In the maritime industry, most commercial vessels use diesel engines as the main propulsion for propeller, generators or auxiliary equipment. They have consumed a very large amount of fossil fuels and produced high levels of emissions into the environment. Currently, one of the most renewable and environmentally friendly alternative fuels available are known as bio-based fuels. In the maritime sectors, bio-based fuels show many advantages in comparison to fossil fuels due to its renewability and biodegradation. Bio-based fuels can be used directly or in the blend of fossil fuels, and thus, the fuel systems for the application of bio-based fuels to marine diesel engines need to be adjusted aiming at the harmony between fuel properties and fuel system of the as-used marine diesel engines. This report examines the use of traditional and alternative fuels for the marine shipping industry to satisfy the strict strategies of emissions. Some fuel systems are suggested in the case of using bio-based fuels for marine diesel engines. In addition, the experiences of marine diesel engine manufacturers related to the use of alternative fuels are also reported in this study.

**KEYWORDS**

Fossil fuels, alternative fuels, marine diesel engines, fuel system, emissions
International Maritime Organization (IMO) reported that the annual shipboard CO₂ emissions in 2012 were 938 million tons, which constituted about 2.6% of global human-made emissions of the same substance. This scenario is expected to rise three folds by 2050 if no action is taken. Meanwhile the emissions of NOₓ and SOₓ were 15% (19 million tons) and 13% (10.2 million tons) respectively, from their global emissions [4]. In order to cope with this issue, a more stringent regulation is necessary. The latest Marine Pollution (MARPOL) in Annex VI revision recommends limiting the sulphur level from the current 3.50% to 0.50%, effective January 1, 2020. For NOₓ emissions, it was reduced to Tier II and Tier III for global and North American Emission Control Areas, respectively since January 2016.

Currently, the most practical solution is to use low-sulfur fuels when in an ECAs and other situations requiring use of low-sulfur fuels. There are liquid biofuels and fossil fuels that are low in sulfur and can satisfy the fuel sulfur requirements of the ECAs and MARPOL (International Convention for the Prevention of Pollution from Ships) Annex VI. In lieu of using low-sulfur liquid fuels, another option is the use of scrubbers fitted in the engine exhaust to remove the SOₓ. Besides, the price of natural gas is very attractive and as such is a good candidate for serving as a ship’s fuel. There are a number of ships that have been built to use natural gas as fuel, mostly in the coastwise trade or on fixed routes such as ferries.

Compliance with the new emission requirements will raise operating costs for ship owners and operators in terms of new construction ships that will have more complicated fuel systems and perhaps aftertreatment devices and more expensive low-sulfur fuels when in the ECAs and other low-sulfur compliance ports and coastal areas. Existing ships that do not have dual tanks may have to be retrofitted with dual fossil fuel systems so they can perform fuel switching when they enter an ECA.

The paper focuses on evaluating the properties and applicability of different fuels including conventional fuels and alternative fuels in marine diesel engines. These assessments will clarify concerns about alternative fuels including biofuels.

2. FOSSIL FUEL

2.1 Standards and classifications

Fuels must meet minimum requirements that have been laid down by ISO, the International Organization for Standardization, in collaboration with the association of diesel engine manufactures, the Cimac is an interested group in the field of the “non-automotive combustion engines for gas and diesel engines as well as gas turbines.

The requirements are stipulated in the standard specification ISO-8217: 1996/2005 for refined marine fuels, which was last updated in 2010. ISO 8217 defines the requirements of petroleum fuels use in marine diesel engines and boilers, to ensure reliable engine operation with fuel from refining processes. Each specification has a test method indicating a minimum or a maximum value acknowledged by the ISO. There are generally two types of marine fuels: (1) distillate and (2) residual fuels. Fuel grades are designated by codes, consisting of a group of letters: the initial ISO, F (for the class of fuel), D or R (distillate or residual), M for marine, and a letter from A to Z that has no particular significance, but is related to the particular properties of certain product specifications, ending with a number corresponding to the maximum kinematic viscosity of the residual fuel. For example, marine residual fuel can be designated ISO-F-RMG 380, or RMG 380 for short (Table 1) [5].

There are different types of residual fuels, including light fuel oil (LFO) and heavy fuel oil (HFO). LFO is of lower viscosity and density than HFO. LFO is classified ISO-F-RMA through RMD. HFO, also known as heavy diesel oil (HDO) or marine fuel oil (MFO), is classified ISO-F-RME through RMK, and is the most common marine fuel, taking up about 47-66% of the marine fuel mix. There are different grades (viscosities) of residual fuel, of which 380 and 180 centistokes at 50°C are the most common. HFO with 380 centistokes, which is colloquially referred to as bunker fuel, needs to be heated before fuelling and use. HFO is used in combustion equipment on ships, including the main engine, auxiliary engines, and boilers. A low-sulfur version of HFO, LSHFO (low sulfur heavy fuel oil) contains less than 1.5% sulfur and is also available in low (180 Centistoke) or high (380 Centistoke) viscosity.

Intermediate fuel oil (IFO) is a blend of both refinery distillate MGO and residual fuel, with less gas-oil than MDO. It is a ‘middle distillate’ petroleum fraction, combining heavy and light crude fractions to a

### Table 1: ISO distillate marine fuel specifications [5]

<table>
<thead>
<tr>
<th>Specification</th>
<th>Unit</th>
<th>Limit</th>
<th>DMA</th>
<th>DMZ</th>
<th>DMB</th>
</tr>
</thead>
<tbody>
<tr>
<td>Kinematic viscosity</td>
<td>cSt</td>
<td>Max</td>
<td>6.0</td>
<td>6.0</td>
<td>11.0</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Min</td>
<td>2.00</td>
<td>3.00</td>
<td>2.00</td>
</tr>
<tr>
<td>Density at 15°C</td>
<td>Kg/m³</td>
<td>Max</td>
<td>890</td>
<td>890</td>
<td>900</td>
</tr>
<tr>
<td>Cetane number</td>
<td></td>
<td>Min</td>
<td>40</td>
<td>40</td>
<td>35</td>
</tr>
<tr>
<td>Sulphur</td>
<td>Mass %</td>
<td>Max</td>
<td>1.5</td>
<td>1.5</td>
<td>2.0</td>
</tr>
<tr>
<td>Flash point</td>
<td>°C</td>
<td>Min</td>
<td>60</td>
<td>60</td>
<td>60</td>
</tr>
<tr>
<td>Acid number</td>
<td>Mg KOH/g</td>
<td>Max</td>
<td>0.5</td>
<td>0.5</td>
<td>0.5</td>
</tr>
<tr>
<td>Total sediments</td>
<td>Mass %</td>
<td>Max</td>
<td>-</td>
<td>-</td>
<td>0.10</td>
</tr>
<tr>
<td>Oxygen stability</td>
<td>g/m³</td>
<td>Max</td>
<td>25</td>
<td>25</td>
<td>25</td>
</tr>
<tr>
<td>Cloud point</td>
<td>°C</td>
<td>Max</td>
<td>n/a</td>
<td>n/a</td>
<td>n/a</td>
</tr>
<tr>
<td>Lubricity</td>
<td>µm</td>
<td>Max</td>
<td>520</td>
<td>520</td>
<td>520</td>
</tr>
<tr>
<td>Pour point</td>
<td>°C</td>
<td>Min</td>
<td>-6 to 0</td>
<td>-6 to 0</td>
<td>0 to 6</td>
</tr>
<tr>
<td>Water</td>
<td>Volume %</td>
<td>Max</td>
<td>n/a</td>
<td>n/a</td>
<td>0.30</td>
</tr>
<tr>
<td>Ash</td>
<td>Mass %</td>
<td>Max</td>
<td>0.10</td>
<td>0.10</td>
<td>0.10</td>
</tr>
</tbody>
</table>
specified viscosity, most commonly available with a maximum of 180 or 380 Centistokes. IFOs have good ignition characteristics due to the high percentage of the paraffinic material present and are commonly used in low-speed 2-stroke engines. ISO 8217 specifies the following criteria for residual fuels, as shown in Table 2, of which the limits on density, kinematic viscosity at 50°C, and flash point are of most importance for engine compatibility [5].

<table>
<thead>
<tr>
<th>Specification</th>
<th>Unit</th>
<th>Limit</th>
<th>RMA 10</th>
<th>RMG 180</th>
<th>RMG 380</th>
</tr>
</thead>
<tbody>
<tr>
<td>Kinematic viscosity</td>
<td>cSt</td>
<td>Max</td>
<td>10</td>
<td>180</td>
<td>380</td>
</tr>
<tr>
<td>Density at 15°C</td>
<td>Kg/m³</td>
<td>Max</td>
<td>920</td>
<td>991</td>
<td>991</td>
</tr>
<tr>
<td>Sulphur</td>
<td>Mass %</td>
<td>Max</td>
<td>3.5%</td>
<td>or statutory requirement in SECA</td>
<td></td>
</tr>
<tr>
<td>Flash point °C</td>
<td>Min</td>
<td></td>
<td>60</td>
<td>60</td>
<td>60</td>
</tr>
<tr>
<td>Acid number mg KOH/g</td>
<td>Max</td>
<td></td>
<td>2.5</td>
<td>2.5</td>
<td>2.5</td>
</tr>
<tr>
<td>Total sediments Mass %</td>
<td>Max</td>
<td></td>
<td>0.10</td>
<td>0.10</td>
<td>0.10</td>
</tr>
<tr>
<td>Pour point °C</td>
<td>Max</td>
<td></td>
<td>0 to 6</td>
<td>30</td>
<td>30</td>
</tr>
<tr>
<td>Water</td>
<td>Volume %</td>
<td>Max</td>
<td>0.30</td>
<td>0.50</td>
<td>0.50</td>
</tr>
<tr>
<td>Ash</td>
<td>Mass %</td>
<td>Max</td>
<td>0.040</td>
<td>0.100</td>
<td>0.100</td>
</tr>
<tr>
<td>Vanadium mg/kg</td>
<td>Max</td>
<td></td>
<td>50</td>
<td>350</td>
<td>350</td>
</tr>
<tr>
<td>Sodium mg/kg</td>
<td>Max</td>
<td></td>
<td>50</td>
<td>100</td>
<td>100</td>
</tr>
<tr>
<td>Aluminum + silicon mg/kg</td>
<td>Max</td>
<td></td>
<td>25</td>
<td>60</td>
<td>60</td>
</tr>
</tbody>
</table>

2.2 Properties

2.2.1 Viscosity

This is a measurement of the viscosity or “resistance to flow” of fuel. It is measured by the times taken for a fluid to drain from a graduated cylinder through a calibrated opening. The longer the discharge time the thicker the oil and the higher the viscosity. The unit of measure is centistokes indicated by cSt. This can also be indicated by mm²/second. Naturally, every engine manufacturer has his own prescribed viscosity range for optimum atomization. Medium-speed engines with a high number of revolutions and therefore a shorter process time often have lower viscosity fuels. Two-stroke low-speed crosshead engines with a longer process time often have fuels with a viscosity that can increase up to 15 cSt.

2.2.2 Density

This signifies the mass in kilograms per m³ at 15°C. This is very important with regard to, for instance, the required storage space and the settings of the centrifuges. The most advanced centrifuges can clean fuel with a density of 1010 kg/m³ at 15°C.

2.2.3 Flashpoint

The flash point is the minimum temperature at which the fuel vapor formed over an oil sample that has warmed-up in a special heating device, first burns after being ignited with test flame. The Pensky Martens closed cup flash point tester is a well-known and often applied instrument for determining the flash point. In the shipping industry, the minimum flash point of 60°C is enforced due to safety issues (explosion and fire hazards). Fuel for large engines and backup generators forms an exception. To ensure low-temperature ignition of these engines a flash point of 43°C is allowed. Modified rules apply to the M.O.B (man overboard boat) which is equipped with an outboard motor and where very light petroleum is used as a fuel.

2.2.4 Flow point

This is the lowest temperature expressed in degrees Celsius at which a fuel can be treated or still flows. This is about three degrees above the solidifying point. The solidifying point is of the utmost importance in the storage and processing of fuels. Furthermore, the fuel must be pumpable. Once the heavy oil has solidified, it is extremely difficult to liquefy it by using heating coils. The oil often only liquefied around the coils as the oil no longer circulates. When using heavy oil heating is an absolute necessity.

2.2.5 Carbon residue or Conradson carbon number

This is a measurement for the formation of carbon and coal deposits during combustion. This is important when considering the contamination of the combustion space in which the atomizer nozzles, the exhaust valves, the pistons, the piston rings, and the piston grooves are found and in the exhaust system containing among others the turbo blower, the exhaust gas boiler and the silencers. The carbon residue is determined in the Conradson apparatus; fuel is heated in the crucible. At high temperatures, the lighter hydrocarbons vaporize and the heavier hydrocarbons are cracked, breaking down the long chains into smaller ones.

2.2.6 Ash content

This represents the inorganic material content that is left behind after combustion at extremely high temperatures when the carbon is removed. For ship fuels, the ash content lies between 1/1000 and 9/100 percent mass. If the ash content in the fuel is considerably higher than the sum of the parts of sodium, aluminum, and silicon, further research is required. Ashes may cause wear and engine corrosion.

2.2.7 Water content

Fuels always contain a small amount of water. This enters during transportation, processing in the refinery and storage in tanks, especially air bay condensation. A maximum of 1% of water is allowed in fuel. In reality, 80% of the fuels contain less than 0.3% water. At high water content values, the heat value of fuel decreases.

2.2.8 Sulfur content

This is one of the most common elements in liquid fuels. The sulfur content in heavy oil varies from 1.5 to 3.5. Sulfur poses problems in the form of low-temperature corrosion. Together with water and oxygen, which are always present in air, sulfur forms sulfuric acid. Sulphuric acid can damage the cylinder liner, for instance, the exhaust systems at low engine loads. Sulfur in the fuel, once it is burned, is converted to sulfur oxides which have damaging consequences for the environment, especially air pollution.

2.2.9 Cetane index

This is only applicable to gasoline and distillate fuels. It is a measure of the ignition quality of the fuel in a diesel engine, and the cetane number is based on the density and the distillation of the fuel. The higher the rpm of the engine, the higher the cetane index required.

2.2.10 Total sediment

These are ash-like substances or insoluble hydrocarbons. The heavy oil contains asphaltenes which are usually soluble in the fuel. Fuels that...
contain insoluble asphaltenes are called unstable fuels. These unstable fuels may contain large quantities of sediment, overloading the centrifuges and causing them to work poorly.

2.3 Application

2.3.1 Fuel-line systems of four-stroke, high-speed engine, fuel MDO

These are often very straightforward systems. From an elevated tank, the diesel oil passes through a fuel filter towards the high-pressure fuel pump. The atomizer drain or return pipe is also connected to the fuel tank. If the tank is not placed in an elevated position, the engine is equipped with a low-pressure fuel pump. It is important that the filter, transfer pumps, and lines can be easily bled. It is also advisable to fit a water tap at the bottom of the fuel filter.

Figure 1 describes the fuel system of a Caterpillar-diesel power unit, general. This consists of an elevated storage tank with a fill and bleeds connection. A drain for water and dirt is fitted at the bottom of the tank. Via an automatic float system or a manual stop valve, the day tank can be maintained at the correct level. From the day tank, the fuel flows to the low-pressure fuel suction pump. This provides a certain fuel pre-pressure to the mechanically driven fuel injectors. A suction filter has been placed before the fuel suction pump to protect the pump, after the fuel pump a duplex filter is installed to clean the fuel. In the engine, the supply and return lines are fitted with a flexible section in order to avoid damage to the fuel lines as a result of vibration. The fuel return line has an integrated fuel cooler.

A fuel system for diesel oil of a Caterpillar, Series 3500 B MEUI (Figure 2). The diagram is self-explanatory. The green section of the line has no pressure build-up. The pressure governor above the fuel tank by-passes the fuel to the storage tank at high pressure. The suction line for both low-pressure fuel suction pumps is located to the left of the tank. The filter in the suction line protects the pumps. Sometimes a water separator is also placed here. The grey housing left in the drawing is called the “Engine Control Module” (ECM) and controls all the important engine functions.

Figure 1: The fuel system of a Caterpillar-diesel power unit [16]

Figure 2: A fuel system for diesel oil of a Caterpillar, Series 3500 B MEUI [17]
2.3.2 Fuel-line systems of four-stroke, medium-speed engine, fuel HFO

Engines in this category use very elaborate fuel systems. The heavy oil must be cleaned and attain the correct pressure and temperature before it reaches the high-pressure fuel pipes. When using heavy oil, it is of the utmost importance that the fuel temperatures during the various stages of the pre-treatment are read, such as the sedimentation or settling tanks is 60 to 80°C; the separator is 95 to 98°C; the fine filter to the engine is about 125 to 135°C. Figure 3 show an example of the system of a Caterpillar-Mak 43-C propulsion diesel engine.

![Figure 3: The system of a Caterpillar-Mak 43-C propulsion diesel engine [5]](image)

MaK diesel engines are designed to burn a wide variety of fuels. See table 1 about the information on fuel requirements in section MDO / MGO and heavy fuel operation or consult the Caterpillar technical product support [18]. Diesel oil can be pumped from storage tank DT4 to the diesel oil tank DT1 via the suction filter DF3 and diesel oil trim pump DP3. Additionally, from the storage tank DT4, diesel oil can be pumped via an electric heater DH2 using the diesel oil trim pump DP5 to the diesel oil separator, where additional cleaning occurs. The fuel is then pumped to the diesel day tank DT1. From the elevated diesel oil tank, the diesel oil flows through the duplex filter DF2, the flow meter FQ1 and the diesel oil preheater DH1. Following, one of the two diesel oil feed pump to pump the fuel through a very fine filter to the high-pressure fuel pumps KP1. Spilled fuel oil is collected in the spillage collection fuel oil tank KT1. This fuel flows back into the day tank DT. The high-pressure fuel pump return line feeds the day tank DT via a flow meter FQ1.

Table 3: The information on fuel requirements in section MDO / MGO and heavy fuel operation or consult the Caterpillar technical product support.

<table>
<thead>
<tr>
<th>Designation</th>
<th>MGO</th>
<th>Max. viscosity [cSt/40°C]</th>
<th>MGO</th>
<th>Max. viscosity [cSt/40°C]</th>
</tr>
</thead>
<tbody>
<tr>
<td>ISO 8217:2010</td>
<td>ISO-F-DMA</td>
<td>2.0 – 6.0</td>
<td>ISO-F-DMB</td>
<td>11</td>
</tr>
<tr>
<td></td>
<td>ISO-F-DMB</td>
<td>11</td>
<td></td>
<td></td>
</tr>
<tr>
<td>ASTM D 975-78</td>
<td>No. 1D</td>
<td>2.4</td>
<td>No. 2D</td>
<td>4.1</td>
</tr>
<tr>
<td></td>
<td>No. 2D</td>
<td>4.1</td>
<td>No. 4D</td>
<td>24.0</td>
</tr>
<tr>
<td>DIN</td>
<td>DIN EN 590</td>
<td>8</td>
<td>-</td>
<td>-</td>
</tr>
</tbody>
</table>

2.3.3 Fuel-line systems of two-stroke, low-speed engine, fuel HFO

![Figure 4: A complete fuel treatment system in an RTA58T engine [19]](image)
**3. ALTERNATIVE FUEL**

Currently, along with the development of material technology and science that was applied to shipbuilding, maritime fields, as well as the reduction of maritime environment, alternative fuels used for marine diesel engines have been considered as the critical issues aiming at the sustainable development of maritime [20-31]. There are liquid fossil fuels, liquid biofuels, and gaseous fuels that are in use or can be used by ships for compliance with the existing and forthcoming environmental pollution requirements. The feed-stocks for current and future marine fuels are shown in Table 4.

<table>
<thead>
<tr>
<th>Table 4: The feed stocks for current and future marine fuels [32,33]</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Feedstock</strong></td>
</tr>
<tr>
<td>Natural gas, bio-gas</td>
</tr>
<tr>
<td>Fuels</td>
</tr>
</tbody>
</table>

**CNG** = compressed natural gas; BTL = biomass-to-liquid; GTL = gas-to-liquid; DME = dimethyl ether; and LBG = liquefied bio-gas.

**3.1 Properties**

Straight vegetable oils (SVO), also known as pure plant oils (PPOs), are oils extracted from plants solely for use as a fuel [34][48][54]. These oils do not undergo any intermediate processing steps but are introduced in diesel engines directly from extraction. Studies have shown that they can be used to replace IFO or heavy oil in high-performance engines (all sizes of carriers and cargo ships), though generally not considered practical fuels for large-scale or long-term use. Biodiesel is also commonly known as fatty acid methyl ester (FAME) [35][49][57], obtained from vegetable oil or animal fat, which has been converted with methanol or ethanol. Sodium methylate is commonly used as a catalyst. FAME is more suitable fuel than SVO for diesel engines, with lower boiling point and viscosity than SVO [36][37][50], leading to better engine performance. Biodiesel has a higher flash point (149°C) and cetane rating than conventional diesel and degrades quickly in water. FAME, however, has a high cloud point which can result in filter clogging and poor fuel flow at temperatures lower than 32°C. The biodiesel produced is generally used for automobile transport and is typically not used 100% in diesel engines, but rather as a blend with petroleum diesel (5-30%). In blends of 1-2%, biodiesel may be used as a lubricity additive, especially with ULSD [33], which by itself has poor lubrication properties. For blends higher than 7%, additives such as ethanol can be added as a solvent to prevent phase separation during blending [38].

In 2009, the Greenhouse Gas Council of the IMO collected seven types fuel, distilled oil, heavy oil, LPG, biodiesel and crude vegetable oils, synthetic diesel (FTD) and other recyclable fuels. However, given the level of environmental impact, including emissions from use and emissions from the production of fuels, LNG and biodiesel are more highly valued.

Bio-methanol is the second-generation biofuel. Methanol is converted to DME as a substitute for LNG / mixed composition: Replacement of diesel for car and ship engines (clean fuel, but engines must be improvement). The reason is that biomass-to-methanol/DME is foreseen to be the most energy-efficient pathway to procuring transport energy by 2050. Conversions of marine vessels to methanol are significantly less costly than conversions to LNG because of the simplicity of the storage system for methanol. Although methanol itself is slightly costlier than LNG, the trade-off between methanol and LNG involves the complexity of the fuel system versus the cost of the fuel. Methanol has properties that are similar to those of methane when it is injected into an engine. It can be used in a dual-fuel concept, as proposed by Wärtsilä (Figure 5) [39].

**Figure 5: A dual-fuel concept, as proposed by Wärtsilä** [40]

Biodiesel is extracted from the original vegetable oil or animal fat, which is equivalent to diesel. Biodiesel can be used directly or mixed with diesel in a certain proportion and delivered to the diesel engine. Depending on the mix ratio, there will be different types of biodiesel fuel blends: B5, B10, B20, ..., B100 (in which: 5%, 10%, 20%, ..., 100% is the component of biodiesel in the mixture) [41][42]. The main challenges are:
- Low cetane number
- High water content
- Poor lubricity

However, the use of bio-crude as a feasible marine fuel is yet to be proven. CNG is made by compressing natural gas to less than 1% of the volume it occupies at standard atmospheric pressure. It is stored and distributed in containers at a pressure of 200–248 bar (2900–3600 psi), usually in cylindrical or spherical shapes. LNG achieves a higher reduction in volume than CNG. The liquefaction process condenses the natural gas into a liquid at close to atmospheric pressure by cooling it to approximately −162°C (−260°F). The energy density of LNG is 2.4 times that of CNG or 60% of that of diesel fuel. This makes LNG attractive for use in marine applications where storage space and endurance are critical [43][53]. A third concern to be addressed is methane slip from larger marine engines burning gas. Methane slip will be present, especially on four-stroke, dual-fuel engines (Figure 6), partly from the scavenging process in the cylinder and partly from the ventilation from the crankcase, which is being led to the atmosphere. In addition, there is some uncertainty as to whether future regulations will allow LNG tanks to be situated directly below the outfitting/accommodation of the ship. If not, this constraint could cause difficulties in retrofitting certain ships.

![Figure 6: Dual-fuel engines: diesel and methane](image)

3.2 Application

3.2.1 Dual fuel

In this diesel process, a very small percentage of between 1 to 10% liquid heavy fuel or diesel oil is injected. During the intake stroke, gas is admitted just before the inlet valves [58]. The liquid fuel ignites the air/gas mixture. The advantage is that the exhaust gases are cleaner than when heavy fuel oil or diesel oil are used. The CO₂ production is reduced since a gaseous fuel contains less carbon than a liquid fuel and the emission of soot particles and sulfur is significantly less. Therefore, the contamination of the engine decreases.

![Figure 7: The dual fuel principle](image)

The engine can automatically change over from heavy-fuel oil to gas below an 80% load [59]. This takes approximately one minute. When there is an interruption in the gas supply, the engine automatically changes over to heavy fuel oil.
The one fuel, gas, is admitted just before the inlet valves during the introduction stroke of the engine (Figure 8). Gas and air are intensively mixed. The air factor is between 1.5 and 2.0. This is known as a ‘poor’ mixture 50 to 100% more air is present than required to fully burn all the fuel chemically. At the end of the compression stroke, the very small amount of the air/gas mixture. The ‘pilot’ injector replaces the traditional sparkplug. The process continues according to the diesel principle, which has a higher efficiency than the Otto-principle. The fuel before the injector comprises 1% heavy fuel oil and 99% gas supplied by a ‘pilot’ high-pressure pump unit that via a common rail system provides the injectors with sufficient fuel [60]. With the transition to 100% heavy fuel oil use, the large high-pressure fuel pumps provide sufficient fuel. The injectors have two injectors nozzles, the pilot and main injector [44]. Engine starting and stopping sequences, safety system and change in the operation mode (diesel/gas mode) are also automatically controlled. If any input signal shows an incorrect value, the control system will give the alarm, see Figure 10.

### 3.2.2 Biofuels

In approximately 1900, Rudolf Diesel demonstrated a diesel engine that could run on peanut oil. In 2007, the interest in biofuels was huge (Figure 11) [43][57]. This is the result of the following two points:

Due to the increasingly stringent requirements with regard to the emission of noxious substances in the exhaust gases, amongst which the toxic greenhouse gas CO\(_2\), carbon dioxide. Biofuels absorb CO\(_2\) from the atmosphere during their growth process; the CO\(_2\) is converted to vegetable matter. This is known as photosynthesis. Photosynthesis is the conversion of, amongst others, CO\(_2\) extracted from the atmosphere as a base material and light as an energy source to (energy containing) carbohydrates and O\(_2\), oxygen, which is released into the atmosphere. This is known as ‘CO\(_2\) neutral’[45]. Therefore, when biofuels are burnt, no extra CO\(_2\) is emitted, as is the case with fossil fuels.

Due to the explosive growth in the use of energy, the demand for mineral fuels has increased exponentially. Countries such as China, India, Brazil, and Indonesia require an ever-increasing, as is the fuel price. It is becoming increasingly clear how much large industrial countries. The economic and political need for the development of alternative fuel sources is increasing and in the search for alternatives, subjects such as ‘less dependent on fossil fuels’ are ever more important.

As described above MAN B&W Diesel along with Wärtsilä, are the engine manufacturers with the most experience on biofuels for stationary power generation as well as being the largest engine suppliers to the Norwegian domestic fleet. MAN B&W Diesel manufactures a number of different biofuels compatible engines. In 2006, the first test of biodiesel on their two-stroke low speed engines was carried out in Copenhagen, Denmark [51]. A new milestone was achieved in 2007 when MAN Diesel...
employed palm biodiesel in their four-stroke medium speed engine in Belgium. As for current, MAN Diesel offers a wide range of marine engines that are ideal for biodiesel fuel applications without any modifications. According to the Senior Vice President of Research and Development, MAN Diesel A/S, Thomas S. Knudsen, there is a high demand for two-stroke biofuel engines at the moment. Below is a figure of the different engines tailored for biofuels (Figure 12) [5].

Wärtsilä (Finland) is one of the leading marine engine manufacturers in the world and has started looking for alternative energy sources. In 1995, the company succeeded in testing diesel fuel for diesel engines and by 2003 installed in Germany the first energy system powered by vegetable oils intended for use commercial. Recently, Finland TX has signed a commercial contract with Wärtsilä, which is equipped with three 6L20 4L

Caterpillar verifies the use of biofuel blends. Caterpillar C7 and bigger engine can use 30 percent biodiesel. It is likely that higher blends can also be used in Caterpillar engines, but Caterpillar does not yet warrant such use. Lutz Liebenberg of Rolls Royce Norway states that they have had no experience with biofuels on their marine engines but that they are planning to give it more attention after having received several inquiries from customers.

4. CONCLUSION

The demand for economical and efficient use of energy and associated with environmental protection is increasingly pressing for all countries. The promotion of the use of renewable fuels in the shipping sector in order to achieve the objective of environmental protection that has been concretized by international legal instruments through the MARPOL 73/78 Conventions and SOLAS 74 and other legal documents in the country. IMO also recommends the use of renewable fuels for marine diesel engines such as LNG and biofuels. However, in the future, the use of gas on the ship will have major obstacles due to significant improvements to the fuel supply system for diesel engines. In addition, the safety issue must be the first because the explosion of LNG is much higher than traditional fuels. For biofuels, it is more favourable than LNG gas. Some well-known marine diesel engine manufacturers such as Wärtsilä, MAN B & W, and several other engine builders have studied the use of biodiesel for marine diesel engines and achieved some success but high cost and cannot compete with traditional fuels. In addition, biodiesel production is relatively complex and requires a lot of KOH or NaOH catalysts, along with significant energy consumption in the production process. Therefore, it is feasible to study the direct use of vegetable oil or a mixture of vegetable oil with conventional diesel oil at an appropriate rate.

Furthermore, official mandate by the government and international bodies such as IMO is able to encourage and promote the application of biodiesel in the marine industry. The role of biodiesel is not to replace the existing fossil fuel, but more towards the establishing of balance energy policy that could benefit the international marine community. Last but not least, the authors believe that biodiesel has a bright future as a green alternative energy for marine applications.

REFERENCES


