

Fuels

WinGD Fuel Guideline

DTAA001522




WIN GD

Document ID: DTAA001522
 Revision: -
 Date: 12.07.2024



FUELS

Prod.										
Change History										
	-	mhu019	dst009	12.07.2024	CNAA006312	new Document		-	-	
	Rev.	Creator	Approver	Approval Date	Change ID	Change Synopsis	Activity Code	E	C	
				<h1>FUELS</h1>						
PC-Drawing				Dimension			Guideline			
Copyright WinGD Ltd. All rights reserved. By taking possession of the document the recipient recognizes and honours these rights. Neither the whole nor any part of this document may be used in any way for construction, fabrication, marketing or any other purpose nor copied in any way nor made accessible to third parties without the previous written consent of WinGD Ltd.										
				Design Group		9723	Q-Code	- - -	Standard	WDS
				A4	Document ID	DTAA001522		PC Page/s	2 / 51	

Document ID: DTAA001522
Revision: -
Date: 23.02.2024



List of Changes

Rev.	Release date	Made	Description
-	2024-07-12	bro101	This document was created based on the WinGD Fuel Guideline, the "Concept guidance for distillate fuels (107.428.377) and the "Concept guidance for fuel oil treatment (107.246.880)" and replaces these documents accordingly.

Table of Contents

1	Introduction	7
2	Regulations.....	7
2.1	Diesel fuels.....	7
2.2	Names of hydrocarbon fuels after 1 January 2020.....	8
2.3	ECA-emission control areas.....	9
2.3.1	Overview ECA zones	9
2.3.2	Northern European ECA.....	9
2.3.3	North American and U.S. Caribbean Sea ECA	9
2.3.4	Chinese coastal waters.....	10
2.3.5	Polar regions.....	10
2.4	Gas fuels (LNG)	10
2.5	Biofuels.....	10
3	Diesel fuels.....	11
3.1	ISO 8217 compliance	11
3.1.1	ISO 8217:2024 version	11
4	Diesel fuel parameter description.....	12
4.1	Density.....	12
4.2	Viscosity.....	12
4.3	Calculated Carbon Aromaticity Index (CCAI).....	14
4.4	Lubricity	14
4.5	Cetane Index	14
4.6	Sulphur	14
4.7	Flash point.....	14
4.8	Hydrogen Sulphide (H ₂ S).....	14
4.9	Acid Number.....	15
4.10	Sediment, carbon and asphaltenes.....	15
4.11	Total Sediment.....	15
4.12	Pour point	16
4.13	Water	16
4.14	Ash and Trace Metals	16
4.15	Vanadium and Sodium	16
4.16	Aluminium and Silicon	16
4.17	Calcium and Potassium	18
4.18	Used lubricating oil	18
4.19	Chemical waste.....	18
4.20	Organic chlorides	18
4.21	Cloud point and Cold Filter Plugging Point	18
5	Residual Marine Fuels	19
5.1	Introduction residual marine fuels.....	19

5.2	Very Low Sulphur Fuel Oil (VLSFO)	20
5.2.1	Viscosity of VLSFO	20
5.2.2	Cold flow properties of VLSFO	21
5.2.3	Compatibility and/or stability of VLSFO	21
5.3	Ultra Low Sulphur Fuel Oil (ULSFO)	21
5.4	High Sulphur Fuel Oil (HSFO, S > 0.50 wt%)	21
5.5	Specifications for residual marine fuels	22
6	Distillate Marine Fuels	24
6.1	General about distillate marine fuels	24
6.2	Specifications for distillate marine fuels	24
7	Renewable drop in fuels / Biofuels	26
7.1	Hydrocarbon based renewable fuels	26
7.2	Hydrotreated Vegetable Oil (HVO)	26
7.3	Fatty Acid Methyl Ester (FAME)	26
7.4	Residues of FAME production	27
7.5	FAME specifications	28
7.6	Fuel supply system considerations	29
7.7	Operation on pure FAME biofuel	29
7.8	Other alternative drop-in fuels of non-petroleum origin	29
8	Pilot fuel (DF engines only)	30
9	Diesel fuel storage and handling	30
9.1	Fuel storage	30
9.1.1	Blending of fuels on board	30
9.2	Fuel supply system	31
9.2.1	Fuel oil pumps	31
9.2.2	Heat exchanger	32
9.3	Fuel oil treatment	33
9.3.1	Service and settling tanks	34
9.3.2	Centrifugal separators	34
9.3.3	Separation efficiency	35
9.3.4	Fuel filters	36
10	Methanol	38
10.1	Properties of methanol	38
10.2	Specification of methanol	38
11	Methane (LNG)	39
11.1	Introduction	39
11.2	Liquefied natural gas (LNG)	39
11.3	Gas parameters description	39
11.3.1	Lower Heating Value	39
11.3.2	Methane Number	40
11.3.3	Methane number calculation	41

11.3.4	Ageing of LNG.....	41
11.3.5	Gas impurities.....	42
11.3.6	Gas specifications.....	43
12	Ammonia fuel.....	44
12.1	Ammonia properties.....	44
12.2	Ammonia specifications.....	44
13	Fuel changeover.....	45
13.1	Changeover for diesel fuels.....	45
13.1.1	Automatic fuel changeover.....	45
13.1.2	Manual fuel changeover.....	45
13.1.3	Recommended viscosity at the inlet of the fuel pumps.....	45
13.2	Fuel changeover on DF engines.....	45
13.2.1	Cylinder oil change due to changeover.....	45
13.3	Changeover for SCR operation.....	47
14	Fuel additives.....	47
A	References.....	48
B	Abbreviations.....	50

List of Figures

Figure 1. Sulphur limits introduced by IMO according to MARPOL Annex VI.....	7
Figure 2. Regions with fuel requirements in place or implementation pending	9
Figure 3. Viscosity / Temperature diagram	13
Figure 4. Scuffed cylinder liner surface at TDC with cat fines trapped in graphite flakes.	17
Figure 5. Density vs. viscosity for VLSFO (2023) and HFO (2018).	20
Figure 6. HSFO density vs. viscosity for the first half of 2023.	22
Figure 7. Cleanliness rating according to ASTM D4740.....	30
Figure 8. Installation principle for maximum fuel flexibility.....	31
Figure 9. Schematic illustration of fuel oil temperature at mixing unit and before cooler	32
Figure 10. Simplified view of optimal fuel tanks design for vessels capable operating on residual fuel.....	33
Figure 11. Separation efficiency versus separator throughput	35
Figure 12. Recommendation for fuel oil filter arrangement	36
Figure 13. Minimum requirement for fuel oil filter arrangement.....	37
Figure 14. The maximum achievable power dependence on the Methane Number	40
Figure 15. Simplified LNG gas supply system.....	41
Figure 16. Cylinder lubricant quantity	46

List of Tables

Table 1. Fuels naming after 1 January 2020.....	8
Table 2. Quality comparison between HFO and today's fuel.....	19
Table 3. Specifications for residual marine fuels.	22
Table 4. Specifications for distillate marine fuels.....	24
Table 5. FAME fraction limits from EN 14214 and ratio between residual FAME chemicals and FAME	28
Table 6. Selected properties of methanol in comparison to marine gas oil.....	38
Table 7. Specification of minimum methanol quality for the WinGD X-DF-M engines.....	38
Table 8. Examples of LNG and its physical properties	40
Table 9. LNG composition examples	41
Table 10. Gas specifications	43
Table 11. Comparison of energy properties for ammonia and marine gas oil.....	44
Table 12. Specifications of ammonia for the WinGD engines	44

1 Introduction

This guideline describes specifications of all fuels which can be used in the WinGD engines. The fuels mentioned in the text are divided into liquid and gas fuels. Liquid fuels consist of distillate, residual and renewable fuels and methanol. Gas fuels include Liquefied Natural Gas (LNG) and ammonia.

The parameters of the fuels are described with typical concentrations given. Additional information on storage and handling is also provided. Finally, the regulation situation for the use of each fuel is described.

2 Regulations

2.1 Diesel fuels

Regulation 14 of revised MARPOL Annex VI [1] limits the sulphur content in diesel fuels, which has been gradually decreased in recent years (Figure 1). From 1 of January 2015, a fuel not exceeding 0.10 wt% sulphur must be used in Emission Control Areas (ECA). Additionally, from 1 of January 2020, fuel with less than 0.50 wt% sulphur must be used globally. It is also not allowed to carry fuel with sulphur content above 0.50 wt%. The only exception can be made for vessels equipped with abatement technologies, which reduce sulphur oxide (SO_x) exhaust emissions to the level equivalent to fuels containing 0.50 wt% sulphur.

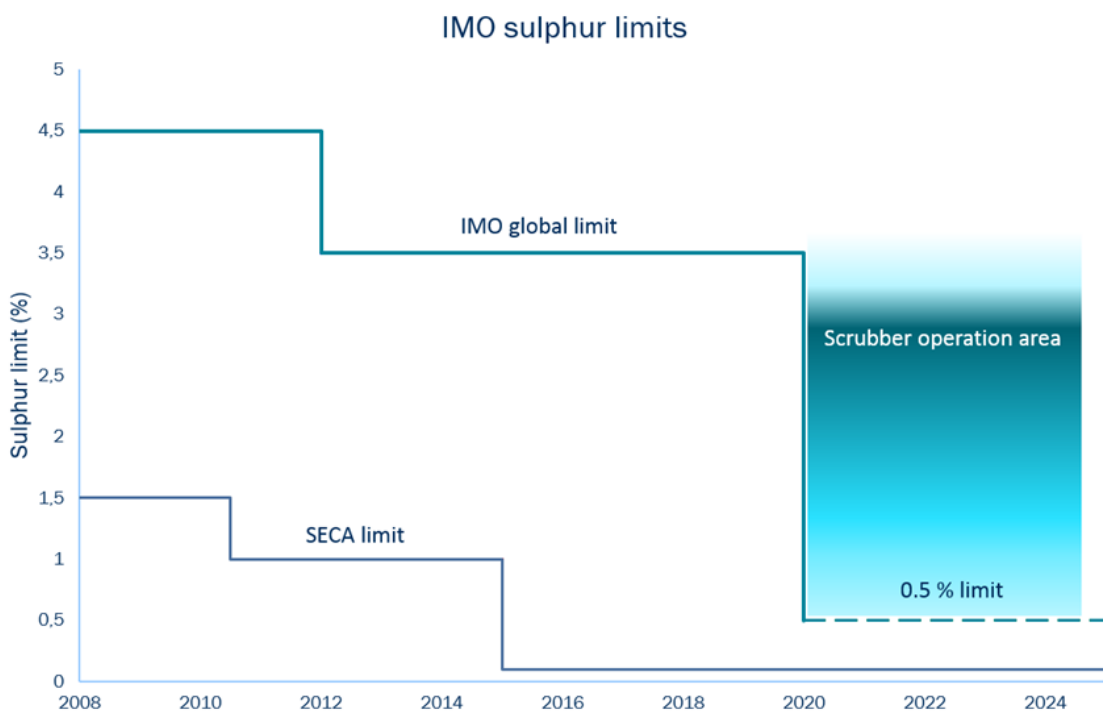


Figure 1. Sulphur limits introduced by IMO according to MARPOL Annex VI [1]

2.2 Names of hydrocarbon fuels after 1 January 2020

The consensus of the marine market is a simplified terminology for liquid hydrocarbon fuels used in the market after 1 January 2020, in accordance with the most relevant characteristics. All liquid hydrocarbon fuels basically fall under the same category: Fuel Oil (FO). The key differentiator is the fuel sulphur content. Grade designations according to ISO 8217 [2] remain applicable; however, using the simplified terminology, as listed in Table 1, allows straightforward determination if fuel is fit for purpose.

Definition of fuel abbreviations:

HFO:	Heavy Fuel Oil
MGO:	Marine Gas Oil
DM:	Distillate Marine (fuels according to ISO 8217 distillate grades)
DF:	Distillate Marine fuel containing FAME
RM:	Residual Marine (fuels according to ISO 8217 residual grades)
RF:	Residual Marine fuels containing FAME
MDO:	Marine Diesel Oil
ULSFO:	Ultra Low Sulphur Fuel Oil
VLSFO:	Very Low Sulphur Fuel Oil
HSFO:	High Sulphur Fuel Oil

Table 1. Fuels naming after 1 January 2020

Sulphur content	HFO (RM or RF grades)	MDO (DMB, DFB)	MGO (DMA, DFA, DMZ, DFZ)
S ≤ 0.10%	ULSFO RM	ULSFO DM	ULSFO DM
0.10% < S ≤ 0.50%	VLSFO RM	VLSFO DM	VLSFO DM
0.50% < S	HSFO RM*	HSFO DM*	HSFO DM*

*Fuels allowed only for ships with exhaust abatement technologies yielding sulphur oxide reductions equivalent to using fuels compliant with the respective sulphur limit.

2.3 ECA-emission control areas

The general concept of emission control areas was introduced by the International Maritime Organization (IMO) in the context of implementation of its MARPOL Annex VI in 1997 [3]. For ECA designated by the IMO, following several refinement steps since the entry into force of corresponding regulations in 2005, the maximum fuel sulphur content today must not exceed a limit of 0.10 wt% [1].

2.3.1 Overview ECA zones

The ECA zones are shown in Figure 2.

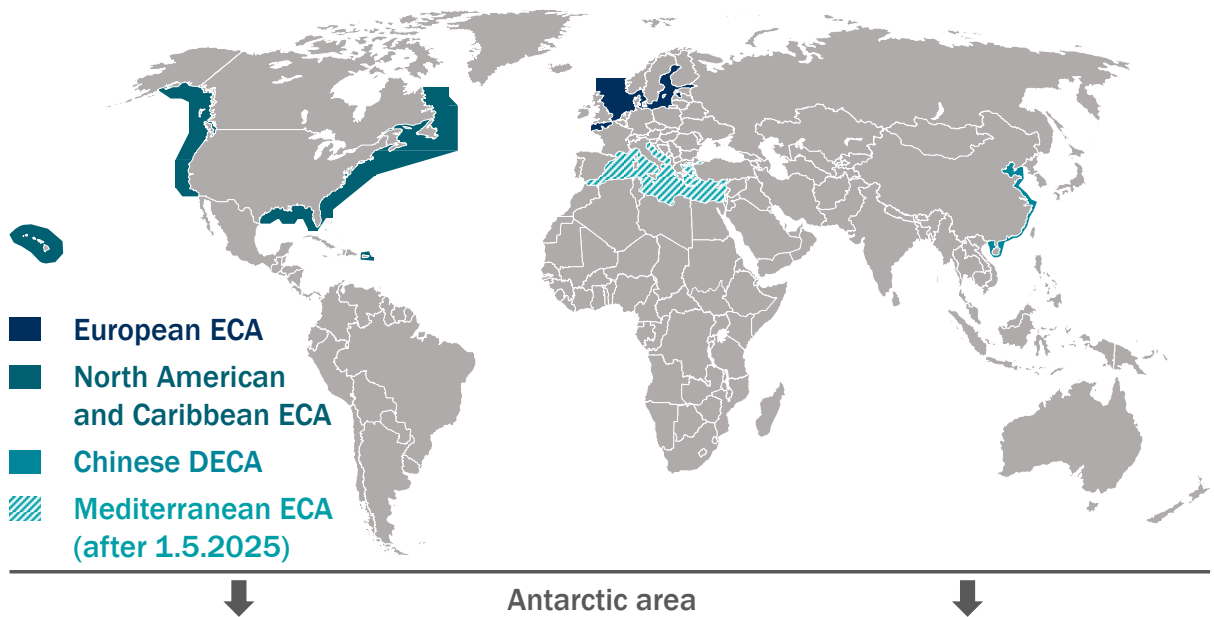


Figure 2. Regions with fuel requirements in place or implementation pending (hatched)

2.3.2 Northern European ECA

The Baltic Sea area and the North Sea, which includes the English Channel, was the first ECA established when introducing MARPOL Annex VI.

A regulation specifically applicable to LNG carriers while at berth was previously issued, allowing a “mixture” of marine fuel and boil-off gas to be used if achieving at least the same reduction in sulphur emissions as when using compliant marine fuel [4]. It introduces a simplified formula to determine the minimum required ratio per mass of boil-off gas and marine fuel (M_{BOG}/M_F) depending on the sulphur content (S_F) of the marine fuel in use:

$$\frac{M_{BOG}}{M_F} \geq 8.6 S_F (\%) - 0.816$$

2.3.3 North American and U.S. Caribbean Sea ECA

The North American ECA covers waters along the coasts of Canada, the United States (including Hawaii) and the French overseas Collectivity of Saint-Pierre and Miquelon was implemented in 2011 [5]. The U.S. Caribbean Sea ECA covers waters adjacent to the coasts of Puerto Rico and the Virgin Islands (the United States) and is in force since 2013 [6].

2.3.4 Chinese coastal waters

China designates its own Domestic Emissions Control Areas (DECAs) with specific emissions control measures, including fuel sulphur limits. The DECA covers the complete 12 nautical mile zone along the Chinese coast, including Hainan Island waters. A maximum 0.10 wt% sulphur limit applies to all vessels entering the inland river emission control areas as well as Hainan Island waters [7] [8] [9]. Note that the same limit is implemented by Korea for the regions adjacent to their major ports [10].

2.3.5 Polar regions

MARPOL Annex I, Regulations 43 [11] and 43A [12], ban the use of heavy fuel oil in the polar regions, with certain exceptions. For the purposes of this regulation, heavy grade fuel oils are defined as:

- crude oils having a density at 15 °C higher than 900 kg/m³
- oils, other than crude oils, having a density at 15 °C higher than 900 kg/m³ or a kinematic viscosity at 50 °C higher than 180 mm²/s
- bitumen, tar and their emulsions.

For the Antarctic waters (sea area south of latitude 60° S), a ban on use as well as carriage of heavy fuel oil is in place since 2010.

General use and carriage of heavy fuel oil in arctic waters, as defined by MARPOL Annex I, Regulation 46.2 [13], is prohibited from 1 July 2024. Waivers may be issued for some ships satisfying specific conditions according to Regulation 43A, however, only temporarily, and in no case beyond 1 July 2029.

2.4 Gas fuels (LNG)

Engines operating on LNG are subject to the same NO_x limits as traditional diesel engines. When burning LNG as fuel, the WinGD X-DF engine technology operates under Otto Cycle lean burning conditions which results in its compliance with Tier III limits. Additionally, LNG contains only trace amounts of sulphur and, therefore, the X-DF engines, when operated on LNG, are not affected by any ECA zone regulations and do not require further emissions abatement systems.

2.5 Biofuels

According to MARPOL Annex VI, Regulation 18.3.2.2, “fuel oil for combustion purposes derived by methods other than petroleum refining shall not cause an engine to exceed the applicable NO_x emission limit...” [1]. This regulation impeded the global use of biofuels on board vessels as NO_x emissions cannot be guaranteed for each of these fuels. However, to allow use of biofuels in marine applications, the Unified Interpretation (UI) of MARPOL Annex VI, Regulation 18.3, was agreed to at MEPC 78 [14] and amended to “synthetic fuels” at MEPC 79 [15]. The UI allows using biofuel blends below 30 wt% without the need for engine recertification. Additionally, if the relevant engine components and settings do not require any adjustment, renewable fuels can be used at 100% concentration (i.e. not blended with fossil fuels).

Please note: UI allows the use of all types of bio and synthetic fuels without the need to measure NO_x. However, this does not mean that the fuels allowed by UI can be used in the WinGD engines. Only fuels defined in this document can be used without restrictions in the WinGD engines.

3 Diesel fuels

The WinGD engines can operate with a variety of hydrocarbon-based fuels including residual, distillate and renewable fuels, if when bunkered they meet ISO 8217 [2] standard and additionally specific WinGD requirements defined in this document. The frequency of engine overhauls can be influenced by the type and quality of the used fuel. Therefore, special attention to fuel selection and management must be paid.

It is important to send samples of the bunkered fuel for analyses at a certified laboratory to ensure full ISO 8217 compliance [2] corresponding to the desired fuel grade. Verification of fuel quality based on Bunker Delivery Note (BDN) or only partial specifications is not sufficient to determine if the fuel is fit for the WinGD engines. To reach the desired parameters at the engine inlet, fuel treatment (such as purification and heating) must be applied as needed.

It is advisable to follow a comprehensive fuel management plan which includes all steps from prior to fuel bunkering until the engine inlet. Prior to bunkering, special attention must be given to the fuel cold flow properties to ensure that these are suitable for the fuel system design and the planned ship routing.

Fuel suppliers must ensure that the supplied fuel is stable and resistant to sludge formation. It must not corrode the engine fuel injection components or contain contaminants like used oil, chemical waste or foreign substances.

According to MARPOL Annex VI, Regulation 18.3 [1], the “fuel oil shall not include any added substance or chemical waste that:

- jeopardizes the safety of ships or adversely affects the performance of the machinery
- is harmful to personnel
- contributes overall to additional air pollution”.

Due to the potential risk of incompatibility of different fuel batches, WinGD does not recommend blending of fuels on board. Deliberate blending of fuels on board must be avoided, which also applies to two or more fuels having the same ISO grade. Blending incompatible fuels can cause filters fouling or sludge formation that can overload or damage fuel preparation equipment. Fresh bunkers must be always put into empty tanks and not added to old bunkers. It is also recommended to pay careful attention during any changeover of fuels with different physical properties, such as density and viscosity.

3.1 ISO 8217 compliance

As mentioned in previous section, WinGD requires the fuel to be bunkered in accordance with ISO 8217 [2]. Usually, after publication of a new edition of the ISO standard, old versions are withdrawn and cannot be used anymore. Although this is ISO practice, maritime industry often uses previous standard versions of the ISO 8217 as a reference for purchasing fuel. WinGD does not encourage using standards older than the version of 2017 and will phase out acceptance of ISO 8217:2017 [16] after wider adoption of ISO 8217:2024 [2].

3.1.1 ISO 8217:2024 version

ISO 8217:2024 [2] was published in May 2024. This newest version of the standard contains new Tables 2 and 4 for the distinction of VLSFO from HSFO fuels. Additionally, this edition contains a bio residual fuel (Table 3) where use of FAME and paraffinic diesel fractions are allowed up to 100% in the fuel. The same allowance for use of FAME and paraffinic diesel is introduced for distillate fuels in Table 1. New annexes are added, and old annexes are revised.

For ISO 8217:2024 [2] there are multiple changes to the tables. The most important are listed below:

- FAME fraction up to 100% is allowed in the fuel (Tables 1 and 3).
- Cetane number was introduced for FAME fuels (Table 1).
- A new oxidation stability method is introduced for FAME containing fuels (Table 1).
- Distinction between summer and winter grade was removed for CFPP and Cloud point (Table 1).
- Reporting of the FAME content is introduced (all tables).
- Reporting of the sediment potential parameters is introduced (Tables 2 and 3).
- Reporting of the lower calorific value is required for FAME containing fuels in (Tables 1 and 3).

Important changes are made to Clause 1 “Scope” and Clause 5 “General requirements” to accommodate use of renewable fuels. Clause 5 lists sources from which the fuel shall consist of. There are only 3 general sources of fuel allowed in ISO 8217:2024, i.e. hydrocarbons from petroleum sources; hydrocarbons from renewable sources, which are indistinguishable from petroleum hydrocarbons; FAME as defined in the ISO 8217 [2].

ISO 8217:2024 Clause 5 lists possible components of ISO 8217 compliant fuel, i.e. hydrocarbon from petroleum sources; renewable hydrocarbons, which are indistinguishable from hydrocarbons from petroleum sources; FAME under the standard defined in the document or mixture of above. For the first listed component, it states that fuel can consist of “predominantly hydrocarbons from petroleum sources”. The word “predominantly” is used to include other trace compounds which are not hydrocarbons but are typically present in fossil fuels. The above-mentioned statement must not be interpreted as allowance to blend other non-hydrocarbon compounds or to blend components not originating from petrochemical refining process, except for those listed in the Clause 5. Use of non-hydrocarbon fuels or blending of non-hydrocarbon components of industrial, natural, waste or other origin into a fuel is strictly forbidden for the WinGD engines, if not previously validated by WinGD.

4 Diesel fuel parameter description

4.1 Density

The fuel composition directly influences its density, with higher aromatic content typically increasing density. Standard measurements of density at 15 °C are not always feasible; therefore, density is often measured at higher temperatures and then converted to the standard reference temperature. According to ISO 8217:2024 [2] specifications, the maximum permissible density for bunkered fuel is 1010.0 kg/m³. Furthermore, when utilizing fuels with density exceeding 991.0 kg/m³, it's necessary to verify that the onboard fuel treatment systems can process such high-density fuels.

4.2 Viscosity

The WinGD 2-stroke engines are designed to operate on fuels as bunkered with viscosity up to 700 mm²/s (cSt) at 50 °C if sufficient fuel heating and treatment is performed prior to the engine inlet. The WinGD fuel injection systems require fuel viscosities at the engine inlet ranging from 2 to 20 mm²/s (cSt). Ideally, the viscosity should be maintained between 13 and 17 mm²/s (cSt) for best performance. For low viscosity distillate and specific residual fuels like RMA 10 grades (as per ISO 8217:2017) or RF/RMA 20 (as per ISO 8217:2024), which can reach required operation viscosity without heating, fuel should be used within a viscosity range of 3 to 17 mm²/s (cSt) without heating.

Minimum viscosity of 2 mm²/s (cSt) at the engine inlet is necessary to prevent leakage in the fuel system. If this minimum cannot be achieved, fuel cooling systems may be required.

If the fuel has viscosity higher than 20 mm²/s (cSt) at the engine inlet, heating is necessary to reduce fuel viscosity to the 13–17 mm²/s (cSt) at operational range. The required temperature adjustment for fuels with different viscosities can be derived from Figure 3. Fuel temperature must not exceed 150 °C to avoid fuel decomposition. The viscosity and temperature settings for fuel separation must follow the separator manufacturer's guidelines to ensure effective contaminant removal.

During fuel changeover, operators must ensure the fuel viscosity at the engine inlet remains within operational limits. Changeover procedures outlined in this document and in the Instruction Manual must be followed, with temperature change rate not exceeding 2 °C per minute.

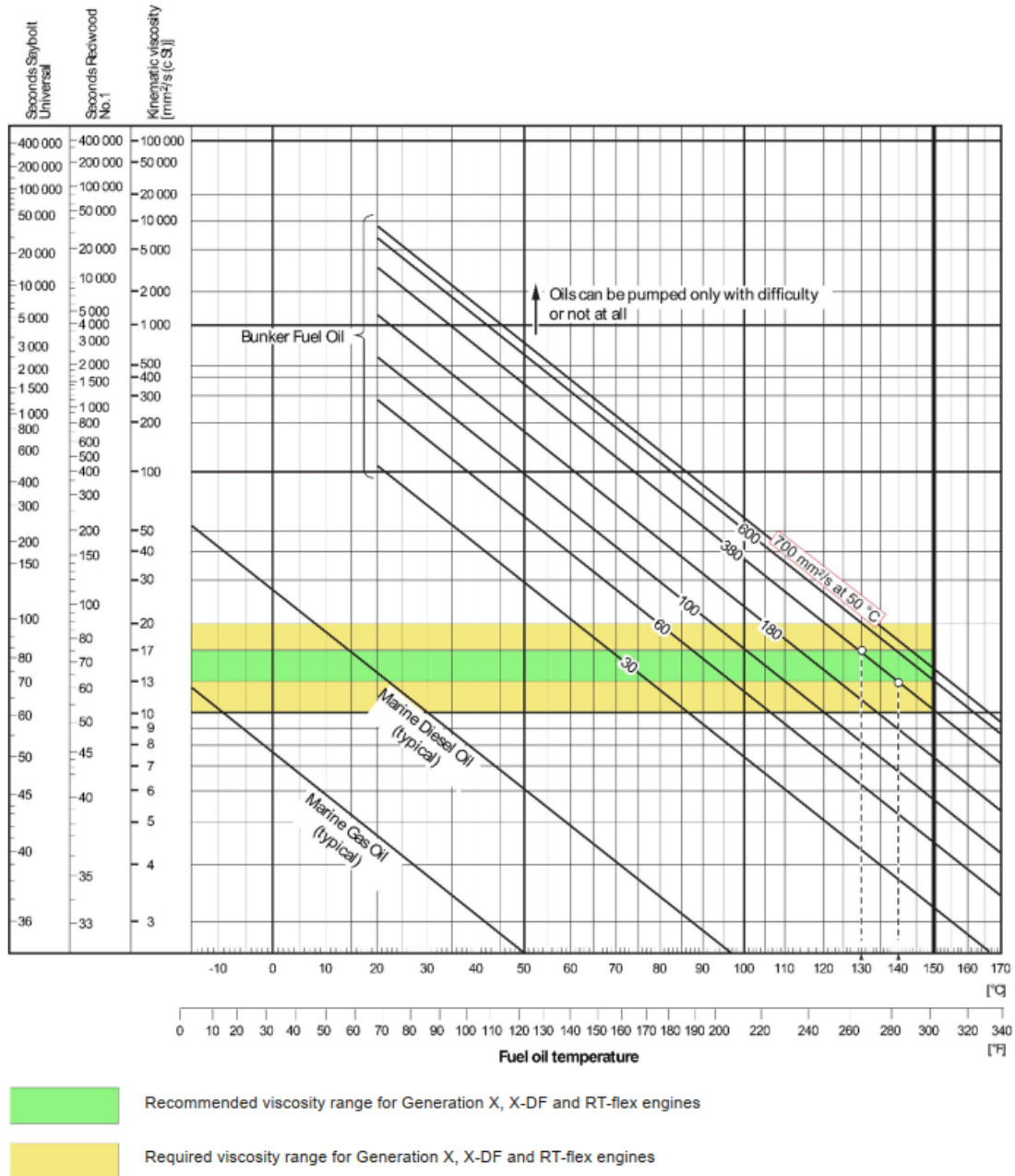


Figure 3. Viscosity / Temperature diagram

4.3 Calculated Carbon Aromaticity Index (CCAI)

The ignition and combustion properties of diesel fuels in engines are determined by engine specific design and tuning, load profile and fuel properties.

The Calculated Carbon Aromaticity Index (CCAI) is a calculated value of ignition properties or ignition delay of the fuel related to the viscosity and density. It was introduced to avoid residual fuels with uncharacteristic density-viscosity relationships. The CCAI has more effect on the performance of higher speed 4-stroke auxiliary engines rather than slow speed 2-stroke engines due to their longer combustion cycles. Although the CCAI indicates ignition performance, it does not provide a measure of the actual combustion quality of the fuel.

4.4 Lubricity

ISO 8217 [2] specifies maximum lubricity Wear Scar Diameter (WSD) of 520 µm for distillate fuels to ensure that the fuel has sufficient lubricity. This prevents premature wear of fuel system components.

4.5 Cetane Index

The Cetane Index is a calculated value that estimates the ignition quality of fuel. This index is determined by fuel density and its distillation range. The acceptable limits of Cetane Index for distillate fuels in the WinGD engines are specified in Table 4.

Please note: Cetane Index cannot be calculated for fuels containing FAME. For this purpose, Cetane Number or Indicative Cetane Number must be used.

4.6 Sulphur

Sulphur limits are not specified in ISO 8217 [2] because statutory specifications put a limit on this value. The WinGD 2-stroke engines are designed to operate with high and low sulphur fuels. If fuels are used with higher sulphur content than local permissible sulphur limit, the vessel must be equipped with necessary emission abatement technologies to fulfil the statutory specifications. It is important to select the correct cylinder lubricant oil matched to the sulphur content of the fuel in use. A guideline to cylinder lubricant selection can be found in the following document:

<https://www.wingd.com/en/technology-innovation/engine-technology/engine-design/tribology-fuels-lubricants/>

4.7 Flash point

The flash point is an important safety and fire hazard parameter for diesel fuels. There can be flammable vapours in the air space above the remaining fuel in the tanks. Special attention must be paid if the fuel temperature is increased above the flash point, as flammable vapours may be formed.

4.8 Hydrogen Sulphide (H₂S)

Hydrogen Sulphide (H₂S) is highly toxic gas and exposure to it at elevated concentrations poses severe health risks, including fatality. Observe appropriate health and safety measures when tanks or fuel lines are opened due to possible H₂S vapours. At low concentrations H₂S vapours smell like rotten eggs; however, at higher concentrations H₂S cannot be sensed. Initial symptoms of H₂S include nausea and dizziness.

4.9 Acid Number

The Acid Number (AN) indicates the total acidity of the fuel. Fuels with acid number above 2.5 mg KOH/g can cause damage to fuel injection systems.

While the acid number can detect the total acidity of the fuel, it does not indicate the strength of the acid. Strong acids, such as inorganic acids, are forbidden to be present in a fuel by MARPOL Annex VI [1]. Inorganic acids can be detected by a Strong Acid Number using the same ASTM D664 method. However, any strong acid present in a fuel, even below detection limit of ASTM D664 method, is not allowed in a fuel.

It is important to measure acid number for fuels containing Fatty Acid Methyl Esters (FAME). Additionally, if such a fuel is stored on board for a prolonged time (e.g. more than 6 months), the acid number should be verified again before usage due to the risk of FAME decomposition and acid formation.

4.10 Sediment, carbon and asphaltenes

High quantities of sediment, carbon and asphaltenes decrease the ignition and combustion quality of the fuel. These constituents also increase wear and may damage engine components. Additionally, due to prolonged storage or onboard blending, asphaltenes present in the fuel may become unstable and drop out from the fuel causing sludge formation in separators, filters and tanks.

To keep risks to a minimum, do not store fuel longer than 4–6 months after bunkering and make sure that bunkers from different suppliers and sources are not blended in the storage tanks on board. When added to a residual fuel of low stability, paraffinic distillate can cause asphaltenes to agglomerate, resulting in heavy sludge formation.

Residual fuels can contain up to 14% asphaltenes but do not cause ignition and combustion problems in 2-stroke engines if the fuel treatment system is properly adjusted.

If sludge occurs in the fuel treatment system, follow the manufacturer's guidelines, because some seemingly common-sense actions (e.g. increase of the separation temperature) may lead to increased sludge formation.

4.11 Total Sediment

Total Sediment is a sum of all insoluble organic and inorganic matter of a fuel measured according to ISO 10307. There are 3 procedures which measure total sediment.

Total Sediment Existent (TSE), which is sum of all insoluble organic and inorganic matter of a fuel. The value is obtained via hot filtration of the fuel according to ISO 10307-1 and is used as a limit for MDO grades DMB and DFB (see Table 4).

Total Sediment Aged is the amount of sediment after two different procedures are followed as described below.

- **Total Sediment Potential (TSP)**, the sample is thermally aged for 24 h under conditions determined in Procedure A of ISO 10307-2. TSP is a method used for the stability of residual fuels and has a limit described in Table 3.
- **Total Sediment Accelerated (TSA)** is the amount of sediment obtained by dilution of the fuel in hexane followed by 1 h storage at 100 °C under conditions determined in Procedure B of ISO 10307-2. TSA is a faster method than TSP and is often used as a substitution of the TSP method – due to a fact that TSA is typically higher than TSP for high viscosity HSFO, and if within limit, TSP is also within limit. For VLSFO this relationship is not always present, therefore, TSA must not be used as substitution for fuels with sulphur content below 0.50 wt%.

Please note: TSP is always a reference method for total sediment of residual fuels, even for high sulphur fuels where TSA can be used as an indicator of TSP.

4.12 Pour point

The operating temperature of the fuel must be at least 5°C to 10°C above the pour point to ensure that the fuel can flow easily. Additionally, paraffinic fuels can cause wax formation even at temperatures well above the pour point. Some pour point depressants used in fuels lower the pour point but not wax appearance temperature. Therefore, for low viscosity paraffinic residual fuels it is recommended to keep the fuel 10°C above the pour point as a precaution.

4.13 Water

Complete removal of water is highly recommended for residual fuels to decrease the quantity of hydrophilic catalytic fines (cat-fines) and sodium in the fuel.

The fuel separator as well as the correct configuration of drains in the settling and service tanks are used to decrease water content of the fuel. Sea water contamination can be distinguished from freshwater contamination by analysis of magnesium content. The ratio between sodium and magnesium in sea water is between 8 and 8.5. To ensure good fuel-water separation, the flow rate and temperature of the fuel through the separator must be adjusted in relation to the viscosity. For high viscosity fuels the separation temperature must be increased, and the flow rate must be decreased in relation to the nominal capacity of the separator. Always consult the separator manufacturers documentation to ensure most efficient operation.

4.14 Ash and Trace Metals

Fuels with low content of ash, vanadium, sodium, aluminium, silicon, calcium, phosphorus and zinc are recommended. High quantities of these materials can increase mechanical wear, high temperature corrosion and foreign particles in the turbocharger, exhaust system and boilers.

4.15 Vanadium and Sodium

Sodium compounds decrease the melting point of vanadium oxide and sulphate salts, especially when the vanadium to sodium ratio is 3:1 or higher. High sodium quantities as well as lithium and potassium in the fuel at the engine inlet can cause damage to the turbocharger, exhaust system and boilers.

4.16 Aluminium and Silicon

Aluminium (Al) and silicon (Si) in the fuel are indicators of catalytic fines. Catalytic fines are small hard round particles of Al and Si Oxides which are remains of catalysts used during the fuel refining process. These particles cause high abrasive wear to pistons, piston rings and cylinder liners and can cause most damage when present in particles of sizes between 10 and 20 micrometres.

Catalytic fines become attached to water droplets in the fuel and as a result are very difficult to remove from the fuel. The combined Al and Si content in bunkered fuel must not exceed 60 ppm (mg/kg) according to ISO 8217. Furthermore, WinGD requires maximum combined content of Al and Si at the engine inlet of 15 ppm (mg/kg).

To achieve the combined content of 15 ppm at the engine inlet, onboard fuel separation must be carried out. The temperature and flow rate through the fuel separator must be adjusted according to the fuel viscosity and be set according to the separator manufacturer's guidelines. Higher temperature and lower flow rate are beneficial for the separation process.

Be aware that catalytic fines can accumulate in the sediment of the fuel tank from previous bunkers. During bad weather conditions, the movement of the ship stirs up previously sedimented catalytic fines from the bottom of the tank and mix them into the fuel. Therefore, the operator must assume that all fuels contain catalytic fines even if the fuel analysis or BDN shows a different result.

Additionally, it is a good practice to perform regular maintenance to remove sludge and catalytic fines from fuel settling and service tanks.

Detection of catalytic fines

The presence of catalytic fines in fuel is determined by analysing aluminium and silicone content in the fuel. Removal efficiency of catalytic fines from the fuels can be identified from the replicas of the liner surface. If particles are found embedded on the running surface of the liner (see Figure 4), it is an indication that the on-board cleaning of the fuel was not sufficient.



Figure 4. Scuffed cylinder liner surface at TDC with cat fines trapped in graphite flakes.

Effects of catalyst fines on engine components

Catalytic fines are hard abrasive particles. These particles of 10 to 20 micrometre in size are the most dangerous, as they are most readily caught in the oil film and in the fine graphite structure of the liners. Smaller particles do not tend to cause wear and larger particles are not easily held in the oil film. If the fuel oil is heavily contaminated with catalytic fines, there can be issues with:

- seizure and wear in fuel pumps
- wear in injection valves
- wear on nozzle holes and needle seats
- wear in injection control units
- wear at piston rod and gland boxes.

Primarily, the abrasion of ring and liner surfaces is caused directly, but some cat fines are retained in the graphite flakes of the metal surface and continue to abrade the running partners for a long time after they have entered the engine.

4.17 Calcium and Potassium

Calcium and potassium are elements not limited by ISO 8217 [2]. However, high concentrations of both in a fuel can lead to lower time between overhauls.

High concentrations of calcium can contribute to higher inorganic deposits in the combustion chamber and increased wear of engine components. WinGD does not specify maximum limit of calcium in fuels.

Potassium contributes to hot corrosion and deposits in the combustion chamber. High concentrations of potassium are not common in traditional fuels but can be present in poor quality biofuels. Contrary to calcium, WinGD limits potassium concentration in the fuels.

4.18 Used lubricating oil

MARPOL Annex VI, Regulation 18.3 [1], and ISO 8217, Clause 5 [2], state that the fuel shall not contain any added substances or chemical waste which either are harmful to personnel or jeopardize the safety of ships or adversely affects the performance of the machinery.

Used lubricating oil and chemical waste must not be mixed into the fuel. Used lubricating oil contains large quantities of calcium (Ca), zinc (Zn), phosphorus (P), other additives and wear metals. Both ISO 8217 [2] and the WinGD specifications do not allow used lubricating oil in the fuel.

4.19 Chemical waste

Chemical waste (e.g. polymers or other chemical substances) must not be added to the fuel. These materials can cause damage to the fuel injection and supply system due to thickening of the fuel or corrosive attack on the components. This results in damage or blockage of filters, pump plungers, injectors or other fuel injection components. Due to countless chemical substances leading to fuel contamination, listing them all is not feasible.

Detection of such contamination with standard methods mentioned in ISO 8217 [2] is usually impossible. However, if ship owners have doubts about the fuel quality, WinGD recommends performing an additional test for each received fuel beyond those mentioned in Tables of ISO 8217 [2]. Analysis by Gas Chromatography – Mass Spectrometry (GC-MS) or Fourier-Transform Infrared Spectroscopy (FTIR) can indicate chemical contamination of the fuel. The presence of all parties during the sample collection, confirmed by a written statement, is a good practice.

4.20 Organic chlorides

Fuel must be free from organic chlorides. If present in a fuel, organic chlorides can cause damage to the fuel injection system. CIMAC WG7 considers fuel to be free from organic chloride if its total concentration does not exceed 50 ppm [17], measured by EN 14077 method [18]. However, any level of organic chlorides above 20 ppm in a fuel must be considered an alert level for the operator, because using such a fuel for an extended period of time can decrease the lifetime of fuel injection components.

4.21 Cloud point and Cold Filter Plugging Point

Before bunkering distillate fuels, ensure that cold flow characteristics such as pour point, cloud point and Cold Filter Plugging Point (CFPP) are correct for the ship design and intended voyage. If the fuel cold flow characteristics are too high for the intended voyage, problems with wax deposits in the storage tanks and in the separators or with clogged filters can occur.

The cloud point can be tested only for clear and bright distillate fuels. Therefore, it is not applicable for residual fuels. Instead, wax appearance temperature can be used as an approximation to the cloud point method.

5 Residual Marine Fuels

5.1 Introduction residual marine fuels

Residual fuels, as defined by ISO 8217 (Residual Marine Fuels) [2], consist of one or more residual fractions obtained from refinery processes. These fuels are created by blending different refining streams to meet specific target specifications and comply with relevant IMO regulations. As a result of the new global marine fuel sulphur limits in force since January 2020, two major residual fuel types are available in the market:

- classical high density residual fuel, which is referred also as High Sulphur Fuel Oil (HSFO) – Table 4 in ISO 8217:2024
- low sulphur fuel oils with lower sulphur content than HSFO, i.e. Very Low Sulphur Fuel Oil (VLSFO – 0.50 wt% S) and Ultra Low Sulphur Fuel Oil (ULSFO – 0.10 wt% S), with lower viscosity and density and characteristics closer to distillate products –Table 2 of ISO 8217:2024.

Therefore, due to the variable properties and other challenges arising depending on the sulphur content of the fuel, low and high sulphur fuels are described separately. However, the same specifications from Table 3 are applicable for both fuel types. Table 2 shows comparison between HFO and today’s fuels.

Table 2. Quality comparison between HFO and today’s fuel

	Sulphur (%)	LHV (MJ/kg)	Viscosity (cSt)	Density (kg/m ³)	Catfines (mg/kg)	Ash content (mg/kg)	Micro carbon residue (wt.%)	Stability	Compatibility	Cold flow properties	Ignition quality
HFO (2018)	2.7	40.3	351	987	24	0.045	13.45	=	=	=	=
ULSFO	0.07	42.5	41	890	12	0.021	3.44	–	– –	–	+++
VLSFO	0.48	41.7	135	940	16	0.020	5.76	–	– –	–	++
HSFO	2.96	40.3	332	984	18	0.043	13.21	=	–	=	+

In comparison to pre-2020 residual HFO: = same properties, – worse properties, + better properties. Values given in table are year median values from 2018 for HFO and 2023 for rest of the fuels. Courtesy of VeriFuel.

In Table 3, the values in the column Bunker limit show the minimum quality requirements of a residual fuel when supplied and bunkered to the ship/installation.

These values correspond to RMK 700H grade from ISO 8217 [2]. However, the use of fuels with lower values of sulphur, ash, carbon, asphaltenes or density can have a positive effect on piston overhaul periods. Lower levels of these constituents can improve combustion cleanliness, which results in cleaner combustion chambers and exhaust gas, and a resultant decrease of the component wear rates.

Close supervision and care must be given to engine maintenance and on-board fuel treatment equipment in general, and especially when the properties of the fuel in use are close to the permitted limits. Poor quality fuels and insufficient or inadequate on-board fuel preparation can lead to problems in handling and/or combustion. Thus, higher maintenance requirements, shorter service intervals and possibly shorter service life of various components of the equipment can be possible.

Bunkered fuel must be processed before it goes into the engine. The design of the fuel treatment system must comply with the related specifications of WinGD. The fuel treatment must remove sludge and decrease catalytic fines as well as water content to the WinGD recommended engine inlet limits.

Viscosity is typically used to classify residual fuels. ISO 8217:2024 [2] has lower limits of viscosity for each of the grades to prevent operational problems on-board the vessels. However, according to ISO 8217:2017 [16] different grades are defined by the maximum viscosity only. Therefore, it is not uncommon to observe much lower viscosity products under high viscosity grades, e.g. fuel of viscosity 20 cSt which is sold under a grade with a maximum viscosity of 380 cSt. The viscosity is measured at the reference temperature of 50 °C. Note that the value of viscosity is sometimes given in SI units mm²/s which is identical to the unit used i.e. centistokes (cSt).

As mentioned above, poor fuel quality can cause damage to the fuel system components, to the fuel injection equipment, to pistons, piston rings or cylinder liners. Damages to the turbocharger, the exhaust system or the boiler can also occur because of poor fuel quality. Thus, WinGD recommends a sample of the bunkered fuel is tested by a laboratory. If the analysis shows that the fuel does not fulfil WinGD specifications, it is recommended to switch to an alternative fuel available on board.

5.2 Very Low Sulphur Fuel Oil (VLSFO)

The most common fuel used in the marine market since January 2020 is VLSFO with sulphur contents of maximum 0.50 wt%. These fuel blends are typically more paraffinic in nature, which results in lower average density and viscosity when compared to HFO (see Figure 5). Additionally, due to its paraffinic nature, when compared to HFO, ignition properties are improved and average lower heating value is increased to approximately 41.7 MJ/kg.

However, there are also drawbacks due to the paraffinic nature of the fuel. Special attention must be paid to high variability of viscosity, cold flow properties and stability of these fuels.

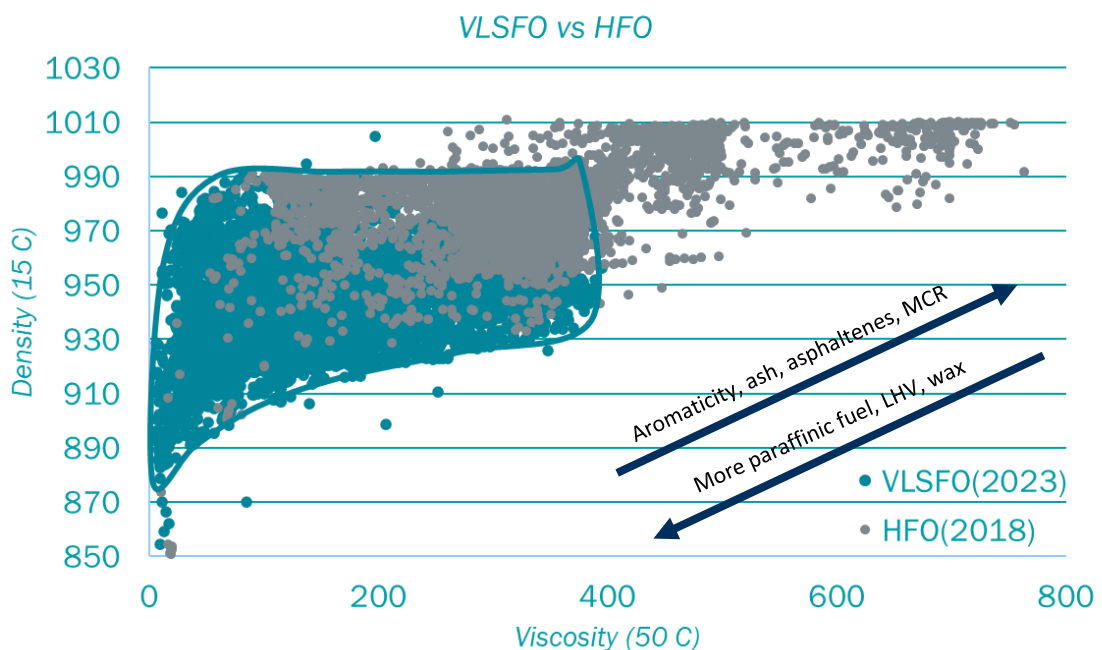


Figure 5. Density vs. viscosity for VLSFO (2023) and HFO (2018). Courtesy of VeriFuel.

5.2.1 Viscosity of VLSFO

Viscosity in ISO 8217:2024 has a minimum and maximum limit for each grade of the fuel. However, in ISO 8217:2017, viscosity of VLSFO can vary significantly within the same grade. Therefore, under the 2017 version of the ISO 8217 [16], fuels sold under RMG 380 grade can have viscosity as low as 2 cSt, and can cause operational problems for the crew if they are unaware of such low viscosity. Therefore, it is necessary

to adjust fuel handling and injection temperature for each batch of fuel. Moreover, WinGD recommends purchasing fuel under the 2024 edition of the standard [2] where grades have minimum viscosity limits.

5.2.2 Cold flow properties of VLSFO

When VLSFO containing high fractions of paraffinic components is exposed to prolonged cold conditions, wax may form. This can affect cold flow properties of the fuel. Therefore, before obtaining a fuel, it is recommended to make sure that the fuel cold flow properties comply with the fuel system design and the planned ship routing. Additionally, for residual fuels with low viscosity it is recommended to keep the fuel 10 °C above the pour point.

5.2.3 Compatibility and/or stability of VLSFO

Depending on the origin and production process used, VLSFO can be predominantly aromatic or paraffinic in nature. This may lead to compatibility problems between different fuel batches even if they are within the same ISO 8217 fuel grade.

To ensure proper stability of the fuel, TSP of the fuel must be below 0.10 wt%. As mentioned in chapter 4.11, TSA cannot be used as a substitute for VLSFO type fuels. If the TSP of the fuel is close to the limit, it is recommended to use fuel with high TSP as soon as possible.

Blending of aromatic and paraffinic fuels on board may result in sludge formation due to incompatibility of the fuels and resultant instability of this blend compared to the original fuel batches. This effect can occur quickly or develop after a prolonged period of time in a tank, even if the blend initially appeared stable.

More information on stability and compatibility of the fuel can be found within CIMAC document [19].

5.3 Ultra Low Sulphur Fuel Oil (ULSFO)

ULSFO refers to a group of residual fuels containing less than 0.10 wt% of sulphur. They have a Lower Heating Value (LHV) similar to that of distillate fuels with an average LHV of 42.7 MJ/kg. However, the viscosity of these fuels is higher than distillates with an average just below 50 cSt at 50 °C. ULSFO represents the cleanest type among the residual fuels, however, still it must not be treated like a distillate fuel and must undergo the normal pre-treatment process applicable for residual fuels.

Furthermore, ULSFO is of similar paraffinic nature as VLSFO and therefore may also encounter problems with a high pour point and wax formation. Every batch of fuel should be bunkered separately and not be blended with other fuels on board due to risk of incompatibility with them.

5.4 High Sulphur Fuel Oil (HSFO, S > 0.50 wt%)

High Sulphur Fuel Oils (HSFO) are typically highly aromatic, high-density fuels closer in its nature to pre-2020 heavy fuel oil (Figure 6). These fuels can only be used in combination with sulphur oxides abatement technologies, such as SOx scrubbers.

HSFO has a similar calorific value to HFO with an average lower heating value of around 40.5 MJ/kg. It contains on average more impurities, such as ash or micro carbon residues, than VLSFO. Typically, it has lower average viscosity and density in comparison to pre-2020 HFO, as only few fuels viscosity above 380 cSt are delivered to the market (Figure 6).

High sulphur fuels are specified under Table 4 of ISO 8217:2024 [2] and under Table 3 of this document.

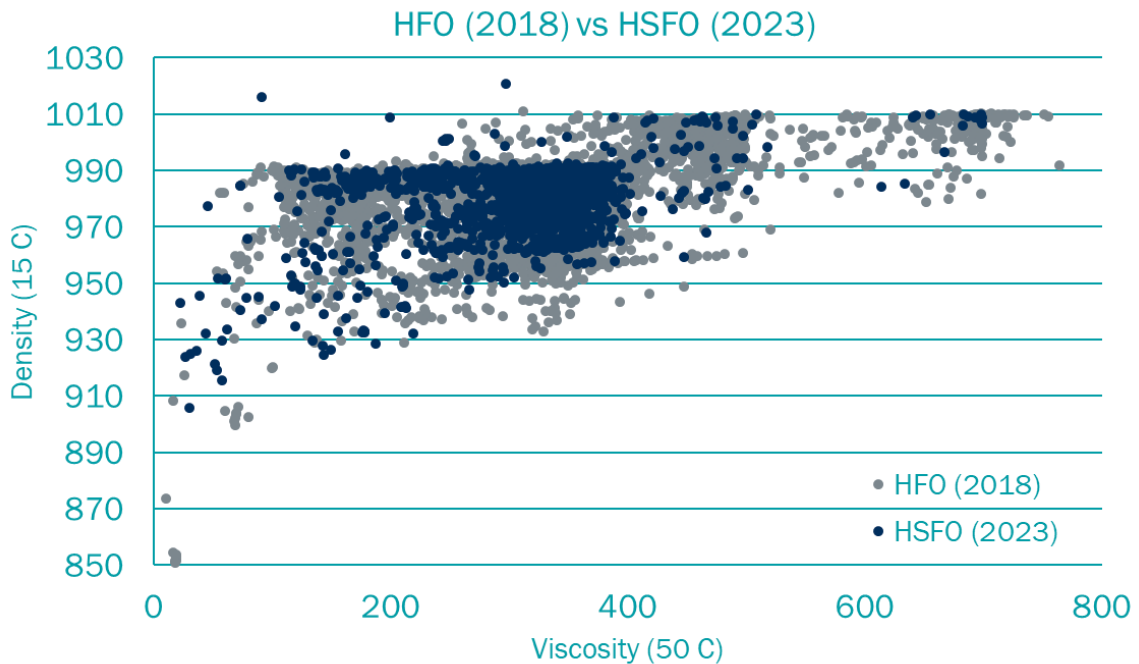


Figure 6. HSFO density vs. viscosity for the first half of 2023. Courtesy of VeriFuel.

5.5 Specifications for residual marine fuels

Table 3. Specifications for residual marine fuels.

Parameter	Bunker limit	At engine inlet	Unit	Test method
Kinematic viscosity at 50 °C	Maximum 700	13 to 17 - heated fuel ^a 3 to 17 - non-heated fuel ^b	mm ² /s (cSt)	ISO 3104
Density at 15 °C	Maximum 1010 ^c	Maximum 1010	kg/m ³	ISO 3675/12185
CCAI	Maximum 870	Maximum 870	-	Calculated
Sulphur ^d	Statutory specifications	Maximum 3.5	mass %	ISO 8754/14596
Flash point	Minimum 60	Minimum 60	°C	ISO 2719
Hydrogen sulphide	Maximum 2.0	Maximum 2.0	mg/kg [ppm]	IP 570
Acid number	Maximum 2.50	Maximum 2.50	mg KOH/g	ASTM D 664
Total sediment potential (TSP) ^e	Maximum 0.10	Maximum 0.10	mass %	ISO 10307-2 According to Procedure A
Total sediment accelerated (TSA)	Report ^f	Report ^f	mass %	ISO 10307-2 According to Procedure B

Total sediment existent (TSE)	Report ⁱ	Report ⁱ	mass %	ISO 10307-1
Carbon residue: micro method	Maximum 20	Maximum 20	mass %	ISO 10370
Pour point (upper) ^f	Maximum 30	Maximum 30	°C	ISO 3016
Water	Maximum 0.50	Maximum 0.20	volume %	ISO 3733
Ash	Maximum 0.150	Maximum 0.150	mass %	ISO 6245
Vanadium	Maximum 450	Maximum 450	mg/kg [ppm]	ISO 14597/IP501/IP470
Sodium	Maximum 100	Maximum 30	mg/kg [ppm]	IP501/IP470
Potassium	Maximum 30	Maximum 30	mg/kg [ppm]	IP501
Aluminium plus Silicon	Maximum 60	Maximum 15	mg/kg [ppm]	ISO 10478/IP501/IP470
Fatty acid methyl ester content by mass ^g	Report	Report	wt.%	ASTM 7963
Lower heating value (LHV)^h	Report	Report	MJ/kg	ASTM D240
Used lubricating oils (ULO) must not be present: Calcium (Ca) and zinc (Zn)	ULO shows if: Ca>30 and Zn>15 or Ca>30 and P>15	Do not use if: Ca>30 and Zn>15 or Ca>30 and P>15	mg/kg [ppm]	IP501 or IP470 or IP500

- For the X, all X-DF and RT-flex engines the fuel viscosity at the engine inlet for heated fuels must be in the range 10–20 mm²/s, however, WinGD recommends fuel viscosity at the engine inlet in the range 13–17 mm²/s. The maximum permitted fuel temperature is 150 °C.
- Viscosity of non-heated fuels must be in the range 2–20 mm²/s, however, WinGD recommends fuel viscosity at the engine inlet in the range 3–17 mm²/s.
- The maximum density limit is 991 kg/m³ if the fuel treatment plant cannot remove water from high-density fuel, maximum density for some old type of separators. Check the fuel separator guideline or speak to the equipment manufacturer.
- In ISO 8217:2017 [16] sulphur limits are not given for residual fuels. Sulphur limits are related to statutory specifications.
- The TSA method according to Procedure B of ISO 10307-2 can be used as an indication of TSP only for high density HSFO. TSP according to Procedure A of ISO 10307-2 remains the reference method in case of dispute.
- Purchasers must make sure that the equipment on board can always keep the fuel at temperature above the pour point, especially in cold climates.
- Bunkered fuel FAME content must be reported in wt%. Upon request, FAME content can be required at the engine inlet by WinGD. Proof that FAME fulfils EN 14214 must be provided.
- For bunkered fuels containing renewable fuels (e.g. FAME) the LHV must be reported according to ASTM D240 together with type of renewable fuel used. Upon request, LHV value can be required at the engine inlet by WinGD. For other fuels, which do not contain renewable fuels, LHV can be calculated.
- Not required for HSFO.

Please note: It is very important that the fuel is fit for purpose to the related engine application.

6 Distillate Marine Fuels

6.1 General about distillate marine fuels

Since 2015 distillate fuels are used more frequently in 2-stroke engines to comply with the new ECA rules. Distillate fuels are easier to handle and use than residual fuels, but caution is nevertheless necessary for some potential problems.

In ISO 8217 [16] the DMX, DMA, DMZ and DMB grades as well as FAME containing DFA, DFZ and DFB grades with maximum FAME content of 100 wt% for the ISO 8217:2024 edition, and 7.0 vol% for ISO 8217:2017 edition. The DMX grade is not applicable for the WinGD 2-stroke engines because of its low flash point and viscosity.

6.2 Specifications for distillate marine fuels

Table 4. Specifications for distillate marine fuels

Parameter	Limits MGO (DMA, DFA, DMZ and DFZ)	Limits MDO (DMB/MFB)	Unit	Test method
Kinematic viscosity at 40 °C	Maximum 6.0 Minimum 2.0	Maximum 11.0 Minimum 2.0	mm ² /s (cSt)	ISO 3104
Minimum kinematic viscosity at engine inlet	Minimum 2.0 (not related to temperature)	Minimum 2.0 (not related to temperature)	mm ² /s (cSt)	ISO 3104
Density at 15 °C	Maximum 890	Maximum 900	kg/m ³	ISO 3675/12185
Cetane Index	Minimum 40	Minimum 35	-	ISO 4264
Sulphur ^a	Maximum 1.5	Maximum 1.5	mass %	ISO 8754/14596
Flash point	Minimum 60	Minimum 60	°C	ISO 2719
Hydrogen sulphide	Maximum 2.0	Maximum 2.0	mg/kg [ppm]	IP 570
Acid number	Maximum 0.50	Maximum 0.50	mg KOH/g	ASTM D 664
Total sediment by hot filtration	-	Maximum 0.10 ^b	mass %	ISO 10307-1
Oxidation stability	Maximum 25	Maximum 25 ^c	g/m ³	ISO 12205
Fatty acid methyl ester (FAME)	report	report	volume %	ASTM D7963 or IP 579
Carbon residue: micro method on 10 % volume distillation residue	Maximum 0.30	-	mass %	ISO 10370
Carbon residue: micro method	-	Maximum 0.30	mass %	ISO 10370
Pour point (upper) winter ^d	Maximum -6	Maximum 0	°C	ISO 3016
Pour point (upper) summer ^d	Maximum 0	Maximum 6	°C	ISO 3016
Cloud point winter ^d	report	-	°C	ISO 3015

Cold filter plugging point winter^d	report	-	°C	IP 309 or IP 612
Appearance	Clear & Bright	^b		
Water	[Maximum 200 ppm] ^e	Maximum 0.30 (0.20 at engine inlet)	volume %	ISO 3733
Ash	Maximum 0.010	Maximum 0.010	mass %	ISO 6245
Fatty acid methyl ester content by mass^f	Report	Report	wt.%	ASTM 7963
Lower heating value (LHV)^g	Report	Report	MJ/kg	ASTM D240
Lubricity, corrected wear scar diameter (WSD) at 60 °C^c	Maximum 520	Maximum 520 ^c	µm	ISO 12156-1
Aluminium plus Silicon at engine inlet	Maximum 15	Maximum 15	mg/kg [ppm]	ISO 10478/IP501/IP470

- a. The purchaser must specify the maximum sulphur content in accordance with the applicable statutory specifications.
- b. If the sample is not clear and bright, the total sediment by hot filtration and water test is required.
- c. If the sample is not clear and bright, the test cannot be undertaken. Therefore, compliance with this limit cannot be shown.
- d. Purchasers must make sure that the pour point is sufficient for the equipment on board, especially for operation in cold climates.
- e. If the sample is dyed and not transparent, the sample needs to be tested using the ISO 12937 method and comply with the limit of 200 mg/kg [ppm].
- f. Bunkered fuel FAME content must be reported in wt%. Upon request, FAME content can be required at the engine inlet by WinGD. Proof that FAME fulfils EN 14214 must be provided.
- g. For bunkered fuels containing renewable fuels (e.g. FAME), the LHV must be reported according to ASTM D240 together with type of renewable fuel used. Upon request, the LHV value can be required at the engine inlet by WinGD. For other fuels, which do not contain renewable fuels, the LHV can be calculated.

7 Renewable drop in fuels / Biofuels

7.1 Hydrocarbon based renewable fuels

Hydrocarbon based fuels of non-petroleum origin can be used as a drop-in fuel in the WinGD engines if they fulfil WinGD fuel specifications and fit under one of the grades of ISO 8217 [16]. Additionally, fuel must be clean of any substances which can adversely affect engine performance according to MARPOL Annex VI, Regulation 18 [1]. Examples of such fuels are Hydrotreated Vegetable Oil (HVO) or other paraffinic fuels, such as synthetic diesel obtained via Fischer-Tropsch synthesis.

7.2 Hydrotreated Vegetable Oil (HVO)

Hydrotreated Vegetable Oil (HVO) is a type of diesel fuel obtained from hydrodeoxygenation of vegetable oil, fats and their derivatives. Crude animal or vegetable waste oil is treated with hydrogen in the presence of a catalyst at elevated temperatures and pressures. The resulting fuel is of very high-purity hydrocarbons similar to automotive diesel. Such fuels can be used on the WinGD engines if they meet ISO 8217 specifications [16]. Complete hydrodeoxygenation is necessary with no remaining untreated fractions of the source material allowed in the final fuel.

The 100% pure HVO meet EN 15940 requirements, excluding those included in Table 2 and 3 of EN 15940 [20]. If pure HVO is used, it must also comply with the requirements of Table 4 in this document. It is important to check that the flash point of the HVO is above 60 °C.

7.3 Fatty Acid Methyl Ester (FAME)

Fatty Acid Methyl Ester (FAME) is typically produced through a process called trans-esterification of fats with methanol. These components are mandatory fuel blends in some countries in automotive and agricultural diesel. The FAME specifications can vary depending on the region, with the most common standards being European EN 14214 [21] and American ASTM D 6751 [22] standards.

ISO 8217:2017 [16] allows for the use of FAME in marine distillate grades DFA/DFZ (MGO) and DFB (MDO) up to 7% by volume. However, the use of FAME in residual marine fuels is restricted to *de minimis* 0.5 wt% to the 2017 edition of ISO 8217 [16].

ISO 8217:2024 [2] allows the use of FAME at 100 wt% concentrations if the requirements of distillate fuels Table 1 or bio residual fuels in Table 3 of ISO 8217:2024 are fulfilled. Additionally, FAME used for blending of the fuel must comply with the EN 14214 standard (except for the sulphur, cloud point and cold filter plugging point requirements in EN 14214). The use of FAME in other fuels sold under residual fuels (Table 2 and Table 4 in ISO 8217:2024) is restricted to *de minimis* levels of approximately 0.5 wt%.

The WinGD engines can operate at 100% FAME content in the fuel. To operate the WinGD engines at 100 % FAME fuels according to EN 14214, there is no need to modify IMO related components and parameters. Therefore, according to the Unified Interpretation of the NO_x code [15], engines operating on these fuels should be treated as NO_x compliant. Additionally, tests performed on the WinGD engines do not show significant changes in NO_x emissions when operating on FAME fuels in comparison to MGO, both on a test engine [23] and in a field trial [24].

Please note that there is no standard for the use of FAME in marine fuels. Often, the term FAME is used for biofuels which do not fulfil the above-mentioned EN 14214 [21] or ASTM 6751 [22] standards. Some not fully converted vegetable oils or fat fractions of unknown purity can potentially pose damage to onboard machinery.

Infra-red methods reporting FAME content do not provide the actual concentration of fatty acid methyl ester chemicals, but rather report concentrations of carbonyl groups within a fuel mixture. Therefore, other compounds of similar structure, i.e. triglycerides, can be mis-interpreted as FAME. When the quality of the fuel in use is in doubt, or in case of suspected fuel-related damages, further investigation is required to verify the exact purity of the FAME fraction. Detailed GC-MS analysis can be used to verify the actual concentration of FAME and types of organic impurities in the fuel.

It is important to mention that once FAME is blended with residual fuel it is impossible to verify the properties required in the above-mentioned EN [21] or ASTM [22] standards.

7.4 Residues of FAME production

To produce FAME that meets the EN 14214 standard [21], a final distillation step is required. The waste by-products (residues) of purification include unreacted fats, various side products and inorganic substances that are remnants of the trans-esterification process. These waste by-products may include free fatty acids, glycerides (mono-, di- and tri-) and glycerol. In addition, they can be rich in potassium (K), phosphorus (P), sodium (Na) or other inorganic metals. Therefore, elevated levels of these species in fuels can indicate insufficient FAME purification or contamination of the fuel by waste by-products from the FAME trans-esterification process.

High concentrations of waste by-products can cause fuel filter clogging, fouling of injectors and further combustion chamber cleanliness issues, which can further lead to operational problems and, in extreme cases, to engine damage. Clogging of fuel filters due to elevated concentrations of FAME residues can be treated to some extent with an increase in temperature of the fuel before the engine while remaining within the limits of allowed fuel viscosity (3–17 cSt). However, any increase in temperature must be taken with due caution, because the clogging of the filters may be caused by sludge formation typical of conventional residual fuels, in which case an increase of temperature will lead to higher sludge generation.

Additionally, residues from FAME production can have a lower oxidation resistance, which can result in faster fuel degradation. As a consequence, this may lead to an increase of fuel acid number, which can result in corrosion of injection system components.

The EN 14214 specifications [21] limit the concentrations of the above-mentioned residue products in fuel. However, the final blend of FAME and residual or distillate fuel is typically not tested for their presence, due to assumption that the FAME fraction is compliant with EN 14214. However, the presence of these contaminants can be detected with advanced analytic techniques, e.g. GC-MS methods. The maximum concentration of FAME residues and minimum concentration of FAME is limited by EN 14214 standard. The approximate ratio of those concentration limits is presented in Table 5. If the concentration ratios of FAME by-products to FAME in a fuel significantly exceed the approximate ratios given in Table 5, it suggests the FAME fraction used for fuel blending is not compliant with EN 14214. As a result, the fuel is not compliant with WinGD specifications. WinGD does not recommend performing advanced analysis on every batch of fuel. Instead, advanced analytic techniques can be treated as an investigative tool in case of problems or suspected fuel contamination.

If the fuel does not contain FAME and residual FAME by-products are present (i.e. the ratio of by-products to FAME content is very high), be on the alert because such a fuel may cause damage to the engine.

Contamination of the fuel by the inorganic components of FAME is limited via potassium (K), phosphorus (P) and sodium (Na) content in the WinGD FAME specifications. Fuel containing FAME should have lower total ash content than standard residual fuel. Therefore, if the total ash content is high and typical fuel inorganic element contents are low, additional analysis for other metals is recommended.

Table 5. FAME fraction limits from EN 14214 and ratio between residual FAME chemicals and FAME

Chemicals	Limit	wt. %	Approximate ratio of residuals vs. FAME (x/96.5)
FAME	Min.	96.5	-
Methanol	Max.	0.2	> 0.003
Monoglyceride	Max.	0.7	> 0.008
Diglyceride	Max.	0.2	> 0.003
Triglyceride	Max.	0.2	> 0.003
Free Glycerine	Max.	0.02	> 0.0003
Total Glycerine	Max.	0.25	> 0.003

7.5 FAME specifications

FAME based biofuels or their blends with distillate or residual fuel must comply with the following specifications:

- All fuels must fulfil the specifications of both Table 3 in ISO 8217:2024 [2], and those of Table 3 from this document.
- Prior to blending, FAME must comply with the EN14214 [21] or ASTM6751 [22] standards. The supplier must provide a certificate that the FAME used for blending fulfilled one of these standards. Both standards are equivalent, but in case of disputes the EN 14214 specification must be used. For further information on verification of FAME purity, see Chapter 7.4.
- Acid number must not exceed 2.5 mg KOH/g.
Note: Maximum acid number of FAME allowed when certified with EN 14214 is 0.5 mg KOH/g. The maximum allowed acid number for residual fuels is 2.5 mg KOH/g. Blend of both must decrease the acid number of residual fuel proportionally to FAME content. Therefore, if a B30 blend exceeds 2 mg KOH/g or a B50 blend exceed 1.5 mg KOH/g acidity, it is recommended to perform additional analysis for the determination of free fatty acids or other corrosive compounds in a fuel as a precaution. No strong acids are allowed.
- The inorganic content of the fuel must be verified. FAME must not contain any untypical elements normally seen in marine fuels. Any unusual increase of inorganic constituents must be investigated.
- Additionally, the final fuel blend with FAME must fulfil following requirements:
 - Phosphorus content must not exceed 15 ppm.
 - Silicon content at the engine inlet must not exceed 15 ppm.
 - Potassium content of the fuel must not exceed 30 ppm.
 - Sodium content of the fuel must not exceed 30 ppm (at the engine inlet).
 - Fuel must be free of organic chlorinated compounds (see Chapter 4.20).

7.6 Fuel supply system considerations

Although FAME has good ignition properties and a positive effect on fuel lubricity, certain considerations must be taken into account before using such fuels. Properties of FAME which can lead to potential issues on board are listed below:

- oxidation tendency which can decrease the possibility of long-term storage
- affinity to water which may cause microbial growth
- poor low-temperature flow properties leading to filter clogging problems
- FAME material particles can appear on exposed surfaces and filter element
- tendency to increase the acid number of the fuel if degradation occurs over time.

If FAME is used in the fuel blend, it must be ensured that the on-board storage, handling, treatment, service and machinery systems can be used with such a product. Before using such fuels WinGD recommends:

- Contact the supplier for guidance and experience obtained with usage of the fuel.
- Verify the suitability of the fuel supply system for FAME usage. Materials, such as copper, lead, zinc, tin, bronze, brass, can induce oxidation of FAME in storage and, therefore, make fuels unusable.
- Biodiesel can have good solvency properties and can remove deposits from the fuel supply system and feed them to the engine. To avoid this, it is recommended to clean the components of the fuel supply system that may come into contact with biofuel, before fuel changeover.
- Avoid contamination of the fuel by water. This can lead to corrosion or microbial growth and consequent fouling of reticulation, pumps or filters.

7.7 Operation on pure FAME biofuel

Fatty Acid Methyl Esters (FAME) have a reduced lower heating value. The lower energy density requires injecting a larger fuel volume to achieve the same energy release during the combustion phase. This leads to higher power estimation compared to the real engine power. To optimize the engine operation (e.g. to avoid earlier activation of limiters in extreme cases), it is recommended to compare the current performance data with the shoptest data to identify differences. The shaft power meter value must be used as a reference for the engine power. The TC speed or scavenging air pressure can be used to evaluate the engine power in case no shaft power meter is available. Adjust the following parameters if needed:

- **Fuel Quality Setting (FQS).** Evaluate the compression pressure and the combustion pressure. Adjust the combustion pressure with help of the FQS based on the shoptest results and the ignition ratio.
- **Injection Quantity Correction.** The injection quantity correction can be used to correct the fuel command's scaling. The injection quantity correction can be increased on all units equally until the fuel command drops to the expected level. Compare the engine power calculated by WiCE with the actual engine power measured by the shaft power meter. Adjustments up to 110% are expected.

Note: For engines using WECS and UNIC system, please follow Wärtsilä Technical Bulletin RT-268 [25].

Note: During fuel changeover from FAME back to diesel, the parameters must be adjusted to the previous standard values.

7.8 Other alternative drop-in fuels of non-petroleum origin

There are many industrial streams or experimental fuels which may be viewed or tested by some owners and suppliers as a marine fuel. In case of doubts or planned tests of such fuels, please contact WinGD for assistance and an opinion. Although some of the fuels may be suited in the future for continuous vessel operation, WinGD cannot take any liability whatsoever for fuels which are not fulfilling ISO 8217 [2] or fuels which are not validated and do not have an active Non-Objection Letter issued by WinGD.

8 Pilot fuel (DF engines only)

In gas operating mode, the WinGD DF and X-DF engines run as a lean-burn engines utilizing natural gas as the main source of fuel. Gas ignition is initiated by injecting a small amount of pilot MGO or MDO and its quality must meet the specifications contained in Table 4.

9 Diesel fuel storage and handling

9.1 Fuel storage

Ship operators should have a suitable plan for the storage of different fuel batches. Deliberate blending of fuels in the storage, settling or service tanks, should be avoided. Each newly bunkered fuel batch should be stored in a separate storage tank. In addition, it is recommended to check the fuel installation and prepare fuel management procedures which ensure minimal mixing of different fuel batches during operation in the fuel system.

Prior to bunkering, special attention must be given to the fuel cold flow properties to ensure that these are suitable for the fuel system design and the planned ship routing. In general, the temperature of the fuel in storage must be kept at least 5 °C to 10 °C above the pour point to ensure proper flow properties. However, to avoid potential wax formation with low viscosity VLSFO RM fuel grades, this fuel must be maintained at 10 °C above the pour point.

The arrangement of a complete pressurised fuel oil system for residual fuel or multiple fuel oils, including the fuel oil treatment and tank arrangement, is shown as system proposal in the Marine Installation Drawing Set (MIDS) and represented in Figure 8 below with the main components.

9.1.1 Blending of fuels on board

Due to the potential risk of incompatibility of different batches of fuels, WinGD does not recommend blending of fuels on board. Deliberate blending of fuels on board must be avoided. This also applies to two or more fuels having the same ISO grade.

If the situation exists that blending of the different fuels cannot be avoided, spot test can be performed to verify compatibility of the fuels. Note that the result of this procedure only provides an indication of compatibility of the fuels in question. For rating ASTM D4740 [26] must be used. It is recommended to accept only cleanliness rating of 1 as a positive result of compatibility test (Figure 7).

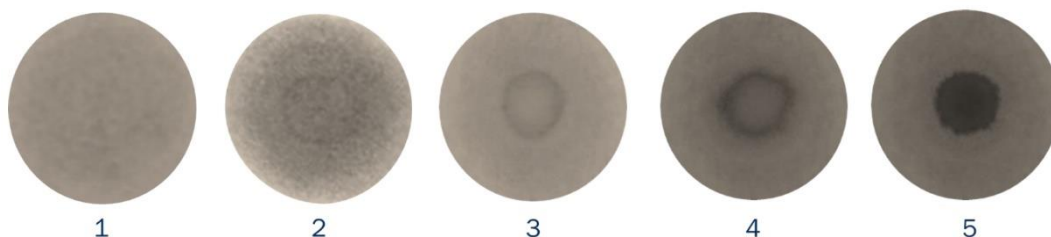
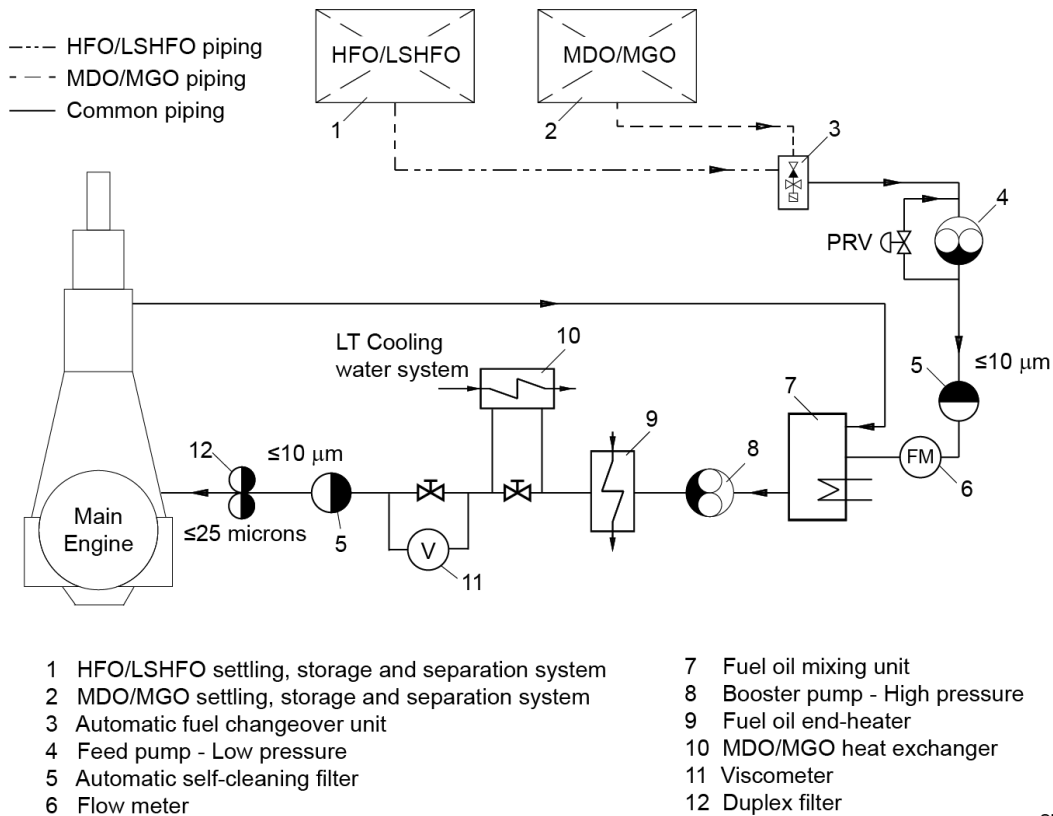


Figure 7. Cleanliness rating according to ASTM D4740[26]

For passing the test in this document, only Rating 1 is considered acceptable.

Certain highly paraffinic/waxy fuels can yield a false negative result during the compatibility check procedure. However, to avoid mistakes in the interpretation of the results, WinGD recommends disregarding this possibility.

9.2 Fuel supply system



SM-0300

Figure 8. Installation principle for maximum fuel flexibility

9.2.1 Fuel oil pumps

Pumps for HFO and MDO/MGO fuel system

For the conventional fuel supply system, the feed pump, booster pump, mixing unit, viscometer, fuel oil heat exchanger and end-heater are necessary for HFO and MDO/MGO (see Figure 8). In addition, a dedicated fuel supply circuit with feed pump together with cooler and filter for the pilot fuel is needed for the DF engines. The feed and booster pump capacities must be specified for the lower fuel oil viscosity, which normally corresponds to the MDO/MGO grade (2–11 cSt at 40°C). As nominal pump capacity decreases with lower fuel viscosities, this must be considered when determining the capacities of the feed and booster pump.

Pump for MDO/MGO only or MGO only fuel system

For the MDO/MGO only or the MGO only fuel supply system, only one fuel feed pump is needed. The delivery head of this pump must equal to the total delivery head of the conventional feed and booster pump. The flow capacity of the fuel feed pump shall equal the conventional booster pump. The dedicated pilot fuel supply circuit is not needed. The supply of pilot fuel can be provided by the main fuel oil supply system.

9.2.2 Heat exchanger

MDO/MGO heat exchanger

The MDO/MGO heat exchanger is used to adjust the MDO/MGO temperature to ensure the required viscosity grade of min. 2 cSt at the engine inlet.

MDO/MGO heat exchanger position and arrangement options

WinGD recommends that an MDO/MGO heat exchanger is installed after the high-pressure booster pump and before the viscometer which regulates the fuel oil end-heater (Figure 5). This ensures that the MDO/MGO viscosity remains within limits, even when the fuel oil end-heater is not completely by-passed and shut-off.

Heat exchanging methods

WinGD recommends the direct heat exchange method for the fuel oil by applying tubular or plate type of heat exchanger, using cooling water from the low-temperature circuit as coolant (LT water of 25–36 °C).

This solution is recommended for the following reasons:

- Heat dissipation capacity is sufficient to fulfil the viscosity requirements, if fuels according to ISO 8217 are in use.
- Automatic temperature control, i.e. no additional temperature control is needed.
- No additional pump and separate cooling medium are required.

Other cooling methods, such as cooling by seawater, are not recommended due to the increased system complexity and unnecessary additional cost. Cooling by chilled water is not required for fuels in accordance with ISO 8217 but can be applicable if at risk of using off-specification fuels.

Heat exchanger heat dissipation

The MDO/MGO heat exchanger heat dissipation (Q) is determined by the following formula:

$$Q = \frac{0.34 \times BSFC \times P \times (T_1 - T_2 + 25.65)}{10^6}$$

Equation 1. Heat exchanger heat dissipation formula.

where:

Q [kW]	heat exchanger heat dissipation at 100% engine load
BSFC [g/kWh]	Brake Specific Fuel Consumption at design conditions and 100% engine load
P [kW]	engine power at 100% CMCR
T1 [°C]	temperature of distillate fuel supplied to engine
T2 [°C]	temperature of distillate fuel at the engine inlet

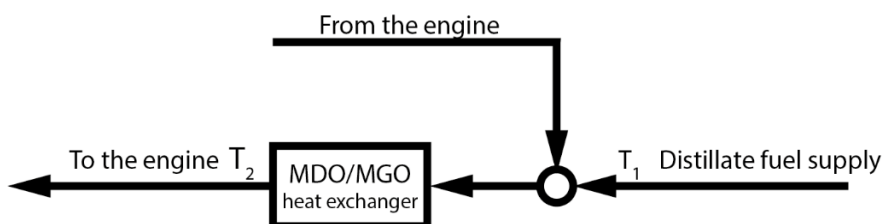


Figure 9. Schematic illustration of fuel oil temperature at mixing unit and before cooler

Example for 8X52DF:

Design conditions at 100% CMCR: P = 7440 kW, BSFC = 182.3 g/kWh

Distillate fuel: DMA, viscosity 2 cSt at 40°C, supply temperature T₁ = 45°C

Target: viscosity of 2.5 cSt at the engine inlet, therefore, DMA oil needs to be cooled down to 28°C

$$Q = \frac{0.34 \times 182.3 \times 7440 \times (45 - 28 + 25.65)}{10^6} = 19.7 \text{ [kW]}$$

Therefore, the cooler with a capacity of about 20 kW is needed for this vessel.

9.3 Fuel oil treatment

It is mandatory to design at least one dedicated service tank for each type of RM and DM fuels to ensure the fuel is immediately available when the specific fuel is required for the ME operation (Figure 10). There are different designs for storage and settling tanks arrangement. WinGD recommends separate storage and settling tank for each fuel type in use. However, minimum one settling tank and service tank need to be used for residual fuels with two centrifugal separators in between them. If the same settling tanks are used for different type of RM fuels, i.e. HSFO and ULSFO, there is a higher risk of fuel cross contamination and issues related to compatibility in the fuel supply system. Therefore, fuel changeover operation must be performed with aim to minimise comingling of different batches of residual fuel in the system.

For MGO/MDO one settling tank is sufficient in most cases.

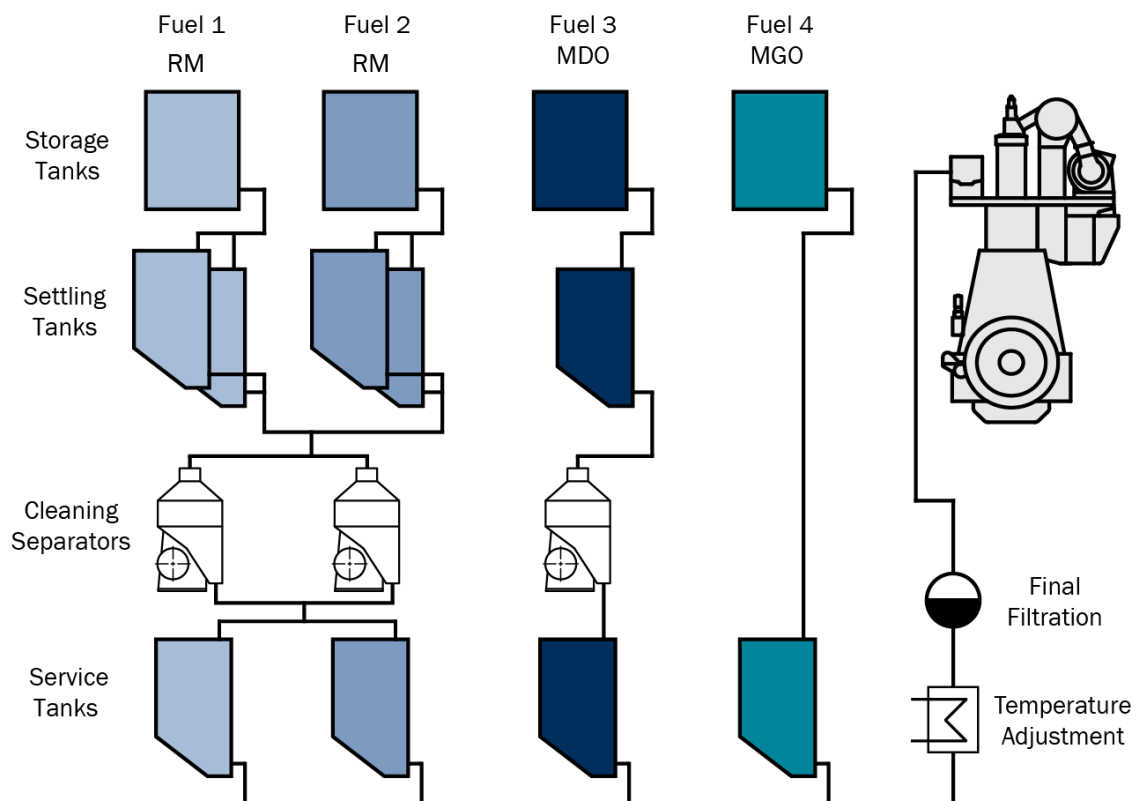


Figure 10. Simplified view of optimal fuel tanks design for vessels capable operating on residual fuel

To protect the engine from serious damages, to reduce cylinder liner wear, to avoid cold corrosion and to improve combustion, the fuel oil must be treated by removing undesired solid particles and water before entering the combustion chamber. For this purpose, an accurate configuration of the fuel treatment system is essential. Proper fuel oil treatment relies on a good centrifugal separation. The centrifugal separators are the main components of the fuel oil treatment system. Good separation performance depends on the proper selection, installation and operation of the separators. Other equipment, e.g. decanters, homogenisers etc., are not a substitute for the application of centrifugal separators.

The standard fuel oil treatment system, shown as proposal in the Marine Installation Drawing Set (MIDS), mainly consists of:

- storage system: settling tanks and service tanks with transfer pumps
- separator supply pumps
- self-cleaning RM fuels separator
- self-cleaning DM fuels separator
- fuel filters.

For further information on fuel cleaning, please refer to CIMAC document “Design and operation of fuel cleaning systems for diesel engines” [27].

9.3.1 Service and settling tanks

Pre-cleaning of the fuel is done in the settling tank(s), where water and sediment settle out by gravity. The tanks need inclined bottoms for easier removal of cat fines and other solid particles from the fuel and provide possibility for draining. The gravitational settling out of water and sediment in heavy fuel oils can be extremely slow and it depends on the fuel oil characteristics, because the higher the fuel oil viscosity and density, the longer is the process. Additionally, the tank geometry has some influence, because wider tanks have higher separation rate of contaminants from fuel oil than taller tanks of the same volume.

Most design features of the service tank are similar to those of the settling tank, having self-closing sludge valves, inclined bottoms, level monitoring sensors and remote closing valves in the discharge leading to the separators and engine systems. The service tank is to be equipped with drain valve arrangement at its lowest point, an overflow pipe to the overflow tank and re-circulating piping to the settling tank – for additional cleaning of the fuel. The inlet of this recirculation pipe must be close to the bottom of the service tank to drain water which can still be present in the fuel after leaving the separators (e.g. due to condensation or coil leakage).

Ideally, with the main engine operating at CMCR, the fuel oil separator(s) need to be able to maintain a flow rate from the settling tank to the service tank including continuous overflow back to the settling tank. The sludge valve is to be operated at regular intervals to check the presence of water, being important indication of condition of the separator(s) and heating coils.

9.3.2 Centrifugal separators

As the main components of fuel oil treatment system centrifugal separators cannot get superseded by filters or other additional treatment solutions. The function of the separators is to remove water and solid particles like cat fines from the fuel oil. The fuel reaching the engine must not contain more than 15 mg/kg aluminium plus silicon. Particles of 10 to 20 microns in size are the most dangerous for the engine as they are most readily caught in the oil film and in the fine graphite structure of the liners. Consequently, cat fines of a diameter larger than 10 microns must be removed by the separators.

When using residual fuels, the following standard procedures, as outlined in relevant documents, must still be applied:

- Check every bunker delivery note for fuel density, water, and catalytic fines concentration.
- Adjust separator gravity discs to fuel density if no self-adjusting separator is installed.
- Run your purification system at the efficiency required to reduce any cat fines to below the specified maximum engine inlet levels of 15 ppm.
- If any sign of sludge formation in the separators appears, switch to distillate grade fuels and follow the instructions of the separator manufacturer.

Separator types:

- **Self-cleaning separators without gravity disc.** For new and retrofit installations, self-adjusting separators without gravity discs are recommended. Since they are self-adjusting, they do not require gravity discs to be changed for different fuel densities.
- **Self-cleaning separators with gravity disc.** As the use of separators with gravity discs comprises certain disadvantages, the installation in new buildings is not recommended.

9.3.3 Separation efficiency

Minimum separation efficiency of 80% must be achieved, i.e. 80% by weight of the impurities removed. For the separator capacity determination, it is recommended to refer to the throughput rates which are provided according to the certified flow rate definition. This ensures sufficient separation efficiency.

For rough estimation of the effective throughput capacity, which is connected to the maximum fuel oil consumption of the diesel engine plant plus a safety margin of about 20%, the following formula can be applied:

$$\text{Throughput capacity} = 1.2 \cdot \text{CMCR} \cdot \text{BSFC} / 1000 \text{ [kg/h]} \rightarrow \text{[L/h]}$$

where:

- BSFC brake specific fuel consumption at CMCR [g/kWh]
- CMCR contracted maximum continuous rating [kW]

Separation efficiency

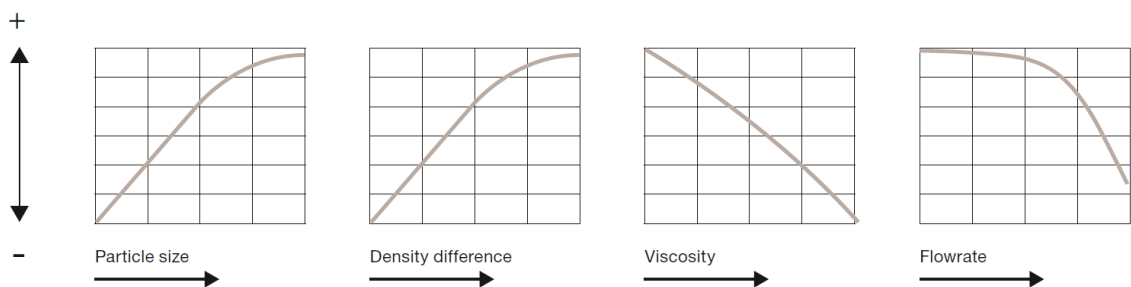


Figure 11. Separation efficiency versus separator throughput (Source CIMAC [27])

As shown in Figure 11, the separation efficiency is inversely proportional to the flow rate. The higher the flow rate, the less time is available for separation. It is therefore essential to match the centrifuge capacity to the total fuel consumption (main engine, auxiliary engines and boiler).

Separation efficiency also depends on the fuel viscosity as well as the difference between the fuel and water densities. For high viscosity fuels, where the fuel density is close to water density, separation of catalytic fines is difficult. Therefore, for high viscosity fuels the inlet fuel temperature must be at least at 98°C.

For low viscosity VLSFO the same separation efficiency can be achieved with lower temperature of fuel in the centrifuge. It is advised to follow the separator manufacturer viscosity-temperature guidance because overheating of low viscosity fuels can lead to unnecessary sludge formation. For correct separator arrangement and setting, the manufacturer's instructions must be observed.

9.3.4 Fuel filters

The fuel oil filters serve as additional protection for the engine by removing residues and catalytic fines not removed from the fuel by the separators.

Filter installation and requirements

The arrangements of the fuel oil filters are shown in the fuel oil system proposal in the Marine Installation Drawing Set (MIDS). Cat fines and other residues are primarily removed by the fuel oil separators. However, a minimum of one filter set close to the engine inlet is required for additional protection of the engine against foreign particles.

Recommendation: A fine filter in the feed system with additional filter in the booster system.

A 10-micron (absolute sphere passing mesh size) fine filter is installed in the 'cold' feed system. This installation position is recommended because the flow rate in the feed system is lower compared to that in the booster system and the risk of filter clogging is limited due to the lower fuel oil temperature. The filter protects the engine against serious damages because it catches most of the cat fines not removed by the separator.

In addition, such a filter provides good indication if the separator efficiency is sufficient or if improvements are required. Taking the filter fineness into account, an automatic filter with good self-cleaning performance should be selected.

Additionally, a filter of maximum 25 microns (absolute sphere passing mesh size) is installed in the booster system close to the engine inlet. Its task is to protect the engine against foreign particles coming from the system. A duplex filter is sufficient as most particles are already kept by the fine filter in the feed line.

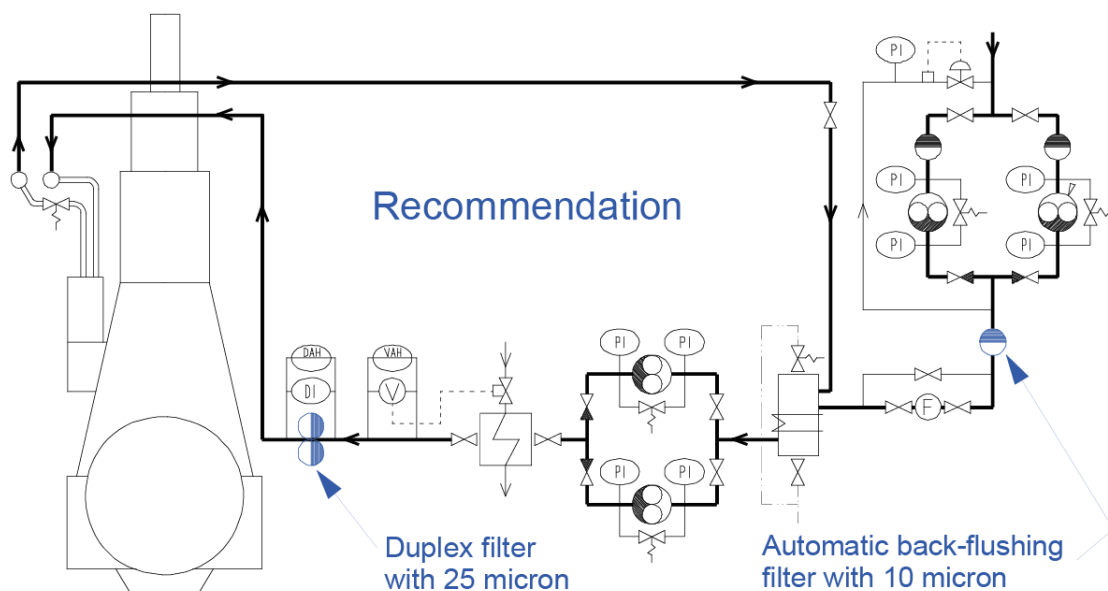


Figure 12. Recommendation for fuel oil filter arrangement

Minimum Requirement: A fine filter in the booster system as single arrangement.

A 10 micron (absolute sphere passing mesh size) fine filter is installed in the booster circuit close to the engine inlet. The high temperature in this circuit can increase the risk of filter clogging due to agglomeration of asphaltenes. The filter needs to be laid out for a maximum working temperature of 150°C (special high-temperature gaskets are required).

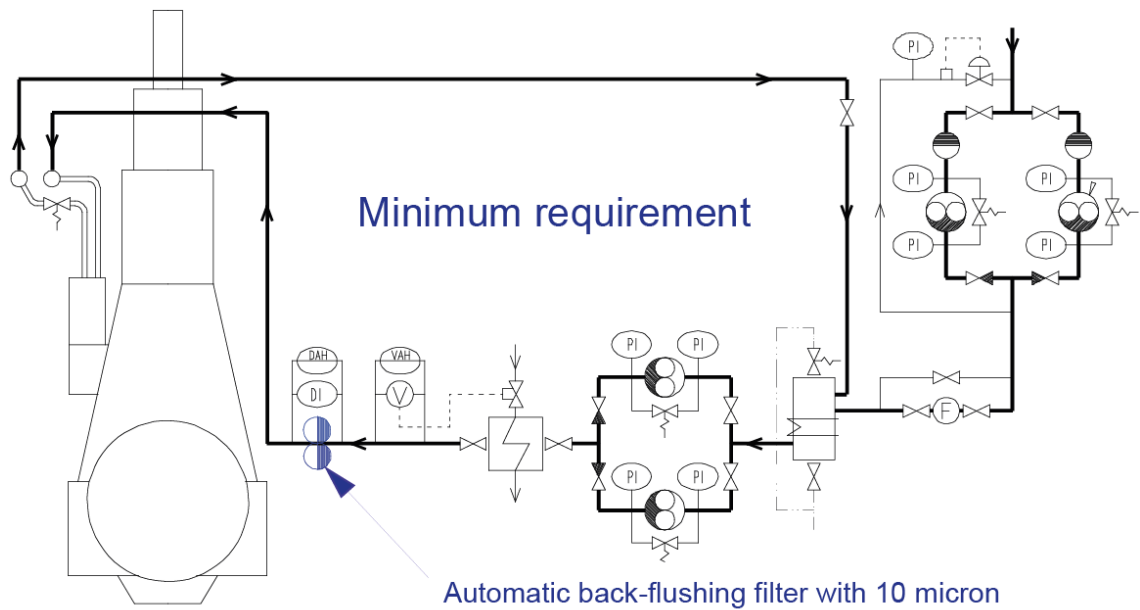


Figure 13. Minimum requirement for fuel oil filter arrangement

10 Methanol

Methanol, also known as methyl or wood alcohol, is a colourless organic liquid at ambient temperature and pressure. Methanol can be used in the X-DF-M named engines where M stands for Methanol.

10.1 Properties of methanol

Methanol is the lightest of the alcohols composed of methyl and hydroxyl groups. Due to its low molecular weight methanol is very volatile and has much lower flash point in comparison to standard diesel fuels (Table 6). It also has lower Lower Heating Value (LHV) and density, which requires the volume of storage tanks to be bigger by a factor of 2.5 when compared to traditional fuels, such as diesel.

Table 6. Selected properties of methanol in comparison to marine gas oil

Properties	Unit	Methanol	Marine gas oil
Flash point	°C	10–12	min. 60
Density	kg/m ³	790 (at 20°C)	890 (at 15°C)
Lower Heating Value (LHV)	MJ/kg	19.9	42.7
Relative volume per energy content	–	2.5	1
Boiling point	°C	64.7	150–380
Explosive limit in air	vol%	6–36	1–6
Solubility: methanol in water/water in methanol	wt%	100	N/A

10.2 Specification of methanol

Methanol minimum quality standards for the WinGD X-DF-M engines are shown in Table 7. WinGD allows for other alcohols to be present in a methanol up to 5 wt%. Additionally, water can be also present up to 5 wt%. Fuel must be free of sulphur and chloride each with maximum content not higher than 0.50 mg/kg.

Table 7. Specification of minimum methanol quality for the WinGD X-DF-M engines

Characteristic	Unit	Limit	Methanol	Test method reference
Purity (on a dry basis)	wt%	min	95	IMPCA 001-14
Water	wt%	max	5	ASTM E1064-12 ^a
Ethanol	wt%	max	5	IMPCA 001-14
Acetone	mg/kg	max	30	IMPCA 001-14
Chloride	mg/kg	max	0.50	IMPCA 002-98
Sulphur	mg/kg	max	0.50	ASTM D3961-98 or ASTM D5453-12
Appearance	N/A	–	clear and bright ^b	IMPCA 003-98

- a) Method valid up to maximum 2% water content
b) Homogeneous clear and free of suspended solids

11 Methane (LNG)

11.1 Introduction

The WinGD DF and X-DF engines can operate on fuels which consist of a gas mixture of light hydrocarbons in a composition similar to natural gas. The gas fuel must predominantly comprise of methane together with limited amounts of other light hydrocarbons and nitrogen. Such a gas is commonly known as Liquefied Natural Gas (LNG) when stored at cryogenic conditions. The specifications of LNG are defined within ISO 23306 [28]. The specification applies to all sources of LNG independent of natural, synthetic or biological origins.

11.2 Liquefied natural gas (LNG)

Liquefied Natural Gas (LNG) is a mixture of light hydrocarbons (predominantly carbon chain length C1–C4) which is liquified and kept at temperatures around -163°C . The LNG can contain a small quantity of heavier hydrocarbons (C5+) or nitrogen.

LNG is burned in the WinGD engines as gas using the Otto Combustion Cycle. LNG is introduced into the combustion chamber via gas admission valves above the scavenge ports during the compression stroke and ignited using small volume of diesel fuel at appropriate time.

The main constituent of LNG is methane (CH_4) with typical concentrations above 80 vol% after reliquification. The ratio between methane and other components in LNG, which affects its heating value and combustion properties, is referred to as the Methane Number.

The composition and properties of bunkered LNG change in time due to natural boil-off (evaporation) of LNG, starting with the lighter fractions which comprise that LNG. Evaporation favours in the following order: nitrogen, methane followed by heavier hydrocarbons. This process is called ageing and is described below.

The ISO 23306:2020 [28] is a new standard for LNG used for marine propulsion fuel. WinGD recommends only to purchase fuel according to this standard. This standard provides reassurance for operators related to LNG quality and certain limits for LNG parameters.

11.3 Gas parameters description

11.3.1 Lower Heating Value

The Lower Heating Value (LHV) or Lower Calorific Value (LCV) is the total amount of heat released by the complete combustion of specified quantity of gas with oxygen at constant pressure and defined metering temperature which does not include the recovery of latent heat of water vapor condensation.

The lower heating value is affected by the composition of the gas. The LHV can be described as MJ per kg fuel or MJ per m^3 at specific set temperature and pressure. Higher methane content gives higher energy content per kg of fuel, simultaneously resulting in lower energy content per volume of fuel (see Table 8).

The lower heating value at the engine inlet can be influenced by the nitrogen content in the fuel especially in cases where natural boil-off LNG is used as fuel. Nitrogen is gas with the lowest boiling point in LNG and will evaporate first into the boil-off. Because nitrogen is most easily evaporated from bunkered LNG, there is increased concentration of it in the boil-off gas shortly after bunkering. Additionally, bad weather conditions can also increase the amount of nitrogen in the natural boil-off. As nitrogen is an inert gas which does not combust, its presence in the boil-off gas decreases the total energy content of the boil-off fuel mix. In extreme cases this can lead to the inability to reach full engine load due to the LHV of the gas being burned by the engine being too low. Depending on the ship setup, different countermeasures can be deployed, such as enriching boil-off fuel with additional forced boil-off or switching to Fuel Sharing Mode (FSM) with diesel until the level of nitrogen in the gas being burned decreases to a level where exclusive gas operation is possible.

Table 8. Examples of LNG and its physical properties (values from ISO 23306 [28])

	Composition (%)	Liquid LNG density kg/m ³ *	LHV (MJ/kg)	LHV MJ/m ³ liquid (Tank)	LHV MJ/m ³ gas** (Engine inlet)	Methane Number MWM
High methane content (lean gas)	M: 99.71 E: 0.09 P: 0.03 B+: 0.01 N: 0.17	421.39	49.8	20985	39.91	99
Low methane content (rich gas)	M: 87.33 E: 8.33 P: 3.33 B+: 0.97 N: 0.04	467.35	49.2	22994	45.32	68

M: methane(C1), E: ethane(C2), P: propane(C3), B+: butane and higher hydrocarbons, N: nitrogen (N₂)

* calculated according to ISO 6578 (T = -160 °C)

** calculated according to ISO 6976 (0 °C and 101.3 kPa)

The minimum gas fuel energy needed for the engine to reach full power output is 28 MJ/m³(n). However, the exact value depends on the gas supply pressure. The layout of the gas supply system can be seen in the Marine Installation Manual (MIM).

11.3.2 Methane Number

The Methane Number (MN) is a value related to gas composition. It describes the resistance of any gaseous fuel to knocking (uncontrolled combustion or auto-ignition) during the operation in Otto Cycle mode. Methane Number it is not related to methane percentage, but to amount of heavier hydrocarbons in a fuel mix. The methane number decreases with increasing amounts of heavier hydrocarbons in the fuel. The heavier the hydrocarbon is, the more influence it has on the methane number. This is demonstrated in Table 9 where 3 examples of three different possible LNG compositions are shown. The WinGD engines provide 100% output for methane numbers between 65 and 100 (Figure 14).

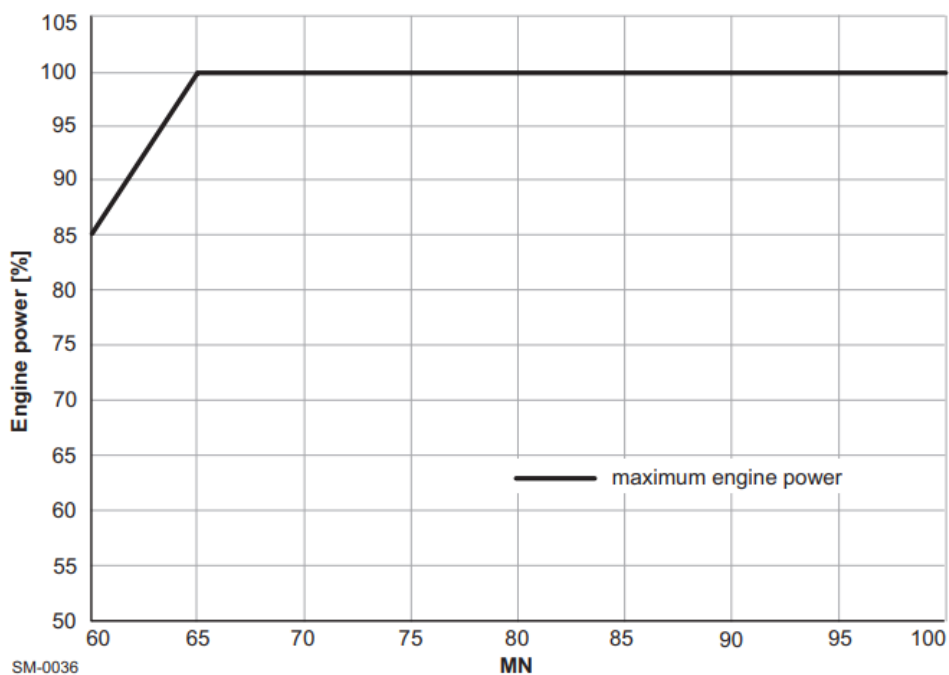


Figure 14. The maximum achievable power dependence on the Methane Number

If the Methane Number is too low, pre-ignition of the premixed charge may occur. This can lead in extreme cases to engine knocking. However, there are countermeasures which can be undertaken in case of preignition, such as Dynamic Combustion Control (DCC). For further information, please refer to the Marine Installation Manual.

Table 9. LNG composition examples

Name	Example 1	Example 2	Example 3
Methane	90%	90%	90%
Ethane	10	7	6
Propane	0	3	3
Butanes	0	0	1
Pentanes	0	0	0
Hexanes+	0	0	0
Total	100	100	100
MN (MWM)	80	76	70
MN (PKI)	79	74	70

11.3.3 Methane number calculation

WinGD uses a Methane Number calculation method based on EN 16726 [29] which is described in the text as the MWM method. An application provided by the European Association of Internal Combustion Engine Manufacturers (EUROMOT) allows for calculating the Methane Number of natural gas mixtures. The application can be accessed with the following link:

<https://www.euromot.eu/wp-content/uploads/2019/07/MWM-MN-Code-for-distribution-2016-04-22.zip>

The LNG standard ISO 23306 [28] provides an alternative method known as Propane Knocking Index Methane Number. A description of this method can be found in Annex A of the standard.

11.3.4 Ageing of LNG

Ageing or weathering of LNG is caused by evaporation of its more volatile components. Ageing leads to decrease of the methane concentration in the LNG which decreases the Methane Number and changes physical properties, such as energy content or density of the fuel in the tank. The ageing rate is correlated to the boil-off rate of LNG.

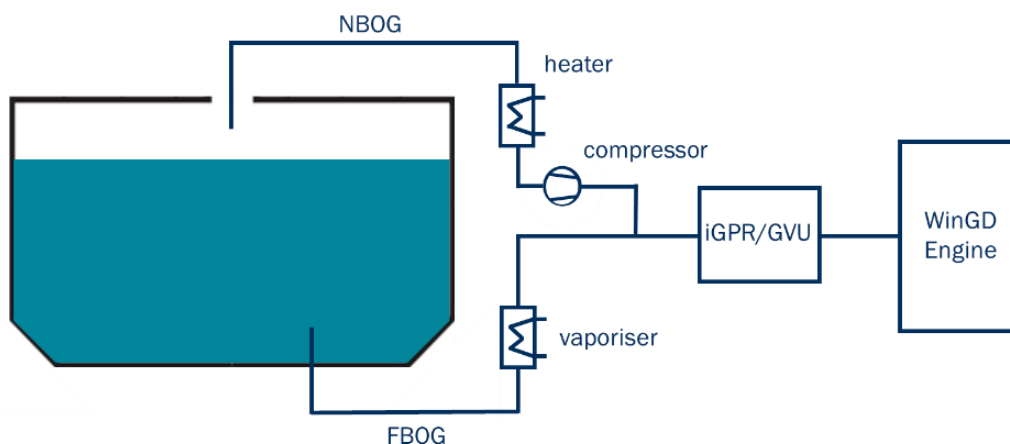


Figure 15. Simplified LNG gas supply system

The Boil-Off Rate (BOR) depends on the design of the tank and storage system, operation profile and LNG handling. Ingress of energy into the LNG tank increases the BOR and therefore affects ageing. The BOR is mainly influenced by:

- temperature and pressure of the LNG in the tank
- load profile of the engine using the LNG as fuel
- use of natural boil-off gas (NBOG) or forced boil-off gas (FBOG) (see Figure 15)
- reliquification of evaporated (boiled-off) LNG
- weather conditions (mechanical excitation from vessel movements)
- onboard fuel handling operations such as mixing, which also includes “rollover” phenomena, i.e. sudden mixing in the tank of two LNG layers of different density.

11.3.5 Gas impurities

Fuels for the WinGD engines must be free of substances which cause damage to machinery [1] and must be in compliance with marine LNG specifications according to ISO 23306 [28]. LNG can contain different impurities originating from production or handling of the fuel. The most common sources of impurities are listed below.

It is important to mention that LNG typically does not contain many impurities due to the nature of its production. Natural gas is liquified at a temperature of approximately -163°C . At this temperature most of the impurities are either frozen and filtered out (e.g. CO_2) or boiled-off and lost as gas (e.g. hydrogen and oxygen). LNG purification is performed at a liquification plant. Therefore, the main cause of some impurities may be improper handling of the fuel in storage or during bunkering operations.

Water

Water should not be present in LNG. WinGD does not specify minimum water content, instead the gas supplied to the engine must have a dew point of -20°C or below. For LNG, water is not present in the liquid as it is removed at the liquification plant. Incorrect handling or improper bunkering of LNG can lead to its contamination with water. Any water crystals present in LNG can lead to issues in the gas supply system.

Particulate matter

Particulate matter must not be present in LNG as this can damage the fuel supply system and in extreme situations the engine. Particulate matter is not normally present in LNG but can originate from:

- improper cleaning of the vessels LNG tanks after commissioning
- improper bunkering operation
- improper fuel handling and or maintenance.

Oil

Oil must not be present in gaseous fuels and is typically not present in LNG. If oil is detected in the fuel, immediate inspection of fuel supply system must be performed because leakage from other systems is most likely the source of this contamination.

Hydrogen sulphide (H_2S)

H_2S is not present in LNG in significant concentrations. Hydrogen sulphide is a very toxic gas and its presence in the engine must be avoided.

Ammonia

Ammonia is toxic and should not be present in LNG.

Hydrogen

More than 3 vol% of hydrogen in a fuel can be considered on the project specific bases. Hydrogen is not normally present in LNG.

Halogens (Cl, F)

Halogens must not be present in gas fuel. They are not present in LNG in significant concentrations.

11.3.6 Gas specifications

For continuous operation without reduction in rated output, the LNG used as the main fuel in gas mode must fulfil the quality requirements presented in Table 10. The gas properties are defined at the engine inlet or Gas Valve Unit (GVU inlet). For further information, please refer to the Marine Installation Manual.

Table 10. Gas specifications

Property	Limits (values given in m³ are at 0°C and 101.3 kPa)
Lower Heating Value (LHV)	≥ 28 MJ/m ³
Minimum methane number	65 for 100% engine power 60 for 85% engine power
Influence of methane number on the maximum engine output	See Figure 14.
Methane content	≥ 70 vol%
Hydrogen sulphide (H₂S)	≤ 0.05 vol%
Hydrogen (H₂)^{a)}	≤ 3 vol%
Ammonia	≤ 25 mg/m ³
Chlorine and fluorine	≤ 50 mg/m ³
Dew point of water	≤ -20°C
Oil (aerosol liquid and vapour)	≤ 1 mg/m ³
Gas cleanliness	Gas is considered as sufficiently clean ^{b)}

- a) Hydrogen content higher than 3 vol% must be considered on a project-specific basis.
- b) Contamination from the gas supply system must be avoided. Particulate matter or other substances which can harm the engine must not be present. Ensure correct flushing of pipes, and a high cleanliness of tanks and bunkering connections etc.

12 Ammonia fuel

Ammonia (NH₃) is a colourless, toxic gas at ambient temperature and pressure. It has a pungent smell, and has lower density compared to air. To be in the liquid state, it needs either been cooled down at -33°C at atmospheric pressure or pressurised to the corresponding pressure/temperature point. Ammonia can be used in the X-DF-A engine types where A stands for ammonia.

12.1 Ammonia properties

Ammonia is a non-carbon-based gas fuel consisting of nitrogen and hydrogen elements. It can be stored under cryogenic conditions at -33°C or in pressurized tanks. Its energy density is much lower than traditional hydrocarbon fuels and requires almost 3 times the volume to store the equivalent amount of energy. It has much higher Lower Explosivity Limit (LEL) and flash point than other fuels, e.g. methane, which makes it safer in terms of explosion risk. However, due to its inherent toxicity there is need of stringent safety consideration and emission monitoring to avoid harm to the crew and environmental pollution. A comparison of the properties of ammonia and MGO can be seen in Table 11.

Table 11. Comparison of energy properties for ammonia and marine gas oil

Characteristic	Unit	Ammonia	Marine gas oil
Flash point	°C	132	60
Density	kg/m ³	680 ^a	850 (at 15°C)
Lower Heating Value (LHV) at ISO condition	MJ/kg	18.6	42.7
Relative volume per energy content	-	2.8 ^a	1
Boiling point at 1 bar	°C	-33	150–380
Explosive limit in air	vol%	14–27	1–6
Solubility: fuel in freshwater	wt%	32 ^b	N/A

a) Storage condition -33°C and 1 bar(a)

b) Condition 25°C and 1 bar(a)

12.2 Ammonia specifications

The minimum quality requirements for ammonia for the WinGD X-DF-A engines is shown in Table 12. The water content of ammonia should be between 0.1–0.5 wt%. A small amount of oil is acceptable if levels do not exceed 0.4 wt% of total fuel.

Table 12. Specifications of ammonia for the WinGD engines

Characteristic	Unit	Limit	Ammonia
Purity (on a dry basis)	wt%	min	99.5
Water	wt%	range	0.1*–0.5
Oil	wt%	max	0.4
Oxygen	ppm	max	2.5*

* - values not required by WinGD, but generally recommended as a good practice for ammonia systems

13 Fuel changeover

13.1 Changeover for diesel fuels

When fuels of different viscosities are changed one to the other, the temperature must be adjusted to reach the required viscosity between 2 cSt and 20 cSt at the engine inlet. The temperature of the fuel entering the engine must be adjusted gradually at maximum rate of 2 °C per minute to avoid thermal stress on the fuel system components. It is especially important to follow this recommendation if such changeovers are performed on a regular basis.

For residual fuels, a fuel management procedure (suited to the specific fuel system in use) must be prepared to minimise the mixing of fuels from different batches during fuel changeover.

Before filling the settling tank with a new batch of fuel, ensure that the quantity of previous fuel remaining is kept to an absolute minimum. If a settling tank contains unused fuel when filling it with a new batch of fuel, frequently drain this tank to check for possible sludge accumulation. The service tank should be emptied before filling it with a new batch of fuel. If it is not possible to empty the service tank completely, ensure that the quantity of previous fuel remaining is kept to an absolute minimum level.

13.1.1 Automatic fuel changeover

WinGD recommends the installation and use of an automatic fuel changeover system to prevent problems during the changeover procedure. Advantages of such a system are:

- Due to proper temperature control, the system decreases the risk of damages due to reduced thermal stress on engine components.
- The changeover procedure can be performed at up to 100% engine load.
- The automated changeover is faster compared to a manual changeover.

13.1.2 Manual fuel changeover

If a manual fuel changeover is performed, the changeover must be safe. Refer to the related procedures in the Instruction Manual (IM). Make sure that during the procedures RM fuel never can flow into the MGO/MDO tank and pipe system.

Please note: If an automatic changeover system is installed and available, WinGD recommends avoiding manual fuel changeovers.

13.1.3 Recommended viscosity at the inlet of the fuel pumps

For the temperature necessary to make sure that the fuel upstream of the inlet to the fuel pumps is at the correct viscosity, refer to the Viscosity / Temperature Diagram in Figure 3. The viscosity of fuel must not be less than 2 cSt (see Chapter 4.2).

13.2 Fuel changeover on DF engines

Changeover procedures depends on type of fuel used on the DF engine, its configuration and contracted operating modes. For more details, please see the Instruction Manual (IM) for the engine in question.

13.2.1 Cylinder oil change due to changeover

Before changeover, make sure that the cylinder oil which is currently in use can also be used with the new fuel. This prevents damage of the piston running system because of an incorrect BN or lubricant type. To select proper oil, please refer to the "Lubricants".

<https://www.wingd.com/en/technology-innovation/engine-technology/engine-design/tribology-fuels-lubricants/>

13.2.1.1 Engines with iCAT

If the engine has an iCAT system (integrated Cylinder Lubricant Auto Transfer system), during a fuel changeover please note:

- If the iCAT system is in auto mode, the iCAT system automatically changes over the cylinder oil at the correct time.
- If the iCAT system is in manual control (no iCAT functionality mode), you must manually change over the cylinder oil at the same time as the diesel fuel changeover.

13.2.1.2 Engines without iCAT

If the engine has no iCAT system, WinGD recommends to monitor the changeover of the cylinder oil. To perform a calculation of the cylinder lubricant quantity and to make sure that the cylinder lubricating feed rate is known, see Figure 16.

1. Make sure that you know the cylinder lubricant quantity that is between the changeover valve and the lubricating quills including the measurement tube.
2. Calculate the related lead time for the cylinder oil to get to the lubricating quills.
3. Use this lead time to have the correct timing for the changeover of the cylinder oil.

Please note: When you change from low sulphur to high sulphur fuels, WinGD recommends starting the changeover of the cylinder oil from low BN to high BN in advance. This prevents operation with high sulphur fuel and low BN cylinder oil.

Cylinder lubricant quantity in piping and measuring tank:

$$\text{Volume piping: } \Sigma V = \frac{\Sigma d^2 \cdot \pi}{4} \cdot l \quad [V] = m^3 \quad [d] = m \quad [l] = m$$

$$\text{Mass: } m = \rho \cdot V \quad [m] = kg \quad [\rho] = \frac{kg}{m^3} \quad [V] = m^3$$

The density of the cylinder lubricant can be found in the technical data sheet. If not available, an average value of $920 \frac{kg}{m^3}$ is suitable for this purpose.

$$\text{Total mass: } \begin{aligned} & \text{Mass of cylinder oil in measuring tank [kg]} \\ & + \\ & \text{Mass of cylinder oil in piping [kg]} \end{aligned}$$

Lead time until new lubricant is in use:

$$\text{consumption} = \frac{\text{effective feed rate} \cdot \text{current power output}}{1000}$$

$$\text{lead time} = \frac{\text{total mass}}{\text{consumption}} \quad [\text{lead time}] = h \quad [m] = kg$$

$$[\text{consumption}] = \frac{kg}{h} \quad [\text{effective feed rate}] = \frac{g}{kW \cdot h} \quad [\text{current power output}] = kW$$

Figure 16. Cylinder lubricant quantity

13.2.1.3 Cylinder oil for gas operation

WinGD recommends using “DF validated” cylinder oils during gas operation. These cylinder lubricants were tested and validated on DF engines running on gas for extended test time. For suitable validated products, please refer to “Validated engine oils for the WinGD engines” .

<https://www.wingd.com/en/technology-innovation/engine-technology/engine-design/tribology-fuels-lubricants/>

13.3 Changeover for SCR operation

To comply with the IMO Tier III regulations for NO_x emission control areas (NECA), the engine can be equipped with an exhaust gas treatment system, e.g. High- or Low-Pressure SCR (HP SCR / LP SCR).

Depending on the design of the SCR, it may can be operated if the fuel sulphur content meets the requirement of the SCR system supplier. Information about the permissible fuel sulphur content must be provided by the SCR system supplier. In general, LP SCR systems cannot operate with fuel sulphur content level above 0.5%, while HP SCR systems can be designed for up to 3.5% sulphur content. To ensure the required fuel sulphur content, a fuel changeover (including system flushing) may be needed.

14 Fuel additives

WinGD does not recommend using fuel additives. Additives are not necessary for fuels that comply with the ISO 8217 [2] standard or fuels for which WinGD provided Non-Objection Letter (NOL).

Please note: Non-Objection Letters regarding fuel additives issued by Wärtsilä Switzerland Ltd. are no longer valid and not supported by WinGD.

WinGD does not accept liability or responsibility for the performance or potential damage caused by any fuel additives.

A References

- [1] "Revised MARPOL Annex VI, Regulations for the Prevention of Air Pollution from Ships and NOx Technical Code 2008," International Maritime Organization, London, 2009.
- [2] "ISO 8217:2024, Petroleum products, synthetic and renewable sources - Fuels (class F) - Specifications of marine fuels, Seventh edition 2024-05," International Organization for Standardization, Geneva, 2024.
- [3] International Maritime Organization, *MARPOL Annex VI, Regulations for the Prevention of Air Pollution from Ships and NOx Technical Code*, London, 1997.
- [4] "COMMISSION DECISION on the establishment of criteria for the use by liquefied natural gas carriers of technological methods as an alternative to using low sulphur marine fuels meeting the requirements of Article 4b of Council Directive 1999/32/EC," relating to a reduction in the sulphur content of certain liquid fuels as amended by Directive 2005/33/EC of the European Parliament and of the Council on the sulphur content of marine fuels (2010/769/EU), 2010.
- [5] "RESOLUTION MEPC.190(60)," International Maritime Organization, London, 2010.
- [6] "RESOLUTION MEPC.202(62)," International Maritime Organization, London, 2011.
- [7] "China Emission Control Areas Implementation - Second Edition," China Classification Society, 2017.
- [8] [Online]. Available: <https://www.dnvgl.com/news/new-requirements-for-nox-emissions-for-vessels-engaged-in-chinese-domestic-trade-125086>. [Accessed 30 November 2018].
- [9] "Notice on Latest implementation requirements of Ship Emissions control measures in Yangtze River Delta," China Classification Society, 2018.
- [10] Republic of Korea, *Special Act on the Improvement of Air Quality in Port Areas Etc.*, 2019.
- [11] "RESOLUTION MEPC.189(60)," International Maritime Organization, London, 2010.
- [12] International Maritime Organization, *RESOLUTION MEPC.329(76) - AMENDMENTS TO MARPOL ANNEX I (PROHIBITION ON THE USE AND CARRIAGE FOR USE AS FUEL OF HEAVY FUEL OIL BY SHIPS IN ARCTIC WATERS)*, London, 2021.
- [13] International Marine Organization, *REPORT OF THE MARINE ENVIRONMENT PROTECTION COMMITTEE ON ITS SEVENTY-EIGHTH SESSION, MEPC 79/15*, London, 2022.
- [14] Marine Environment Protection Committee,, MEPC.1/Circ.795/Rev.6, London: International Marine Organization, 10 June 2022.
- [15] Marine Environment Protection Committee, MEPC.1/Circ.795/Rev.7, London: International Marine Organization, 16 December 2022.
- [16] "ISO 8217:2017, Petroleum products - Fuel (class F) - Specifications of marine fuels, Sixth edition 2017-03," International Organization for Standardisation, Geneva, 2017.
- [17] CIMAC WG 7 Fuels, "2022 Organic Chlorides, marine fuels incidents," CIMAC, Frankfurt, 2022.
- [18] CEN - European Committee for Standardization, *EN 14077 Petroleum products - Determination of organic halogen content - Oxidative microcoulometric method*, 2003.
- [19] CIMAC Working Group 7 Fuels, "Overview and interpretation of total sediment test results in the context of ISO 8217:2024," International Council on Combustion Engines (CIMAC), Frankfurt, 2024.
- [20] CEN - European Committee for Standardization, *EN 15940 Automotive fuels - Paraffinic diesel fuel from synthesis or hydrotreatment - Requirements and test methods*, 2019.

- [21] CEN - European Committee for Standardization, *EN 14214 Liquid petroleum products - Fatty acid methyl esters (FAME) for use in diesel engines and heating applications - Requirements and test methods*, 2019.
- [22] American Society for Testing and Materials, *ASTM D 6751 Standard Specification for Biodiesel Fuel Blend Stock (B100) for Middle Distillate Fuels*, 2023.
- [23] China, "Reduction of the impact on the arctic of black carbon emissions from international shipping. Black Carbon emission measurement results of a marine low-speed diesel engine using biodiesel. PPR 10/INF.4," PPR Sub-committee, International Marine Organisation, London, 2023.
- [24] W. Gottschalk, T. Scholz and B. Rozmysłowicz, "Biofuel Application and Emissions Behavior on a Two-stroke Main Engine," *MTZ worldwide*, vol. 83, pp. 52-59, 2022.
- [25] Wärtsilä Service Switzerland Ltd, "RT-268: Biofuels impact for engines and related auxiliary systems.," Frauenfeld, 2023.
- [26] "ASTM D4740-20, Standard Test Method for Cleanliness and Compatibility of Residual Fuels by Spot Test," American Society for Testing and Materials, West Conshohocken, 2020.
- [27] CIMAC Working Group 7 Fuels, "Design and operation of fuel cleaning systems for diesel engines.," International Council on Combustion Engines (CIMAC), Frankfurt, 2024.
- [28] ISO (International Organization for Standardization), *ISO 23306 Specification of liquefied natural gas as a fuel for marine applications*, Geneva, 2020.
- [29] CEN - European Committee for Standardization, *CSN EN 16726 Gas infrastructure - Quality of gas - Group H*, 2018.
- [30] "[17] MEPC 72/17 Report of the Marine Environment Protection Committee on its Seventy-Second Session," International Maritime Organization, London, 2018.

B Abbreviations

Al – Aluminium
AN – Acid Number
ASTM – American Society for Testing and Materials
B100 – fuel with 100 wt% of biofuel
B30 – fuel with 30 wt% of biofuel
B50 – fuel with 50 wt% of biofuel
BDN – Bunker Delivery Note
BN – Base Number
BOR – Boil-Off Rate
BSFC - Brake Specific Fuel Consumption
Ca – Calcium
CCAI - Calculated Carbon Aromaticity Index
CFPP - Cold Filter Plugging Point
CI – Cetane Index
CIMAC - The International Council on Combustion Engines
Cl – Chlorine
CMCR - Contracted Maximum Continuous Rating
CN – Cetane Number
cSt – Centistoke
DCC - Dynamic Combustion Control
DECA - Domestic Emissions Control Areas
DF - Dual-Fuel engine
DFA – Distillate Marine – fuel grade A, which contains FAME
DFB – Distillate Marine – fuel grade B, which contains FAME
DFZ – Distillate Marine – fuel grade Z, which contains FAME
DM – Distillate Marine
DMA – Distillate Marine – fuel grade A
DMB – Distillate Marine – fuel grade B
DMX – Distillate Marine – fuel grade X
DMZ – Distillate Marine – fuel grade Z
ECA – Emission Control Area
EN - European Standards
EUROMOT - European Association of Internal Combustion Engine and Alternative Powertrain Manufacturers
F – Fluorine
FAME – Fatty Acid Methyl Ester
FBOG – Forced Boil-Off Gas
FO – Fuel Oil
FTIR - Fourier-Transform Infrared Spectroscopy
GC-MS - Gas Chromatography – Mass Spectrometry
GVU – Gas Valve Unit
H₂ - Hydrogen
H₂S – Hydrogen Sulphide
HFO – Heavy Fuel Oil
HSFO – High Sulphur Fuel Oil
HVO – Hydrotreated Vegetable Oil
iCAT - integrated Cylinder Lubricant Auto Transfer system
iGPR - integrated Gas Pressure Regulator
IMO – International Maritime Organisation

IP – International Petroleum test methods
ISO - International Organization for Standardization
K – Potassium
KOH – Potassium Hydroxide
LCV – Lower Calorific Value
LEL – Lower Explosivity Limit
LHV – Lower Heating Value
LNG – Liquefied Natural Gas
MARPOL - The International Convention for the Prevention of Pollution from Ships
MBOG - Mass of the Boil-Off Gas
MDO – Marine Diesel Oil
MEPC - Marine Environment Protection Committee
MF – Marine Fuel
MGO – Marine Gas Oil
MIM – Marine Installation Manual
MN – Methane Number
MN MWM – Methane number - MWM (Motoren Werke Mannheim) calculation method
MN PKI – Methane Number – Propane Knocking Index calculation method
Na - Sodium
NBOG – Natural Boil-Off Gas
P - Phosphorus
ppm – parts per million
RM – Residual Marine
RMA – Residual Marine - fuel grade A
RMK – Residual Marine – fuel grade K
SF – Sulphur Content
Si - Silicon
TSA - Total Sediment Accelerated
TSE - Total Sediment Existent
TSP - Total sediment Potential
ULSFO – Ultra Low Sulphur Fuel Oil
VLSFO – Very Low Sulphur Fuel Oil
WinGD – Winterthur Gas & Diesel
WSD - Wear Scar Diameter
wt% - weight percent
Zn - Zinc