IGNITION QUALITY OF RESIDUAL FUELS IN DIESEL ENGINES

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SUMMARY AND INTRODUCTION.

The key to efficient operation of a diesel engine is in the controlled ignition and combustion of the fuel. One factor which has a significant impact on these processes is the ease with which the fuel will ignite in the engine. In particular, the time delay period between the commencement of fuel injection into the engine, and fuel ignition occurring, is critical. The duration of this period, called the ignition delay, can impact on power output, combustion efficiency (and hence fuel efficiency and exhaust emissions), and engine maintenance. Ignition delay is influenced primarily by engine design and operation, and to a lesser extent by the characteristics of the fuel.

Research in the eighties has demonstrated that, in addition to engine and operational parameters, the aromaticity of the fuel has a pronounced effect on ignition performance. A good correlation was established between the carbon aromaticity and the readily available physical properties density and viscosity of residual fuel oil. This correlation, designated as the Calculated Carbon Aromaticity Index (CCAI), makes it possible to obtain an indication of the ignitability of the fuel and to rank fuels on ignition quality, similar to the cetane index for distillate fuel. From later experience it is recognised that the CCAI is only a first estimation of ignition performance and that also other fuel parameters must play a role. A laboratory test rig has been developed to measure ignition performance on small scale, which confirms the correlation between ignition delay and CCAI. In addition the possible relationship between CCAI and the stability of residual fuel is being discussed.

WHAT IS A RESIDUAL FUEL?

Diesel engines, in particular low speed low speed marine propulsion engines, are often using residual fuel oils. These fuels are distinguished by differences in viscosity, boiling range, combustion characteristics, chemical composition and many other properties. They consist for the major part of residues from crude oil processing. A residual fuel is a mixture of several refinery streams like short residues, long residues, gasoil, cracked residues etc. Blends of these components are made to a specifications like viscosity, density sulphur content and stability. A viscosity specification is related to pumpability of the fuel in the customers plant and atomisation in the engine. A density specification is to assure the effectiveness of separators that are used to remove (traces of) water and other impurities from the fuel. A specification on sulphur content keeps the SO_2 emissions within limits. The stability specification prevents the flocculation of asphaltenes in the fuel, thus preventing blockage of filter systems and problems with injection pumps and injectors.

Residual fuels are extremely complex mixtures which can roughly be divided into paraffinic and naphtenic/aromatic (asphaltenic) types according to crude oil origin. They can be considered as a dispersion of asphaltenes in an oily medium (the continuous phase) which is known as the 'maltenes'. The definition of the asphaltenes and the maltenes relates to the fact that when a fuel is diluted with low molecular weight paraffinic solvent such as heptane, a brown or black precipitate is produced. The toluene soluble part of the precipitate is defined as asphaltenes, the remainder being impurities like sand, rust etc. The heptane soluble part of the fuel oil is defined as the maltenes. Thus the asphaltenes together with the maltenes comprise the residual fuel; the proportion of each will depend on the nature of the fuel oil.

DIESEL ENGINE COMBUSTION

The principle behind the operation of a diesel engine is the compression-ignition cycle. Downward movement of the piston causes air to be drawn into the engine cylinder where it is compressed on the upward stroke of the piston. This compression heats the contents of the cylinder to around 550°C, which is about the same as a red hot element in an electric oven. Fuel is injected as the piston approaches the end of the compression stroke (also called Top Dead Centre -TDC) and ignites spontaneously. The increase in pressure generated by the fuel burning provides the power of the engine.

In order to more fully understand the meaning of the term ignition delay, and the influence that this can have on diesel engine performance, it is necessary to look more closely at the combustion process of the fuel in the engine. This process occurs in three distinct phases.

Firstly, the fuel is injected into the engine under high pressure as a stream of very fine liquid droplets. As these droplets meet the hot air in the cylinder they begin to vaporise and mix with the surrounding air.

Secondly, after a short delay, the heat of compression causes spontaneous ignition to occur, and a period of rapid uncontrolled combustion follows as the accumulated vapour formed during the initial injection phase is vigorously burned. This delay, between the commencement of injection of the fuel droplets and the moment of spontaneous ignition of the fuel vapour, is known as the ignition delay period, and occurs in all diesel engines.

The third phase is a period of controlled combustion which maintains pressure on the piston, and is characterised initially by the steady and even combustion of the fuel as it continues to be injected into the engine, and ends with the complete burn out of the fuel after injection has terminated.

During phases two and three, the pressure in the engine cylinder rises rapidly and considerable stresses are imposed on the piston. It is desirable to keep the *rate* of pressure rise as low as possible, and this is achieved by ensuring that the minimum quantity of fuel is present in the cylinder prior to ignition. This means that the ignition delay period should be as short as possible. Power output of the engine is optimised if ignition takes place at piston TDC and is followed by smooth and rapid combustion. To satisfy these requirements it is necessary in practice to begin the injection of fuel just before TDC to allow for the effect of the ignition delay.
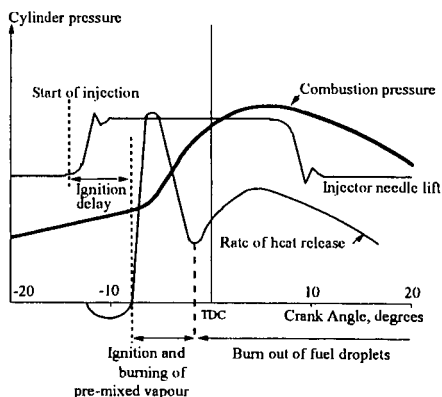

Figure 1a. Fuel combustion - good ignition characteristics

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Figure 1a. is a diagram illustration showing the relationship between the fuel injection into the engine, and the pressure variation which occurs in the engine cylinder as the fuel ignites and combusts. In normal operation, given good ignition and combustion characteristics, the pressure variation will follow the smooth profile indicated by the "*Combustion pressure*" curve in the diagram, well within the design parameters of the engine.

IGNITION DELAY

Too short an ignition delay period does not normally create operational problems, but there is likely to be a loss of fuel efficiency. An extended ignition delay however can lead to poor running of the engine and, in the extreme, to damage of engine components. This is because with long ignition delay a relatively large amount of fuel droplets will have been injected and vaporised in the cylinder by the time ignition occurs. On igniting, this large amount of accumulated vapour will combust almost explosively leading to a sudden and abnormally high *rate* of pressure rise and a high cylinder pressure, beyond that for which the engine was designed or perhaps can tolerate in the longer term.
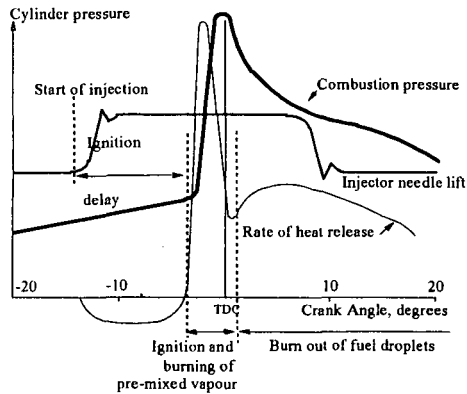

Figure 1b. Fuel combustion - "poor" ignition characteristics

Figure 1b. illustrates the type of effect which can be expected with a fuel having "poor" ignition quality. The effect manifests itself as the characteristic and audible "knock" of a poorly running diesel engine. It causes shock loading on the engine, and possible damage to cylinder heads, pistons, piston rings, liners, crankshafts etc.; a significant drop in power may also occur.

The delay between fuel injection and ignition is, therefore, a most important part of the combustion cycle, and is a function of not only the properties of the fuel, but non-fuel factors like engine design and operating conditions have a much greater effect. In engine operation, ignition delay can be significantly reduced by ncreasing charge air pressure and temperature, the load on the engine and the speed of the engine. The advice to the engine operator is to make every effort to maintain as close as possible to full load thermal conditions at all loads and speeds. Many engine manufacturers promote the use of charge air preheaters at part load operation in order to achieve this ideal, and minimise the potential for fuel ignition problems.

RESIDUAL FUEL IGNITION QUALITY - THE SHELL CCAI CONCEPT [1,2]

Ignition difficulties when using distillate fuels are almost unheard of. For many years the ignition quality of these fuels, such as gas oil, has been characterised primarily by a parameter known as Cetane Number, although to a lesser extent other methods such as Cetane Index or Diesel Index have been used. Current international specifications for marine distillate fuels, such as the ISO 8217: 1996 and BS MA100: 1996, include a minimum specification limit for Cetane Number.

Regrettably there is no similar widely recognised procedure for characterising the ignition quality of residual fuel oil. For a number of reasons the methods used for determining ignition quality of distillate fuels are not relevant, and cannot be applied to residual fuel oils. Therefore in the early eighties Shell Research embarked upon a programme with the objective of gaining an understanding of the factors controlling the ignition performance of residual fuel oils, and to identify means of characterising ignition quality.

Both the physical and chemical properties of residual bunker fuel oil were found to have an influence on ignition performance, physical properties of significance being viscosity and temperature. Atomisation quality is greatly affected by fuel viscosity. Too high a viscosity at injection increases fuel particle size, which reduces spray dispersion, hinders fuel/air mixing in the cylinder, and extends ignition delay. Many engine designs now incorporate fuel management systems capable of operating at temperatures which allow a wide range of residual fuels to be burned without difficulty.

The relevance of the chemical composition of residual fuel oil on ignition was demonstrated in work carried out by Shell Research, which lead directly to the recognition that ignition performance relates to fuel aromaticity. Since aromaticity is a difficult parameter to measure in the absence of specialist laboratory equipment, Shell derived the concept of calculating residual fuel aromaticity. The resulting Calculated Carbon Aromaticity Index (CCAI) can be calculated on the basis of known specification properties of viscosity and density, and it is this parameter which has gained favour as currently the most practical and meaningful method for characterising ignition quality of residual fuel oils.

CCAI can be calculated from the following formula:

$$CCAI = D - 81 - 141 LogLog(Vk + 0.85) - 483 Log(\frac{T + 273}{273})$$

Where: D = density at 15°C, kg/m^3
         Vk = kinematic viscosity (mm^2/s) at temperature T°C

It must be stressed that CCAI is a unit-less number and gives the means of **ranking** the ignition qualities of different residual fuel oils; the lower the number, the better the ignition characteristics. CCAI does **not** give an absolute measure of ignition performance since this is much more dependent upon engine design and operating conditions. **For this reason no attempt has been made to include limiting values in international standards, since a value which may be problematical to one engine operated under adverse conditions may perform quite satisfactory in many other instances. Modern medium speed engines will tolerate CCAI values up to 870 to 875, and values up to 890 and beyond are acceptable to some engine types.** Medium speed diesel engines are more sensitive to fuels having poor ignition characteristics than are low speed cross head engines, which in general are much more tolerant of higher CCAI values.

The limits for viscosity and density currently in place in international marine fuel specifications in themselves provide a control of ignition quality for the main residual fuel oil grades. For example, a 380 mm^2/s (@ 50°C) fuel oil at maximum specification density of 991 kg/m^3 will give a CCAI value of 852, whilst a 180 mm^2/s (@ 50°C) fuel oil having the same density has a CCAI of 861. Ignition characteristics improve with increasing viscosity, or decreasing density.

Ignition difficulties can become more acute at lower fuel viscosity (e.g. below ISO RMD15) if there is not a significant corresponding reduction in density. This is one reason for the lower density limits applying to the lower viscosity grades in the international specifications.
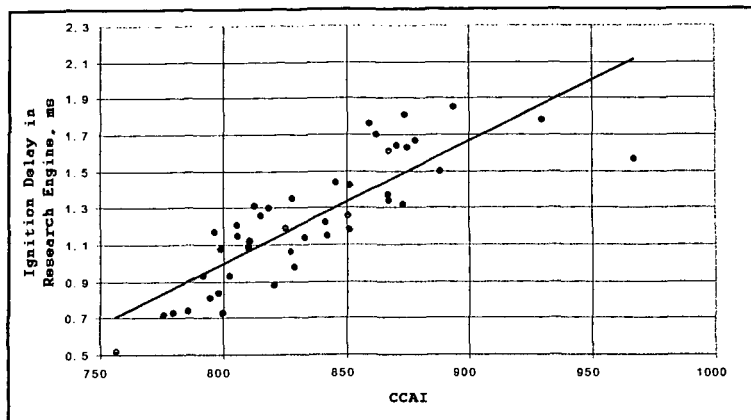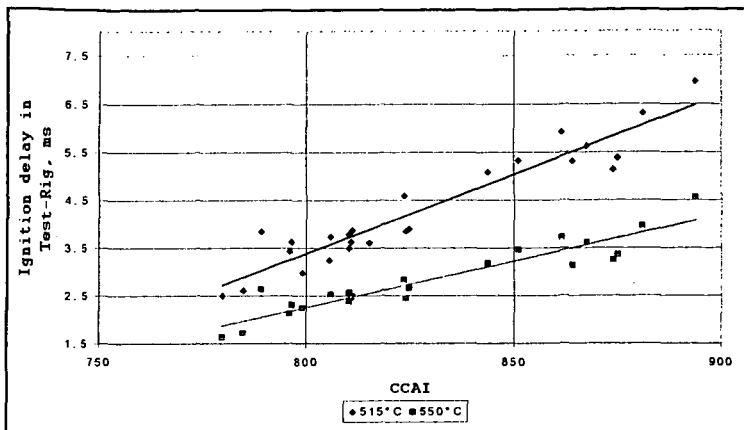

Figure 2: Correlation Ignition delay - CCAI

The correlation between ignition delay and CCAI is not ideal (Figure 2). The scatter of data points around the regression line is rather large. At lower engine outputs the scatter even is larger. This is not only due to experimental errors since cases have been reported where from 2 fuels with comparable analyses one fuel gave ignition problems at low engine output but the second fuel ran as normal. Recent research seems to indicate that there is a correlation with the nature of blending components in addition to CCAI. Combining the ignition delays as a function of CCAI for fuels of the same nature, the scatter around the regression line dramatically reduces. In our research engine at low output differences up to 1 millisecond can be found for fuels with the same CCAI but blended from different components. Obviously this millisecond can be the difference between a running or a stalling engine. More study into the background of this phenomenon is needed.

SMALL SCALE IGNITION DELAY TEST-RIG

Occasionally heavy fuels appear on the market that give engine performance not entirely predicted by their CCAI, while certain fuels can also have an abnormal combustion performance. To assist customers in these cases and for background studies the ignition delay test-rig developed by Shell Research may be used for quick performance testing, giving information on both the ignition and the combustion process. The test-rig consists of an electrically heated cylindrical combustion chamber in which compressed air at a pressure of 50 Bar is allowed to reach a temperature up to 550°C. Using a commercially available injection pump and injector a single quantity of fuel is injected into the combustion chamber. Ignition delay is measured as the time elapsed between the start of injection and the moment the pressure inside the test-rig starts to rise. The combustion process is monitored from the light emission from the 'explosion' in the combustion chamber.

Figure 3: Ignition delay in the Test-Rig as a function of CCAI

A very good correlation between CCAI and ignition delay is found in this test-rig (Figure 3). The correlation is even better than found in the research engine. This may be caused by the fact that in the test-rig there is much more control of the relevant parameters like air pressure and temperature. Because the thick steel walls of the rig are heated from the outside and kept clean from the inside there will be no hot spots or glowing deposits present that can influence the ignition of the fuel. On the other hand in contrast to an engine there is no swirl and twirl in the combustion space. In the Test-Rig usually longer ignition delays are observed than in an engine. One of the reasons is the much higher air to fuel ratio which is being used in the Test-Rig in order to limit the pressure rise due to the combustion of the fuel.
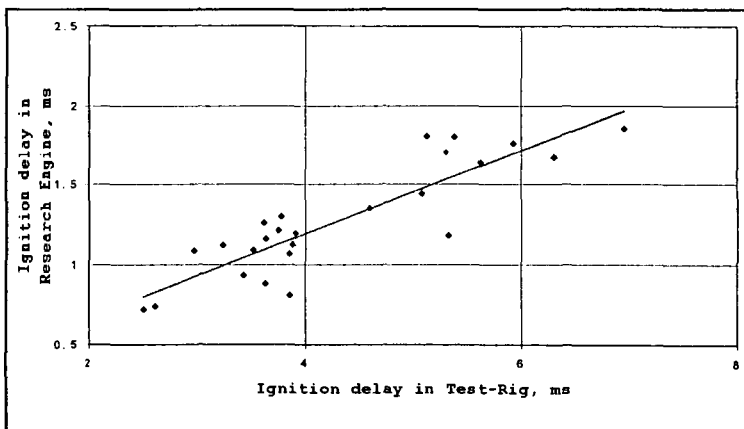
Figure 4: Ignition in the research engine compared to those in the Test-Rig

A satisfactory correlation has been established between ignition test-data obtained in a single cylinder research engine and in the test-rig (Figure 4), particularly at medium to high engine power outputs. It should be emphasised, however, that ignition delay and combustion are very much dependent on engine design and settings, and therefore it will not be possible to translate

a result into the ignition delay in a specific engine. The results can, like CCAI, only be used for a relative ranking of fuel quality. The advantages of the test-rig compared to engine testing are the small amount of fuel sample required (≈ 1 litre) and the short testing time (1 hour).

FUEL STABILITY [2,3]

An unstable fuel will form a sludge which consists of flocculated asphaltenes. In a stable fuel the asphaltenes are 'peptised' (i.e. colloidally dispersed), but if the equilibrium is disturbed part of the asphaltenes will agglomerate and precipitate as 'sludge'. Such a disturbance of the equilibrium between the asphaltene micelles and the maltenes is brought about by a reduction in the aromaticity i.e. the C/H ratio of the maltenes.

It will be clear that in a stable fuel all the asphaltene micelles are completely peptised and in equilibrium with the maltene phase. In the case of stable fuels the concept of 'reserve of stability' is important. It relates to the latitude of the asphaltene micelle/maltene system allowed in dilution or heat treatment without any sludge precipitation. In the case of fuels without stability reserve the equilibrium is so delicately balanced that the slightest change in external conditions will bring about instability. Such fuels of the latter types, although stable immediately after production, will probably commence to throw down sludge as a result of instability development during normal storage and handling. Hence, every effort is made by the refinery to blend fuels having sufficient 'reserve of stability'. This means that, in blending a residual fuel, a distillate stock of sufficiently high aromaticity (high C/H ratio) must be used.

For many years Shell companies have used the Shell Hot Filtration Test as a refinery control for stability. It has been shown that a relation exists between the Shell Hot Filtration Test and the Aromaticity Ratio of the fuel [3]. This is the ratio between the aromaticity of the maltene phase and the aromaticity required by the asphaltenes to remain in solution. For stable fuels the aromatic ratio should be larger than 1 and preferably be larger than 1.1. In an attempt to simplify stability control, we also looked at CCAI as a measure of stability.

Because CCAI represents both the aromaticity of the asphaltene and the maltene phase, it cannot be used to quantify the aromaticity ratio between these two phases. Nevertheless it can give a first indication of potential instability upon mixing of fuels. In a stable fuel the aromaticity of the maltene phase will be higher than the required aromaticity of the asphaltenes. In practice this means that the aromaticity of the maltene phase is higher than that of the entire fuel. When mixing fuels in a tank with about equal CCAI values no instability should therefore be expected. However, with a large difference in CCAI values the chance exists that the aromaticity of the maltene phase decreases to a level at which the asphaltenes with the highest aromaticity requirements become unstable and start flocculating. Because CCAI is not directly related to the required aromaticity of the asphaltenes nor with the stability reserve it is yet not possible to give an indication of how much CCAI difference between the several streams is allowable.

The CCAI apparently can only be used as 'rule of thumb' tool to indicate the compatibility of fuels mixed in a customer's tank. More research is needed to set up a simple way of predicting stability of fuels without performing the elaborate test methods which are now being used to determine the balance between the required and available aromaticity.

References:

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2. Lubricants and Fuels in Ships, Shell Marine Service World Wide.
3. The Stability of Residual Fuels- Theory and Practise of the Shell Concept, 16th CIMAC Conference, Oslo, June 1985