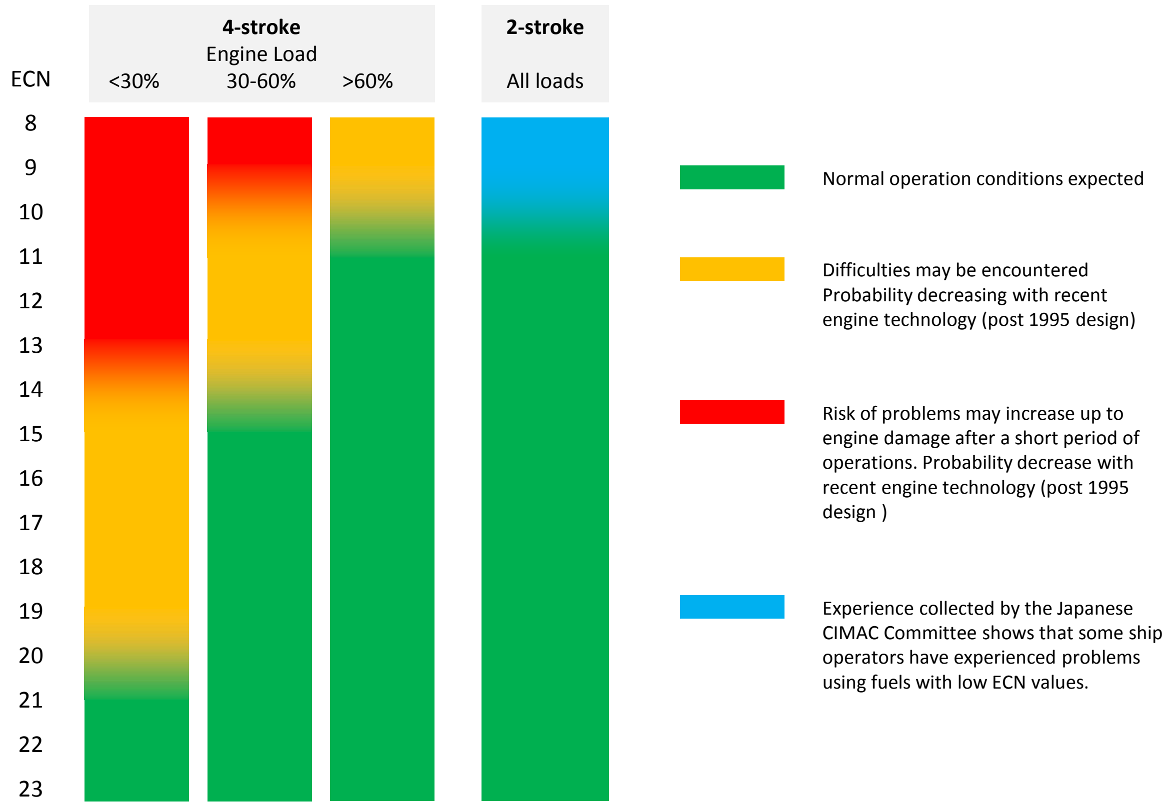

Figure 2: Recommended ECN Operational Reference Ranges [1]

Green: "Normal operation conditions"

Problems related to ignition properties are not expected for engines in good working condition and operated by experienced engineers.

Yellow: "Difficulties may be encountered"

Difficulties, such as engine knocking and irregular running, may be encountered with this ECN range, depending on various factors as discussed elsewhere in this document. The probability is decreased with higher load, engine in optimum condition, lower rpm engines, operator awareness and with recent technology engines (post approximately 1995 design onwards).

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[1] The Operational Reference Values for 4-stroke engines are based on recommendations mutually agreed by engine manufacturers represented in the Working Group.

Red: “Risk of problems”

Risk of problems may increase, potentially leading to engine damage after a short period of operation, depending on various factors as discussed elsewhere in this document. The probability is decreased with higher load, engine in optimum condition, lower rpm engines, operator awareness and with recent technology engines (approximately post 1995 design).

Blue: “2-stroke, low-speed engines”

Experience collected by the Japanese CIMAC Committee shows that some ship operators have experienced problems with 2-stroke low speed engines when using fuels with low ECN values. The reason and background for such problems are not fully understood. See also Annex 3 regarding examples of damage cases.

3.1 Recommendations for use of fuel with suspected poor ignition or combustion properties and or ECN values below recommended ranges

The engine builder should be contacted for detailed guidance as to the degree of sensitivity of specific engines.

3.1.1 Observations during operation

Observe closely for any adverse impact on engine operation, e.g. abnormal engine knocking, starting difficulties, erratic running behavior, sticking exhaust valves and/or increased black smoke. If any of these are observed switch to another fuel or apply one or more of the following remedial actions which may ease or eliminate the problems:

3.1.2 Load

Increase the load wherever practicable and avoid continuous low load operation. If low load operation is unavoidable, it is highly recommended to maintain high charge air temperatures - but within the limits permitted.

3.1.3 Additives

Refer to CIMAC Recommendations No. 25 regarding application of additives.

3.1.4 Blending with other fuel distillates (Emergency operation only)

Blending with a distillate fuel oil in the range of 5 -10% may improve the ignition quality of the fuel. Blending of a residual fuel oil with a paraffinic distillate fuel may result in the precipitation of asphaltenes due to incompatibility of the blend components. A 'Spot test' should, at least, be undertaken prior to blending to check that the fuels are compatible. More rigorous assessments are possible through the various fuel testing services.
Additionally, producing a homogenous blend of a residual fuel oil and a distillate fuel without a blending unit may be difficult to achieve. A spare tank from where the mixed fuels may be re-circulated through a transfer pump or similar is recommended.

Refer also to CIMAC Recommendation no. 25 regarding fuel pre-treatment.

3.1.5 Boilers are an option for using such fuel

If the fuel is deemed not useable in the diesel engines due to poor ignition and combustion properties, the fuel should still be acceptable for use in boilers.

4 Combustion Properties

Work continues to correlate combustion indicator parameters derived from the IP 541/06 test method with in-service experience; however, due to the complexity it is not yet possible to set limits related to combustion characteristics.

See also Annex 2 for details of the test method and other approaches to this issue.

Annex 1: CCAI - Background and Comparison with ECN

Background

CCAI (Calculated Carbon Aromaticity Index) is an empirical index calculated from the density and viscosity of the fuel. It was developed by Shell Research in the 1980's and was first published at the CIMAC Congress in 1983 [3].

CCAI is premised on the following important relationships:

a) the ignition delay of a fuel is correlated with the carbon aromaticity of that fuel;

   and

b) there is a correlation between carbon aromaticity and viscosity & density -"inspection properties" that can be easily measured for any fuel.

Shell established this relationship by performing experiments with laboratory diesel engines where the pressure increase during the combustion process was recorded. Combustion quality is more difficult to measure and quantify than ignition delay, and it was assumed that by measuring the ignition delay, this could also be used as a measure of combustion quality.

Close correlation between ignition and combustion properties holds very well for fuels blended from the "normal" blending components that were commonly used to manufacture marine fuels in the 1980's. This included straight run residues made by atmospheric distillation processing and residues from thermal cracking processes of the day. However, most residual fuel oils available today are composed from a wider range of blending streams and from cracking processes that are far more severe than was the case in the 1980s. A consequence of this is that, the ignition characteristic of a particular fuel may not be so well predicted by CCAI. Normally a poor (high) CCAI value reliably predicts a fuel with poor ignition delay. On the other hand a fuel with a good CCAI value may not perform well in some engines. Efforts were made to improve the reliability of the index using other fuel parameters without success. This work was published in the Copenhagen CIMAC Congress in 1983.

Correlation between CCAI and ECN

When comparing CCAI values with the ECN as measured using the IP 541/06 method, a number of interesting observations can be made:

1. There are large variations in ECN values for fuels with similar CCAI values (Figure 3) *Example: For residual fuels with CCAI around 850 the ECN may vary from less than 10 (long ignition delay) to 25-30 (short ignition delay).*

2. When comparing fuel samples from the same geographical region, a good correlation can be observed between CCAI and ECN within some of the regions (Figure 4). However, the correlations vary from region to region and may not be consistent therefore cannot be relied upon,

3. Furthermore, some regions are characterized by large variations in both CCAI and ECN, while others are characterized with relatively small variations in both CCAI and ECN.

See reference (4) for more details.

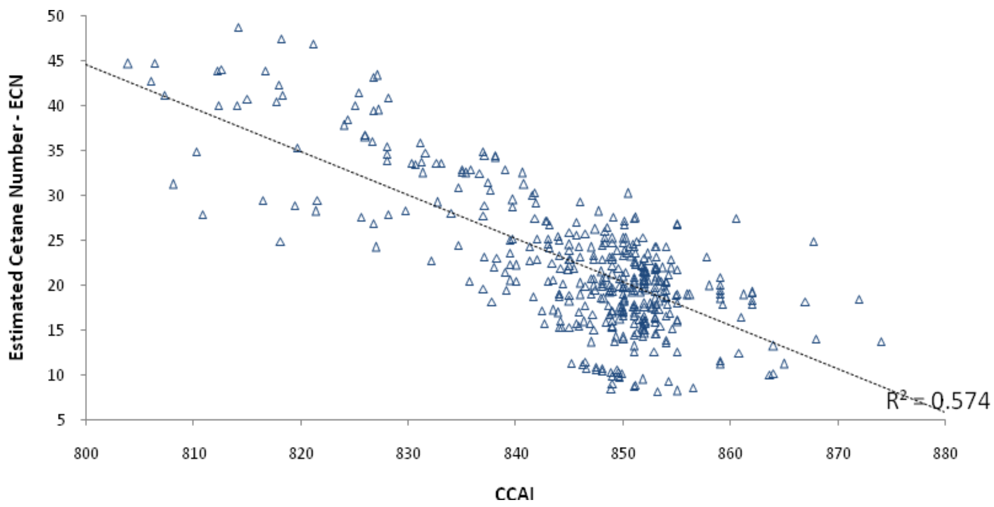
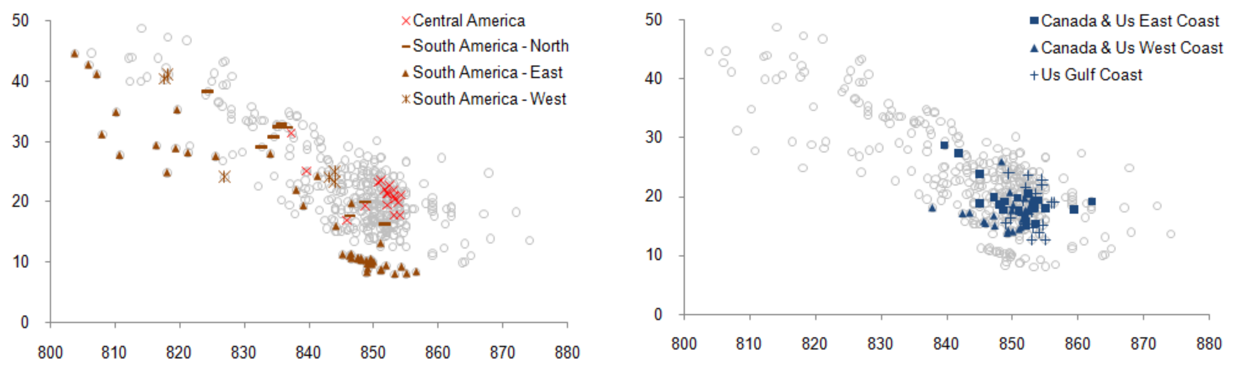


Figure 3: Correlation between CCAI and ECN[2]



[2] Reference [4] and in-house studies by DnV Petroleum Services Pte. Ltd., Singapore

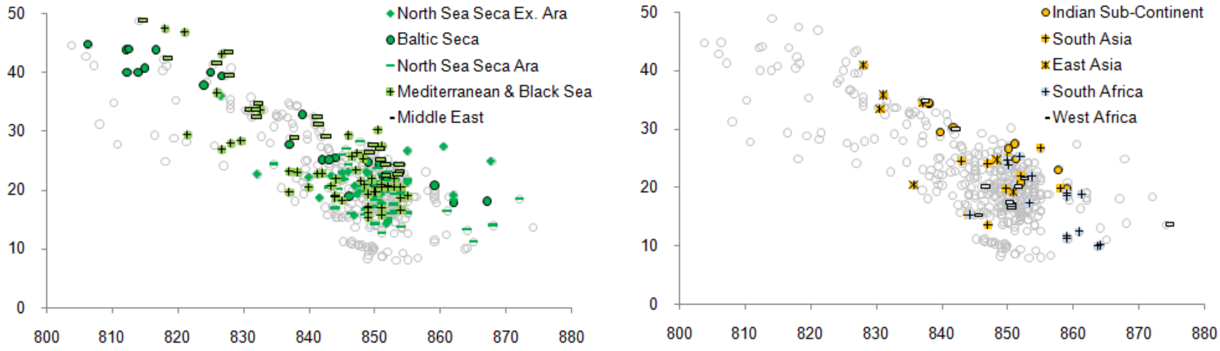


Figure 4: Correlation between CCAI and ECN for fuels from various regions[3]

[3]Reference [4] and in-house studies by DnV Petroleum Services Pte. Ltd., Singapore

Annex 2: Ignition and Combustion Test Methods

A2.1 IP541/06 and the FIA - FCA instrument

Background

Test methods for assessing the ignition and combustion properties of distillate fuels have been available since the 1930's with the introduction of the CFR engine[4] and ASTM method D613(5) for the determination of Cetane Number. Alternative methods have recently been developed based on Constant Volume Combustion Chamber (CVCC) technology: Derived Cetane Number (DCN) as measured by IQT[5] and FIT[6] instruments according to ASTM methods D6890(6) and D7170 (7) respectively however these methods are only applicable to distillate fuels.

During the 1990' several CVCC tools for studying ignition and combustion properties of residual fuel oils where developed. However, these were developed for research purposes, hence were not suitable for operation on a routine basis.

IP541/06 Determination of ignition and combustion characteristics of residual fuel oils

The FIA-100 Fuel Combustion Analyzer (FCA) instrument operated according to method IP541/06 evaluates the ignition, combustion and afterburning characteristics of the fuel when burning in a constant volume combustion chamber. The pressure increase generated during the combustion of the fuel is measured and analyzed in order to determine and quantify the various parameters related to the main phases: Ignition, Main Combustion and Afterburning.

The Estimated Cetane Number is calculated from the ignition parameter Main Combustion Delay (MCD) – see Figure 6; high ECN given by short MCD (favourable), low ECN given by relatively longer MCD (less favourable) as shown in Figure 5.

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4 CFR- Cooperative Fuels Research Engine manufactured by Dresser Waukesha, USA

5 IQT- Ignition Quality Tester from Advanced Engine Technology Ltd., Canada

6 FIT- Fuel Ignition Tester from Dresser Waukesha, USA

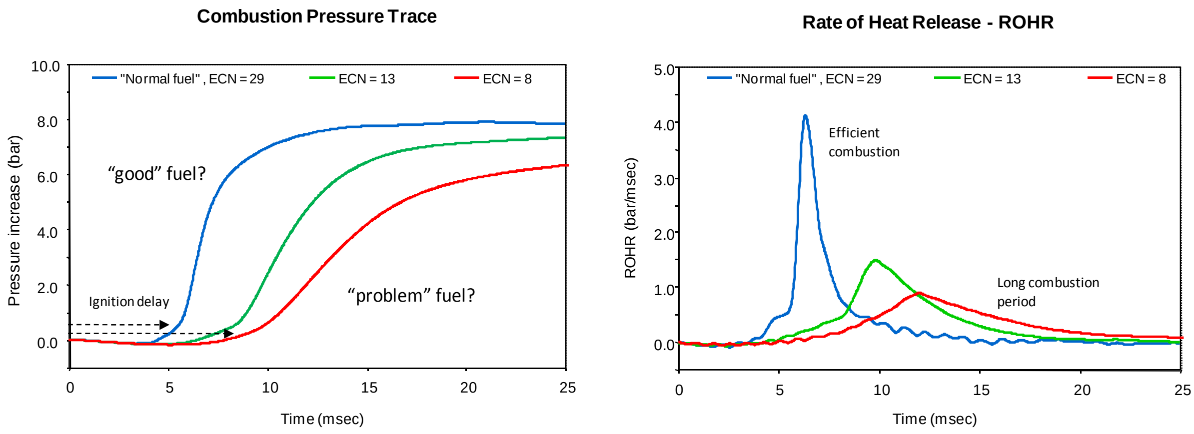

Figure 5: Example of various fuel qualities. Combustion Pressure Trace and Rate of Heat Release measured by FIA-100 Fuel Combustion Analyzer

Combustion trace parameters

Below is a brief description of combustion properties as described in method IP541/06

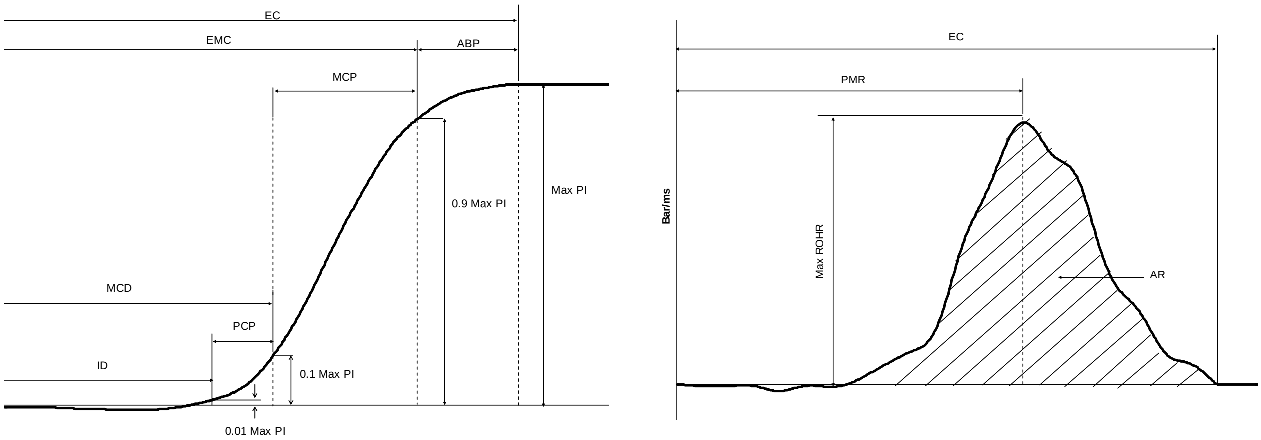

Figure 6: Description of parameters from test method IP541/06

ID **Ignition Delay**	That point in time where the pressure increase, relative to the starting pressure reaches 1% of the maximum pressure recorded at end of combustion.
MCD **Main Combustion Delay**	That point in time where the pressure increase, relative to the starting pressure reaches 10% of the maximum pressure recorded at combustion completion. This is interpreted as the time where the main combustion process starts
ECN **Estimated Cetane Number**	Calculated number based on MCD: $ECN=153{,}15e^{-0.2861MCD}$

Max ROHR - Max Rate of Heat Release level

and

PMR - Position of Max ROHR

A high value of the Max ROHR with a late PMR could be prejudicial for the engine reliability. In addition, the piston rings could also be submitted to unusual conditions

For low Max ROHR, the Combustion Period (CP) is generally longer, meaning a potential trend to late burning inside the cylinder. This could lead to increased smoke and particulate matter (PM) emissions.

Combined with a late PMR, the low Max ROHR will cause lower temperatures by the cylinder expansion, with increased soot and PM emissions

EC - End Combustion
CP - Combustion Period

A long Combustion Period means that some heavy fractions of the HFO might take time to burn in the cylinder, leading to:

- Increased soot and PM
- Increased risk of turbocharger problems
- Increased turbocharger speed and increased exhaust temperature before turbine if the turbine cleaning period is too long.

ABP - After Burning Period

The accuracy of the ABP parameter is quite poor. It is then difficult to compare and significant differences can only be interpreted. Significant long ABP will mainly lead to:

- Increased probability of soot and PM emissions
- Increased probability of deposits and clogging of the exhaust gas system

When using fuels with a long ABP for a longer period of time intervals between the exhaust turbine cleaning should be reduced in order to keep the exhaust system in good operating conditions.

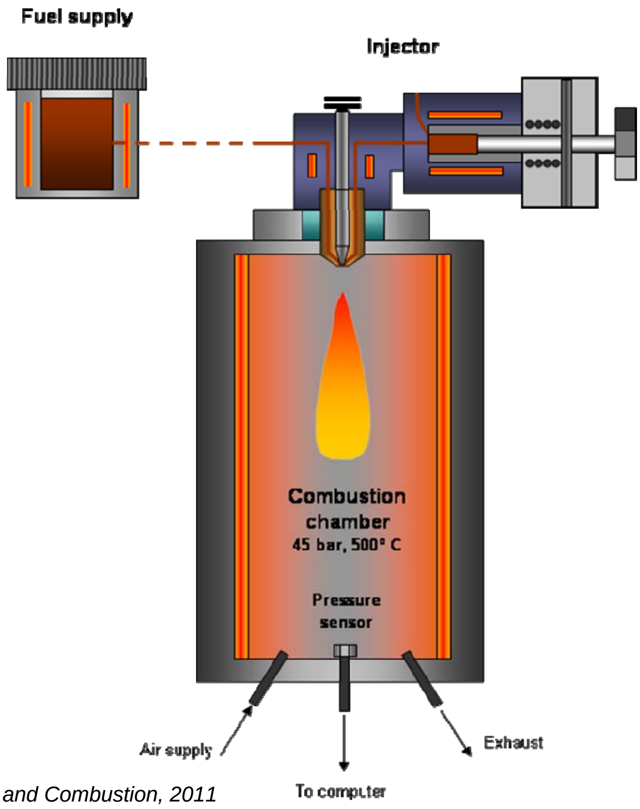

Figure 7: FCA equipment

A2.2 Optical Combustion Analyzer OCA

The Optical Combustion Analyzer (OCA) developed by Okayama University in Japan is another means to investigate the ignition and combustion properties of residual fuel oils (Figure 7). The OCA utilizes a constant volume combustion chamber with optical access that enables high-speed filming of the combustion process.

There is no international standard test method related to the OCA (see Figure 8), but the approach is used primarily for research on residual fuel oil ignition and combustion properties by various researchers in Japan, with a particular focus on the flame propagation and after burning characteristics.

Reference is made to [8].

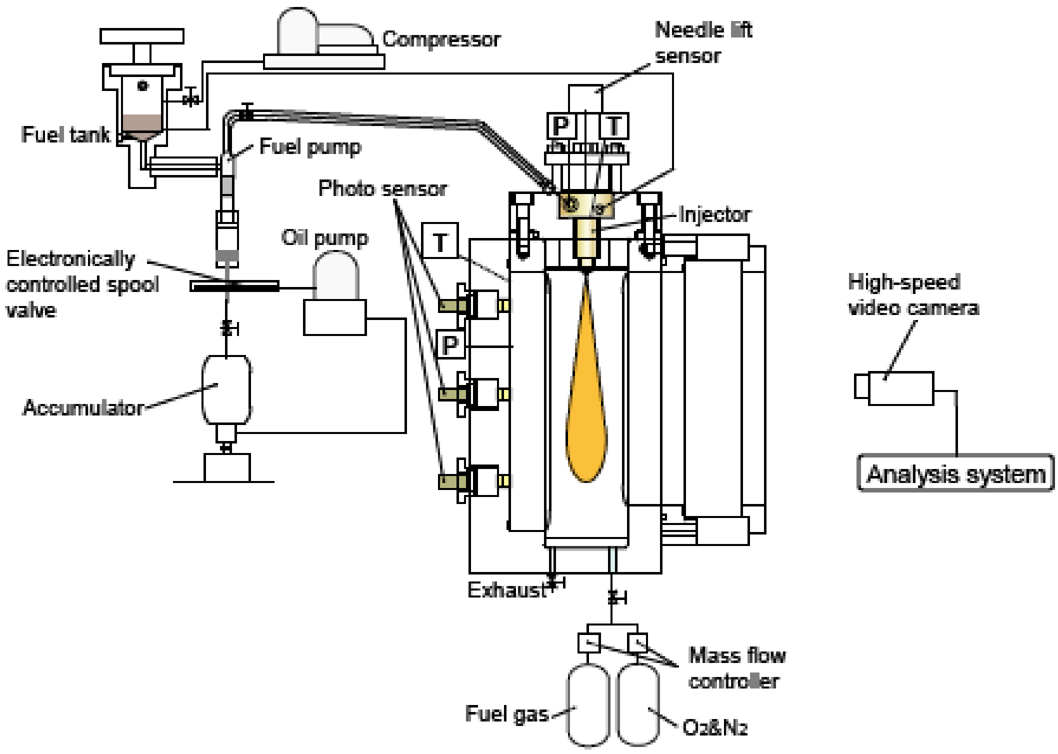

Figure 8: Schematic overview of OCA instrument

Annex 3: Examples of Engine Damage and Problem Cases

	Ship and Engines				Fuel properties									
Case id	Date	Ship		Type	Fuel type	Visc	Dens	CCAI	ECN	Other properties		Problem	Cause	Operational recommendations
DnV Case 1	2008	Tanker Build year 1996	ME: AE:	2-Stroke 4-stroke	RMG380	346	989	852	8.4		ME: AE:.	Heavy knocking Heavy deposits – cyl. heads and valves replaced	Heavy deposits due to bad ignition / combustion	Special operational procedures for aux engines when using fuel with low ECN
DnV Case 2	2008	Car carrier Build year 2006	ME: AE:	2-stroke 4-stroke	N/A	336	989	852	7.6		ME: AE:.	Aux engine valve bridge assy. broken due to sticking valve	Hard carbon deposits of unburnt fuel on valve seat and stem	
DnV Case 3	2007	Car carrier Build year 2006	ME: AE:	2-stroke 4-stroke	N/A	336	981	843	12.9		ME: AE:.	3 of 4 engines: Cyl head deposits, valve stems stuck, bent pushrods	Bad combustion properties, unburnt fuel and soot	
FOBAS Case 1	2010	Box carrier	ME: AE:.	2-stroke 4-stroke	RMG380	216	988	852	8.4		ME: AE:.	Excessive wear on liners. No problems with fuel injection equipment	Heavy deposits in combustion chamber damaging cylinder lubrication	Not use fuel with similar properties from this area on aux engines. Engine adjustments based on ECN values
NYK Case 4	2008	Container Built year 1986	ME: AE:.	2-stroke 4-stroke	380	321	982	845	10.3		ME: AE:	Piston rings broken (4 cylinders) Operational problems (Astern inability)		
NYK Case 9	2010	Bulker Built year 2008	ME: AE:	2-stroke 4-stroke	380	221	987	853	10.3		ME: AE:	All cylinder liner abnormal wear		
#2 Mitsui MOSK Lines	2007	Car carrier Built 1987	ME: AE:.	2-stroke 4-stroke	RMG380	335	980	842	N/A	OCA: Long ignition delay	ME: AE:.	Increased exhaust temperatures. Severe wear on piston ring surface		Reduce engine load. Caution based on OCA: Ignition delay > 4 msec or sum ignition delay and after burning > 10 mse.
#5 Mitsui MOSK Lines	2007	Handy size bulker Built 2001	ME: AE:.	2-Stroke 4-stroke	RMG380	348	984	845	N/A	OCA: Long ignition delay	ME: AE:.	Piston ring blow-by – increased cylinder scavenge temp. All piston rings and cylinder liners replaced		Reduce engine load. Caution based on OCA: Ignition delay > 4 msec or sum ignition delay and after burning > 10 msec

Note 1: OCA
Note 2: Engine load and problems

Note 1:

OCA: See description if Optical Combustion Analyzer in Annex 2.2

Note 2:

Engine load and problems: 2-Stroke engines

Experience from ship operators and researchers in Japan, **quote**

It is thought that the relation between engine load and problems is not simple. As to 2-stroke engines it depends on the revolution (load) of engine, the compression temperature in the combustion chamber, the quantity of injected fuel oil and the ignition and combustion properties of fuel oil. Main problem of 2-stroke engine are abnormal wear of liners and rings, scuffing, break piston rings, blow-by and etc. and they are caused by the damage (lack and/or burn out of oil film) of the sliding surface of liner and rings. When sliding surface of liner exposes to the flame directly, oil film on surface of liner will be damaged by the heat of flame and then abnormal wear may occur.

Higher load means higher ignition temperature and faster ignition, and this provides the better combustion. But higher load needs much quantity of fuel oil, longer injection period and shorter cycle period. When shorter ignition delay cannot compensate the long burning period due to low ECN, sliding surface will be damaged by the flame. On the other hand, in low load operation less than 50 % of load for example, the quantity of fuel oil is lower and the cycle period is longer, when lower fuel oil quantity can compensate lower ECN, sliding surface will not be exposed to flame and problem will be avoided. **Unquote**

Annex 4: Bibliography

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5 Appendix: Acknowledgement, Membership & Disclaimer

By endorsing this document, CIMAC acknowledges the work accomplished by the CIMAC Working Group "Fuels" through its worldwide membership.

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