09 | 2024 v2
CIMAC Guideline

Design and operation of fuel cleaning systems for diesel engines

- Part 1: Properties of today's fuel

- Part 2: Fuel system design

- Part 3: Operational practices

CIMAC WG 7 "Fuels"

Contents

Introduction

The safe handling of fuels on board ship requires four key component elements to align to ensure the fuel as delivered is safely and efficiently stored, cleaned, and conditioned prior to its intended use.

These elements include:

1. The correct selection of the ISO 8217 fuel grade to meet the specific ship's machinery plant and fuel system design, technical and operational requirements.
2. A fuel system designed for flexibility to cope with the global diversity of fuel blends being supplied as expected for the operational profile of the specific ship.
3. Information on the properties of each fuel at point of supply made available to enable effective fuel management.
4. Engineers well trained on the most recent best practices in applying effective fuel management.

Most ships operating today have fuel system designs common to both two-stroke and four-stroke engines meeting the minimum requirements, which are still suitable for the fuels in use. The systems, however, may not necessarily offer the degree of flexibility required to handle efficiently the more widely diverse range of fuel blends being supplied since the introduction of VLSFO (Very Low Sulfur Fuel Oil) grades from January 2020.

Experience in the use of VLSFO since the start of 2020, has highlighted the importance of much more compositional awareness of the fuel properties as supplied and a greater flexibility in system design to manage the more complex storage requirements for segregation, pre-treatment/cleaning and thermal management.

The guideline will also address the quality of distillate fuels.

Scope

The purpose of this document is to provide designers, ship builders and operators with an updated guideline on the key elements of design and operation for fuel cleaning and conditioning systems for commercial ships burning fuels that comply with the ISO 8217 specification for marine fuels. The guidance is valid for both two- and four-stroke engines.

This is an extension to CIMAC document No. 25/2006 *'Recommendations Concerning the design of heavy fuel treatment plants for diesel engines'* [1]*,* which remains valid and may be used in conjunction with this document as applicable.

The guidelines encompass well established best practice designs that have been proven to give reliable performance over a wide range of normal and abnormal operating conditions. The capacity to cope with exceedances from one or more of the influencing fuel parameters is also an important criterion to consider when ensuring safe and reliable vessel operations.

This guideline may also be used as a reference material, as it includes references to other guidance materials, which may be useful when evaluating best practices to enhance fuel management practice by the operators or to address a fuel property quality issue.

This document has been divided into the following three topical parts:

Part 1 - Fuel Properties

A focus on the key fuel properties that dictate the requirements for handling, cleaning, and conditioning of the fuel prior to use.

Part 1 focuses on the core fuel properties and their influence on fuel treatment that need to be understood to address design requirements and to facilitate necessary on-board fuel management. These are:

- For residual type marine (RM and RF) fuels: viscosity, density, water (saline and fresh), cold flow properties, total sediment (Stability), abrasives such as catalytic fines (Al+Si) and extraneous dirt; and

- For distillate type marine (DM and DF) fuels: Viscosity, density, water (saline and fresh) and cold flow properties.

Part 2 - Design

Fuel system design at build, starting from the storage tank layout, determines the level of capacity and efficiency of a ship's fuel system to manage the diversity of marine fuel formulations today. As fuel blend formulations can vary widely between each fuel delivery, the design of a fuel cleaning system needs to accommodate these variants and the variation between different fuel supplies.

Part 3 – Operational Considerations

The operation of a well-designed fuel system still requires informed engineers to apply best practice fuel management, even when the fuel meets the ordered specification and/or is commingled onboard, this is to ensure the fuel delivered to the machinery plant is cleaned, conditioned and acceptable for use in the engines onboard. This section provides further guidance on best practice fuel management making references to other industry documents that were developed to address the changing fuel blend characteristics brought about, especially from the introduction of VLSFO's, increased use of distillate fuels and increased inclusion of biofuel.

Part 1 - Properties of today's fuels

1. Impact of regulation on fuel properties

On 1 January 2020, MARPOL Annex VI Regulation 14.1 reduced the maximum sulfur (S) content of marine fuels when operating outside an Emission Control Area (ECA) from 3.50% m/m to 0.50% m/m.

Switching from high sulfur fuel oils (HSFO), the conventional norm for over 40 years, to the new norm of the very low sulfur fuel oils (VLSFO) of max. 0.50% sulfur content, initially raised concerns that their availability was going to be challenging. Within the first few months of 2020 the max 0.50% sulphur regulation coming into force, the global supply market had, through extensive preparations, managed to make the necessary changes to accommodate for the change in demand to enable VLSFO and distillate fuel grades to be readily available. At the early stage of transition there were only a few reported cases of non-availability where ships had to submit 'fuel oil non availability reports' (FONAR).

One notable consequence of this legislation was a major shift in how marine fuels are blended to meet the sulfur limits. This has resulted in a more diverse range of blended formulations being offered, requiring the receiving ships engineers to have a greater focus on the actual fuel properties of each fuel supplied, to efficiently manage how they might best be stored and handled on board ships.

The anticipation that VLSFO would see a rise in the use of more paraffinic-based refinery streams to blend these fuels came to be and is contrasting to the more aromatic quality of pre-2020 HSFO. These more paraffinic fuels provide an improvement in terms of combustion performance, however by contrast, the handling has proved more of a challenge with a higher risk of incompatibility between different fuels and the need for increased focus on temperature management. This therefore requires more stringent storage segregation considerations and a shift in engineers mind set in the approach to handle these fuels compared to pre-2020 HSFO fuels.

Ships fitted with exhaust gas cleaning systems (EGCS) are still using HSFO. Today HSFO is only supplied in key bunker ports and is currently amounting to approximately 25% of the quantity of the marine fuel oil demand [2].

2. ISO 8217 Marine fuel specification

It is important to understand that the ISO 8217 specification defines the fuel properties at the point of delivery to the ship and not the fuel properties required at engine inlet, thus requiring fuel treatment prior to its use.

While the recommendation is to always use the latest edition of ISO 8217, earlier editions are nevertheless often still used namely those of 2005, 2010/12 and 2017 for a variety of reasons. For the most part, this is due to fuel oil bunker order clauses which are contractually tied in for a certain period, making it difficult to change the ordering specification, and for some it could be due to lack of knowledge, focus or price.

In 2019 concerns were expressed that ISO 8217:2017 would not cover for the VLSFO diverse grades. However, ISO provided reassurance through the ISO/PAS 23263:2019 clearly stating that ISO 8217:2017 applied to all fuel oils, including the ultra-low sulfur fuel oils (ULSFO fuels of $\leq$0.10%S) and VLSFO, and it also does further address some quality considerations that might apply more to fuels with lower sulfur limits leading to quality changes.

The seventh revision of the ISO 8217 standard was released in June 2024. This revision is heavily influenced by the introduction of the use of VLSFO and the growing demand for blends of biofuels. Biofuels are presently mainly fatty acid methyl esters (FAME) although other types of biofuels such as paraffinic diesels and hydrotreated vegetable oils - HVO and synthesis renewables are expected to be more widely included as they become more readily available.

3. Sulfur defining fuel characteristic

While the sulfur content has become the defining characteristic of a marine fuel such as the < 0.10% (ULSFO), $\leq$ 0.50% (VLSFO) and > 0.50% (HSFO) sulfur marine fuel oils, all other specified parameters still need to meet the ISO 8217 and should not be overlooked in the process of buying, receiving, storing, cleaning, conditioning and use of these fuels. ISO 8217:2024 divide residual fuels for fuels with sulfur content below 0.50 % S and above 0.50 % S and set new specifications for them in tables 2 and 4, respectively.

4. Fuel quality observations

Both the system design and effective operational practices can reduce the likelihood of instability occurring, reducing on board operational challenges and help the removal of contaminants to an acceptable level at engine inlet.

One key notable change has been the reduction in the average viscosity being supplied for the VLSFO's. The viscosity has come down from the norm of around 380 cSt to a majority within the range of 80 to 180 cSt at 50 °C. The purchase and use of fuel has therefore become more complex in that as well as sulfur, an understanding of the minimum viscosity a ship would prefer or require to receive is necessary to be specifically communicated in the charter party fuel clause to ensure that the viscosity meet their operational requirements. It is advised to use ISO 8217:2024 as it defines minimum viscosity for all the grades of residual fuels.

It has also been observed, by statistical analysis of the fuels as fuelled, that there is a continued presence of abrasive catalytic fines in VLSFO. As no significant change in the average and maximum of catalytic fines content is observed, the importance of their removal on board the ship remains. However, the lower viscosity (and densities) of the VLSFO's should, according to Stokes law, increases separator efficiency to reduce abrasives across the system.

Another concern, that has come to light is the continued need to be very aware of the likely incompatible nature between different fuels bunkered, and the reduced storage stability time some of these VLSFO fuels might have.

The result of incompatibility between two fuels on board leads to an unstable fuel condition occurring, which may result in the fuel treatment system being overloaded by sludge deposition, which in turn reduces the cleaning efficiently of the plant and can result in the blocking of separators and filters.

Both the system design and effective operational practices can reduce the likelihood of instability occurring, reducing on board operational challenges and help the removal of contaminants to an acceptable level at engine inlet.

5. Fuel properties affecting fuel cleaning

Fuel properties can be grouped into three categories:
1. Fuel properties that are influenced by the fuel cleaning system. Such as abrasive solids (catalytic fines, etc.), water, Sodium, ash content and sediments.
2. Fuel properties that have an impact on the performance and efficiency of the fuel cleaning system. Such as fuel density, viscosity, stability, cold flow properties and the presence of contaminants like unrefined used lubricating oil.
3. Other fuel properties, which are not influenced by the fuel cleaning system, and which do not affect the operation of the fuel cleaning system Such as: e.g. specific Energy, vanadium, sulfur, carbon residue, ignition properties, hydrogen sulphide, flash point.

Categories 1 and 2 are dealt with in this document. Category 3 properties are not dealt with further in this document as they are neither influenced by nor do they influence the fuel cleaning process.

6. Fuel contaminants

The purpose of the fuel cleaning system which combines both design and operational considerations, is to ensure it has the capacity to reduce the level of removeable contaminants typically found in marine fuels to prevent unacceptable levels of wear and damage to the machinery plant.

There are four main categories of contamination originating from the fuel supply that need to be addressed, these being:
- Water (fresh and saline)
- Sediment (asphaltene and ash forming inorganic materials, and extraneous dirt)
- Abrasive Solids (e.g. Catalytic Fines - Al+Si)
- Some other suspect materials, such as some chemical species, not originating from the petroleum refinery processes, whilst potentially damaging to the machinery plant, are unlikely to be able to be removed.

6.1. Water

Water can enter the fuel at any point through the supply chain, its distribution, storage and/or during on-board handling and/or through cross contamination. Water remaining in the fuel after gravitation at the settling tank can be removed via the separators. Whilst the limit for water is generally set at maximum 0.50% in the ISO 8217:2024 standard for RM fuels as supplied, higher levels can be handled. However, gross contamination of much more than 2-3 % may be difficult to remove during normal on-board treatment leading to carry over to the engine, even as an uncontrolled emulsion or as free water in the fuel.

Water can be fresh or saline. Fresh water such as from condensate, leaking steam heating coils or even tap water, is often partly emulsified which lowers the separation efficiency. Saline water has a higher density and is less inclined to emulsify and therefore more easily removed – however if left in the fuel, it can lead to increased corrosion and post combustion space fouling of exhaust and turbochargers due to the higher ash forming presence of sodium.

Emulsified water can be harder to deal with on board under normal operational circumstances. Unremoved water in fuel can also lower the energy content and could lead to operational problems such as corrosion, or fuel injection issues caused by viscosity and temperature changes.

Sodium combined with the vanadium inherent in residual fuel oils can damage engine components, particularly from older engines not so materially protected, such as: exhaust valves, piston tops, turbochargers, and other surfaces as a result of the hot corrosion effect in the event that ISO 8217 specification is not met. If sodium is water soluble it can be removed with the water in settling tanks and in separators. When continuously operating engines on fuel with high sodium content, cleaning of turbocharger using wet or dry cleaning should be carried out more frequently.

6.2. Sediment

Sediments can be in the form of inorganic (ash) and organic (asphaltenic) material.

Ash is made up of incombustible materials derived from metals either present in the fuel source or from other external contamination. Common metals include vanadium and nickel which cannot be removed via separation as they are soluble in oil and part of the fuels organic structure. Calcium may also be part of the fuel organic structure, water or ULO, so some part of the Ca can be removed by fuel cleaning, and some may not be able to be removed. The catalytic fines (measured as Al+Si) and the sodium component of sea water can also contribute to the ash content however these can normally be reduced to acceptable levels through the separation and filtration equipment. This fuel cleaning process can help influence the amount of incombustible material remaining in post combustion spaces.

Asphaltenes, which hold much of the energy in a residual fuel, can be separated from the fuel by the centrifuge if present in the fuel as large enough agglomerates, due to their higher density and the limited stability reserve of the fuel. However, usually asphaltenes will be smaller and well dispersed and will pass through the separators if the fuel has retained its stability and can thereby be combusted.

6.3. Abrasive solids

The main class of abrasive solids are normally catalytic fines. These are small, very hard particles, which originate from catalytic refining processes, and thereby can enter the marine fuel chain accidently as a carryover from the refinery and then as a result of blend stocks containing high amounts of catalytic fines. Specific amounts are normally accepted in fuel as fuelled according to ISO 8217 [3], but in case of insufficient fuel cleaning on board, these catalytic fines may enter the engine with the fuel and potentially cause damage due to their abrasive nature. For two-stroke engines the damage is usually found in the combustion chamber, on cylinder liner, piston rings and ring grooves resulting in high wear and possible scuffing. For four-stroke engines, the damage is primarily found in the fuel system where the atomisers become damaged and worn out resulting in poor combustion and high deposits in the turbocharger.

Catalytic fines are hard and abrasive in nature as they are based on ceramic material (zeolites). They are made to withstand the violent motion and turbulence in the refinery FCC (Fluid Catalytic

Cracking) unit. Ceramics are measured on the Mohrs hardness scale from 1 to 10, where diamond measures 10, and grinding materials: aluminium-oxide (Al_2O_3) and silicon-oxide (SiO_2) measure 9 and 7 respectively. In this scale, the hardness of catalytic fines would measure in the range of 8. Components in the engine are in some cases of almost similar hardness to catalytic fines, such as the hard coating on piston rings but in other areas, such as liner and piston ring base materials, the hardness of the components is considerably less.

These particles can range in size from sub-micron to approximately 50-micron levels. (See Figure 1 and Figure 2). As a hard material will rapidly wear a soft material when in contact, catalytic fines will wear the softer engine components. Many OEMs specify a maximum limit of 7-15 mg/kg catalytic fines at the engine inlet. Therefore, an efficient fuel cleaning system is the only effective way to ensure that these particles are removed from the fuel before it enters the engine. A measurement of the approximate concentration of these particles by taking samples before and after the fuel cleaning operations will give a good indication of the efficiency of the fuel cleaning system. See Part 3 on Operational Practices.
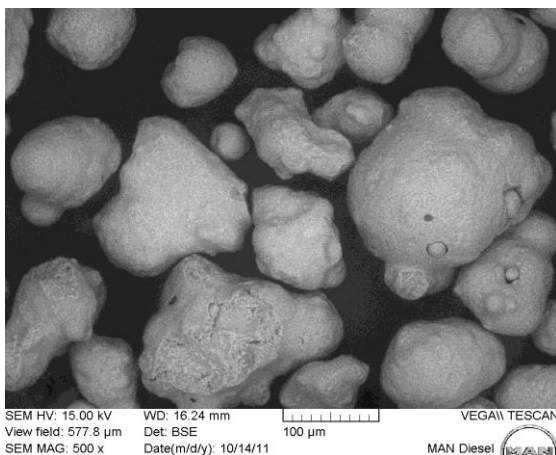

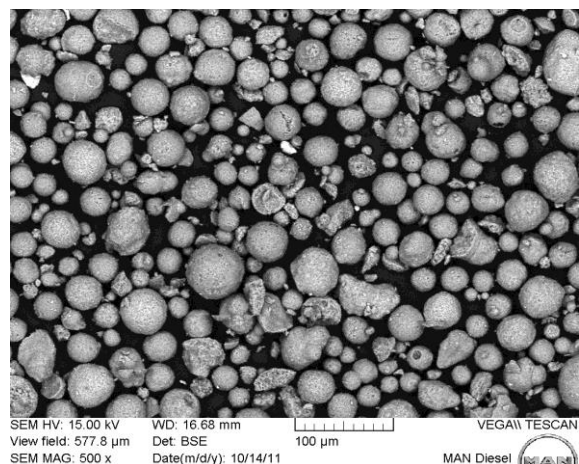*Figure 1 - New, unused catalytic particles for the FCC in the refinery (SEM photo)*

Figure 2 - Catalytic fines received from a refinery (SEM photo)

6.3.1. Limits for catalytic fines in the fuel as fuelled.

Catalytic fines level in marine fuel is measured based on Aluminium (Al) and Silicon (Si). Testing should be done in a laboratory according to ISO 8217 [3]: IP 501, IP 470, or ISO 10478. Marine fuels are purchased according to ISO 8217 international standard: Specifications of marine fuels [3]. The specifications in this standard define amongst others the limit for catalytic fines in fuel oils, expressed as Al+Si (aluminium plus silicon), as delivered to the ship, and thereby still require removal to levels acceptable for engine entry.

Previous editions of the ISO 8217 are still being used, however CIMAC supports the use of the latest edition, as it includes the most current knowledge and guidance. ISO 8217:2010, 2012 and 2017, and now 2024 lists a limit of maximum 60 mg/kg Al+Si for the more viscous grades. Low viscosity grades are limited to 40 or 50 ppm Al+Si. ISO 8217:2005 listed a maximum limit of 80 mg/kg Al+Si for all residual grades.

6.4. Other deleterious materials

The ISO 8217 standard is largely based on parameters related to operational performance / experience rather than compositional requirements for the fuel. The design of the ship's cleaning system, along with normal onboard fuel management best practices being applied, addresses the means to clean fuels based on the normally anticipated contaminants as characterised in this section, the limits of which are covered in the ISO 8217: 2024 [3].

The tables do not cover other deleterious materials or solvency characteristics of biofuels, in specific terms, but are otherwise it is covered more generally under the ISO 8217 Clause 5, the general workmanship clause. In the latest editions of ISO 8217:2024, the Clause 5is also included in the tables. While the occurrence of these deleterious materials is rare, a marine fuel that met the characteristics as listed in the relevant Tables of ISO 8217, may be suspected to be the cause of operational issues being experienced on the machinery plant; the suspicion being directed to other initially undetected deleterious materials being present. Typical symptoms of other deleterious material being present include unusually excessive sludge deposits at the separators and or filters and rapidly degraded, even seized, fuel pumps and injectors.

At this point, it could come into question whether the fuel fails to meet the general requirements of the ISO 8217 standard as defined in Clause 5 and therefore deeming the fuel as supplied having not met the ISO 8217 specification at delivery as initially declared.

Advanced analytical investigative testing would need to be carried out as part of the overall investigation to make steps to determine the root cause of problems experienced. This may reveal deleterious materials otherwise not detected through routine analysis and therefore being outside the scope of any fuel cleaning system to handle.

If a suspect chemical has been identified and quantified, and its presence has been confirmed by other testing labs, the next step is to evaluate if that component – or combination of components – can be the cause of the operational issues.

6.4.1. Establishing cause and effect analysis

The most practical way to identify a correlation between the presence of the component(s) and the experienced operational issues is to perform a cause-and-effect analysis. This is unfortunately not a simple task as it not only requires significant testing work but more importantly, industry collaboration and knowledge sharing. When the same batch of fuel is supplied to numerous ships, it enables a meaningful cause-and-effect evaluation to be seen through common circumstances and association.

The following lists essential considerations when seeking to determine cause-and-effect:

- The ship followed industry best practice for fuel treatment.
- Determine whether the fuel was isolated, had not been commingled with other fuels and or additives used.
- The fuel containing the specific chemical specie(s) was in use at the time the ship experienced problems.
- Presence of the specific chemical specie(s) has caused similar operational issues on other ships.
- Other non-problematic fuels do not contain the specific chemical specie(s), or only contain insignificant amounts of the component(s)
- If available, historical records of similar issues related to presence of same component(s)
- A hypothesis which explains the experienced issues lead to logical explanation of the cause to the effect.

- As applicable, physical metallurgical analysis of the damaged component should be carried out to attempt to confirm the effect and link to the fuel as being the cause.

6.4.2. Gathering a case evidence portfolio

If a specific fuel as defined above is suspected to be the cause of an operational problem, emphasis should be on the ship and its supporting technical office to gather 'evidence' in support of the case, which should include but is not limited to:

- Detailing a record of the events in the log book, observations and mitigating actions taken leading up to, during and after the operational problem / incident in a chronological sequence.
- Collection of 'in use' fuel samples of the fuel passing to the engine as well as before and after the separator – with support detailed documented reports on location time/date witnessed and taken by whom; supported by photos and or videos.
- Collection of retained suspected fuel samples in safe custody, both, ship drawn, and MARPOL and supplier provided, with documentation stating which have or have not been witnessed by the ship.
- Reference should be made in the report to the ship's standing procedures for fuel handling, and cleaning machinery maintenance and operation was demonstrating best industry practice.
- Gather maintenance records of the state and condition of the cleaning equipment along with the specific machinery plant that experienced the operational problems.
- Collate all analysis reports for fuel used before, during and after the incident, including any in use fuel system checks or investigative analysis – should be supported by independent experts reports on fuel quality and marine machinery.
- Record fuel movements onboard along with storage, handling, treatment temperatures
- Damaged components to be photographed and if possible bagged and sealed, uncleaned for possible more in-depth detailed material examination.

6.4.3. Two high profile cases

Two such cases are described below; however, they could not be mitigated by fuel cleaning or normal on-board management, and the steps described above for evaluating the case should be followed.

In 2018 in the US Gulf area there was an unprecedented case of close to 100 ships that had reported operational problems over a short period. It was not possible to identify the root cause of the problems. The CIMAC report and guidance on the outcome of the case and the handling of similar experienced cases, can be found on the CIMAC website.[1]

Another more recent high-profile case was in the first quarter of 2022 in Singapore where more than100 ships were affected by a singularly sourced HSFO fuel causing operating problems. Further investigative analysis identified deleterious materials of high concentrations of total organic chlorides, which were identified as the cause of the rapidly degraded fuel pump, injector, and other sliding fuels system components in a matter of days (See CIMAC[2]).

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[1] CIMAC -2018 marine fuel incidents. https://www.cimac.com/working-groups/wg7-fuels/index.html

[2] CIMAC Organic Chlorides incident https://www.cimac.com/working-groups/wg7-fuels/index.html

7. Fuel properties influencing the performance of fuel cleaning

7.1. Fuel properties affecting separation according to Stokes' law.

Separation efficiency is dependent upon temperature (controlling both fuel viscosity and density), flow rate, particle size and proper separator care, maintenance and set up. A separator's ability to separate contamination from fuel is regulated by Stoke's Law (see equation below).

$$v_c = \frac{d^2(\rho_P - \rho_F)}{18\eta}\omega^2 r$$

Settling velocity (v_c) depends on: Particle size, d, Particle density, ρ_P, Fuel density, ρ_F, Dynamic viscosity of the fuel, η, Centrifugal acceleration, ω, Particle position on circular radius, r.

As such the important fuel parameters are Density, Viscosity, particle size, while these and additional operational parameters are covered in Chapter 10.

7.2. Fuel stability

A more detailed explanation of this aspect of fuel properties is covered in the CIMAC Guideline on: *Marine fuel handling in connection to Stability and Compatibility* (01/2019) [4] and in CIMAC Guideline on: *Overview and interpretation of total sediment test results in the context of ISO 8217:2024*[5].

The following comments provide a high-level overview of guidance in relation to the scope of this document.

Asphaltenes are high molecular weight molecules consisting of mainly aromatic hydrocarbon rings with other elements such as sulfur, oxygen, and heavy metals. They are held in suspension and kept in solution in the fuel. The stability of the fuel is kept by an equilibrium between the aromaticity of the oil matrix and the state of stability of the asphaltenes. If this is disturbed such as by blending with a more paraffinic distillate or more aromatic heavy fuel oils, the asphaltenes can precipitate out and form sludge. It is recommended that different fuel types should not be mixed for these instability and incompatibility reasons.

Co-mingling of fuels may disturb the equilibrium that keeps asphaltenes in suspension which can result in agglomeration and precipitation of these materials to produce sludge. In this case separators can become choked and fuel cleaning becomes more difficult. In the severest case, the separators will become overloaded and run the risk of being damaged due to the destabilising effect on the high-speed rotary action of the separator bowl by the sludge. In this scenario, the fuel has become unusable in the state that it is in. This will require a comprehensive assessment as to how the fuel might be best used if at all.

Additionally, it has been noted that, unlike HSFO, the VLSFO are more thermally sensitive. This means that the fuel temperature needs to be carefully managed to ensure that the cold flow properties are addressed, and at the same time the lower viscosity fuels are not over heated, as otherwise any undue prolonged thermal stress can lead to causing the fuel to become unstable.

7.3. Paraffinic nature - Wax in fuels

The implementation of IMO 2020 VLSFO 0.50% S fuels resulted in a wider range of fuel formulations, which typically are more paraffinic in nature, resulting in lower viscosity and density characteristics

but higher tendency to wax formation. The more paraffinic type fuels are in principle higher in pour point. To avoid the formation of waxes (and related operational issues with blocked filters and separators), CIMAC guides that fuel should be kept at a minimum of 10 °C above the pour point during storage, handling, and use. In case of high pour point VLSFOs, it may be advantageous to heat to higher than 10 °C above the pour point to dissolve the waxes in the fuel cleaning system, but care must be taken not to overheat VLSFO, and separators and filters should be monitored. It should be noted that the fuel can contain undissolved waxes even at temperatures well above the fuel's pour point. At fuel temperatures above the pour point the fuel will remain pumpable even if waxes are suspended in the fuel in crystalline form. The higher temperatures set at the settling and separators should liquify the waxes, attention being given to lower viscosity fuels with high melting point waxes and that heating of the filters and pipes lines with trace heating is available.

Three cold flow characteristics should therefore be considered when evaluating wax precipitation in fuel:

- Pour point (PP), is the industry standard test included in ISO 8217 – this determines the minimum temperature below where (above which *corrected in version v2 in September 2024*) the liquid loses its flow characteristics.
- Wax Appearance Temperature (WAT) for residual fuels – which can be compared to cloud point for distillate fuels – is the temperature at which the smallest observable cluster of wax crystals first occurs[3]. This is on average approximately 25 °C higher than the PP, but can be up to 40 °C higher than the PP.
- Wax Disappearance Temperature (WDT). This is the highest temperature at which a detectable amount of wax remains in a fluid[5]. This can be higher by 5 °C but in some instances as much as 20 °C higher than the WAT.

The WDT is higher than the WAT, due to a higher temperature needed to fully dissolve the wax. The difference between pour point, WAT and WDT varies and can be large, as illustrated in Figure 3 below. The wax appearance temperature and/or wax disappearance temperature test methods, which are not included ISO 8217 but can be considered to aid fuel management decision making onboard, as applicable; it should be noted however that the fuel will usually remain pumpable when temperatures are maintained above the pour point.

Undissolved wax, which is formed below the WAT, can cause operational issues for low viscosity fuels at the separator plant. A challenge to consider for operators is to manage fuel handling and storage temperatures for lower viscosity fuels to ensure that any wax content remains in solution at the inlet to the separator, and importantly that separator temperature is high enough to avoid wax deposition before separator inlet to maintain fuel cleaning efficiency.

When handling fuels with a lower viscosity, it becomes more important to consider the PP to ensure that the fuel is heated above the PP in the storage tanks to maintain pumpability of the fuel to the settling tanks where temperatures are elevated to above typical WAT in preparation for the fuel cleaning in the separator. It should be ensured however, that the low viscosity fuels are not overheated making the fuel viscosity too low, i.e. too thin, for suitable injection into the engine.

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[3] For fuels that are transparent in layers of minimum 40 mm in thickness, the cloud point can be measured by test methods such as ISO 3015 or ASTM D2500. These methods are therefore not applicable to the dark coloured fuel oils. Alternative techniques [IP 389, ASTM D8420] can determine the fuel oil's wax appearance temperature (WAT), which gives an estimate of the cloud point, and wax disappearance temperature (WDT).
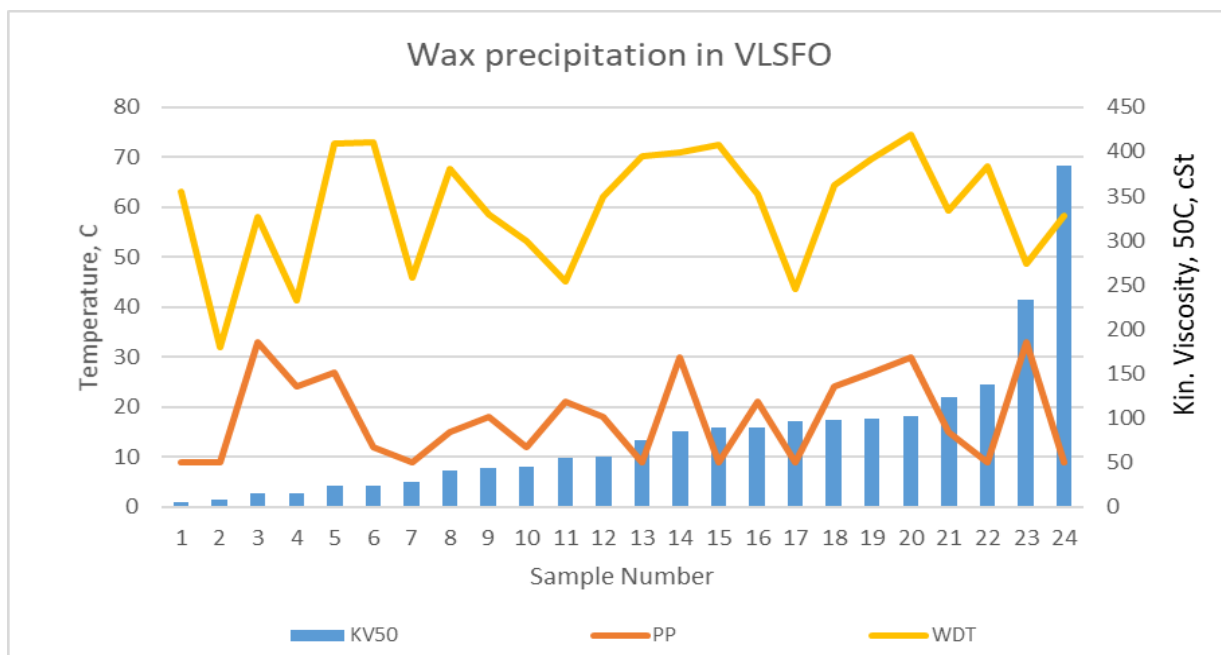
Figure 3 -   PP, WDT in VLSFO samples – courtesy of PAC (Phase Technology) – measurement based on ASTM D5773/IP 446.

For further information on fuel properties for: Pour point (Section 8.5) and for separator operations see Section 16.4. More information can be found in the CIMAC guideline for managing cold flow properties of marine fuels [6].[4]

7.4. Used lubricating oil (ULO)

The addition in fuel oils of certain unrefined ULO in certain concentrations can adversely affect centrifuge performance, as the additives in the lube oil are designed to hold onto water and particles to protect components against damage such as corrosion and wear.

Indications of ULO in its processed/refined form can be found in some fuel supplies; concerns have been raised however, regarding unprocessed ULO at higher percentages being put in marine residual fuels, which may impact on the separator efficiency due to possible retention of abrasives by still active lube oil additives. This resulted in limits being set in ISO 8217, introduced in the 2005 edition, however since then the industry has not received further report of this issue being experienced.

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[4] CIMAC WG 7 Fuels https://www.cimac.com/working-groups/wg7-fuels/index.html

8. Statistical review of post 2020 fuel properties

The following graphs[5] reflect the consensus across the contributing laboratories in the WG7 as to the distribution of the core properties of RM fuels over the period January 2020 – April 2021[6], these typically may vary slightly from year to year but demonstrate the trend at the time of taking.
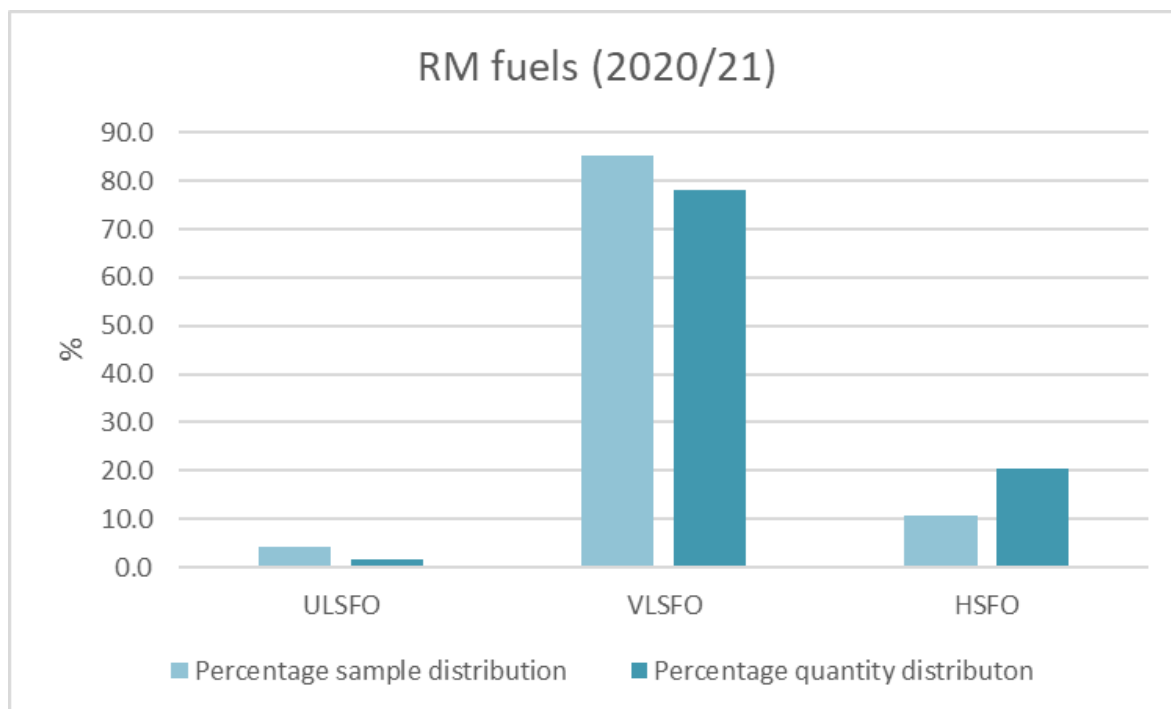

Figure 4 – Typical distribution by the three sulphur categories based on global spread of fuel manifold drip samples tested for RM (residual) type fuels. [11]

The data covers RM grades only, as DM grades generally do not constitute much risk for the higher presence of water and abrasives. ULSFO however, whilst for the most part a DM product, can also be a supplied under the RM category, and therefore can also contain higher levels of water and *abrasives such* as catalytic fines. The catalytic fines are found in slurry oil from cracker bottoms, which can contain up to 400 − 600 ppm catalytic fines and is typically used as a blend stock. Figure 4 indicates the distribution of fuel samples tested and show that most ships are using VLSFO, and thereby the major shift from HSFO to VLSFO in 2020. Comparison of the percentage sample distribution and the percentage quantity distribution, indicates the large liner ships using EGCS (Exhaust Gas Cleaning System) taking high quantities of HSFO.

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[5] Fuel analysis data used in these charts and tables have been sourced from laboratory analysis data, details of the laboratories who have contributed are listed in the acknowledgments. [11].

[6] Further information and details on 2020 fuel oil quality in comparison to 2018 can be found in the document IMO/MEPC 76/5.

8.1. Sulfur

Figure 5 shows the average sulfur content of 2020 fuels as reported by the IMO monitoring programme. Note that HSFO can only be used in combination with an EGCS, after which the sulfur oxides must be able to meet either the 0.50% or the 0.10% sulfur oxides emission equivalent limit whilst operating outside and inside respectively the Emission Control Areas.
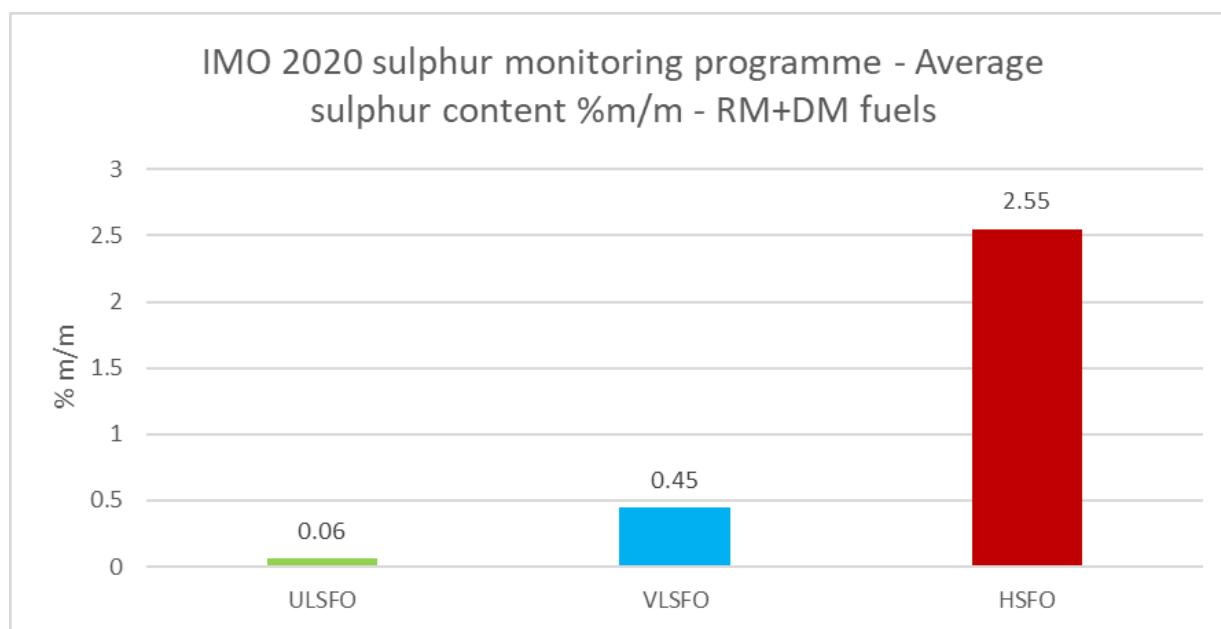

Figure 5 - Average sulfur content as reported by IMO annual sulfur monitoring programme for 2020 [7] for all fuel types.

8.2. Density

Table 1 and Figure 6 below show the density of RM fuels analysed. Note the significant difference between the different fuel types. The table is indicating the min. and max. values for the fuel grades and an average of the sample distribution. The density of RM samples plays a significant role in how well the fuels are cleaned and impurities separated.

Table 1- Density distribution. Max./min./average of measured data. RM type only. [8]

Density, kg/m³ (RM)			
	Average	Min	Max[7]
HSFO	981.4	857.4	1018.4
VLSFO	938.3	834.5	1021.9
ULSFO	893.5	828.3	968.0

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[7] The maximum specified density in ISO 8217:2024 is either 991.0 (RF or RMG) or 1010.0 (RMK) kg/m³
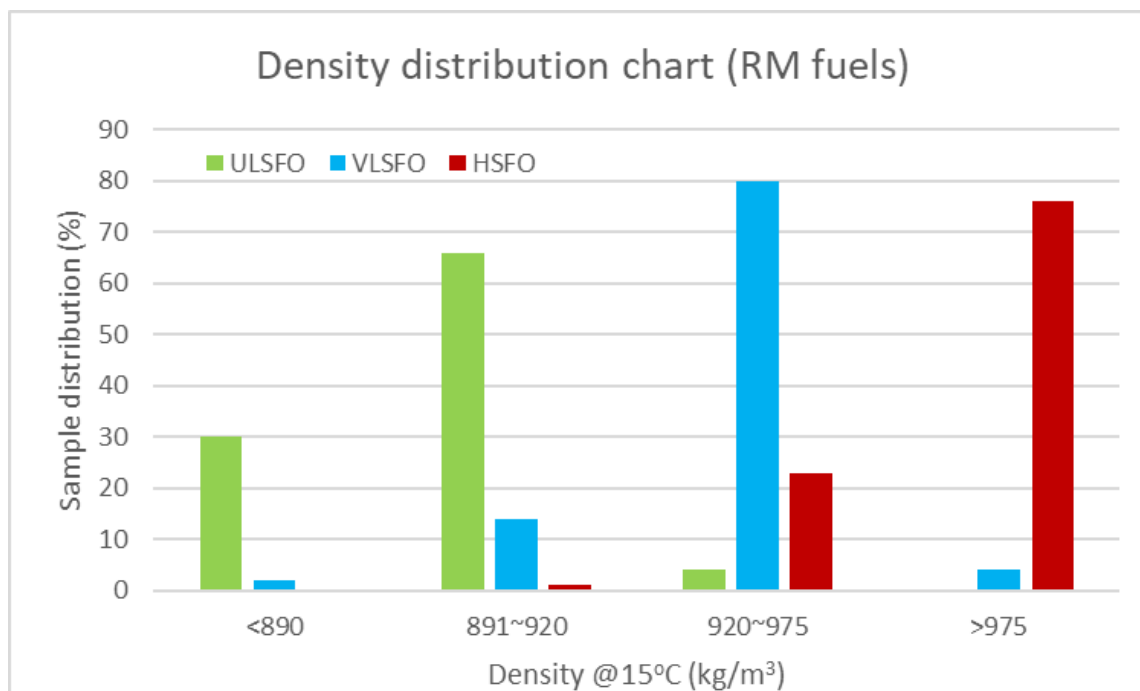
Figure 6 - Typical density distribution of HSFO, VLSFO and ULSFO, RM type only. [11]

Data illustrates that the majority of VLSFO fuels have noticeably lower density than HSFO.

8.3. Viscosity

The diversity of viscosity between the pre 2020 HSFO and post 2020 VLSFO, illustrated in Table 2 and Figure 7 shows a marked reduction in the average viscosity. With HSFO lying between 180 cSt to 380 cSt and VLSFO, the bulk of fuels today, lying between 40 cSt to 180 cSt.

The significance of this lies in both the design of the fuel system and attention to fuel management. The fuel system must have the capacity to manage the broader range of temperature control required at different points in the system, and between different fuels loaded and stored in different storage tanks.

Table 2 - Viscosity distribution. Max./min./average of measured data. RM type only. [8]

Viscosity, cSt (RM)			
	Average	Min	Max [8]
HSFO	302.54	9.00	742.20
VLSFO	128.00	2.00	678.40
ULSFO	28.30	1.60	91.00

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[8] the maximum specified viscosity in ISO 8217:2024 is 700,0 cSt (RMK 700H). For evaluation of recipient test results see CIMAC Guidelines 2024 The interpretation of Marine Fuel Analysis Test Results
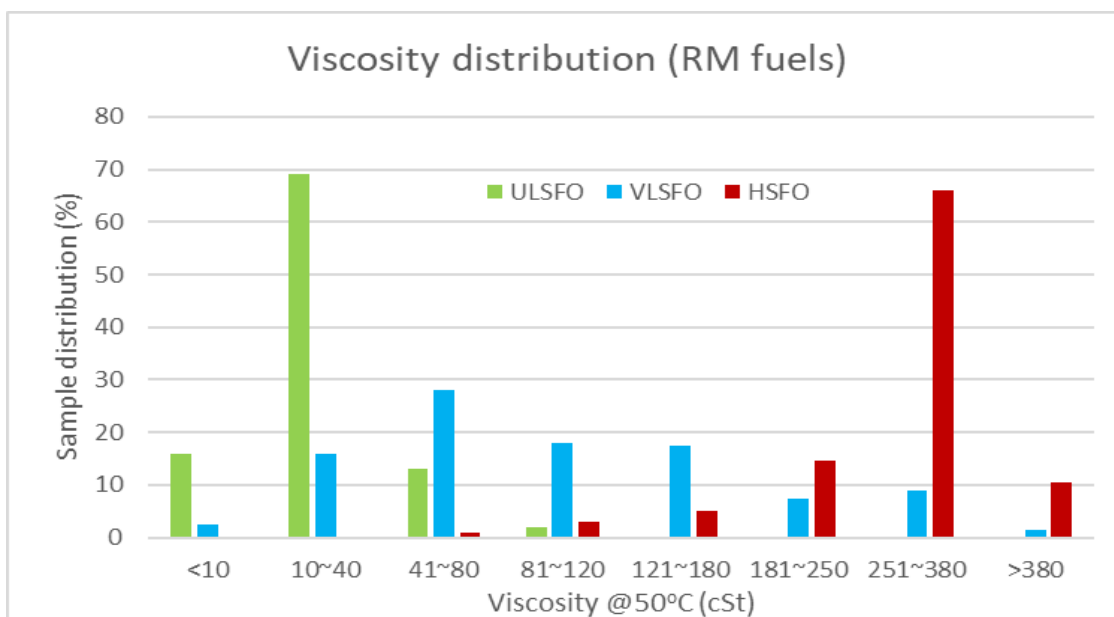
Figure 7 - Typical Viscosity distribution of HSFO, VLSFO and ULSFO, RM type only. [11]

8.4. Catalytic fines

In Figure 8 and Table 3, we see the typical distribution of the average catalytic fines content across the three sulphur fuel grades, with HSFO still showing slightly higher catalytic fines content than VLSFO overall. The data clearly indicates that fuel cleaning is still a very important process to remove these abrasives.
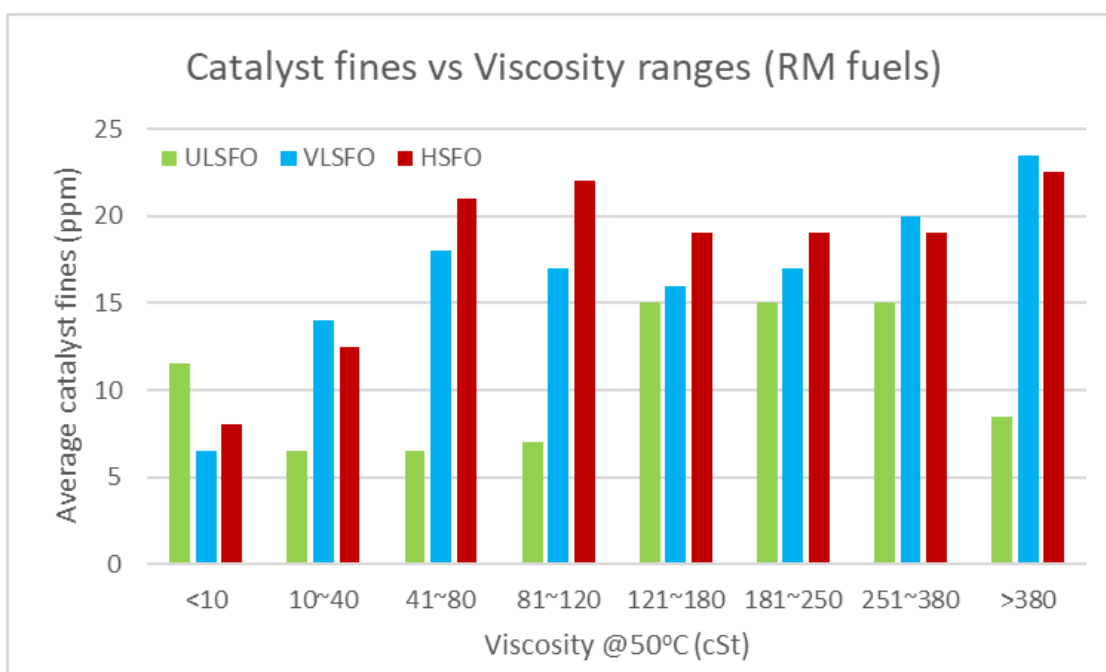

Figure 8 - Typical average catalytic fines content in relation to viscosity content in HSFO, VLSFO and ULSFO (RM type only) as fuelled. [11]

Table 3 - Distribution of catalytic fines content of HSFO, VLSFO and ULSFO, RM type only. [8].

Catalytic fines, ppm (RM)				
	Average	Median	Min	Max
HSFO	19[9]	15	<1	346 [10]
VLSFO	18	14	<1	311[11]
ULSFO	7	4	<1	49

Figure 9 below shows the distribution range of catalytic fines. The amount of catalytic fines is almost evenly spread in the range between 7-50 ppm Al+Si, and not many catalytic fines are found above 50 ppm.
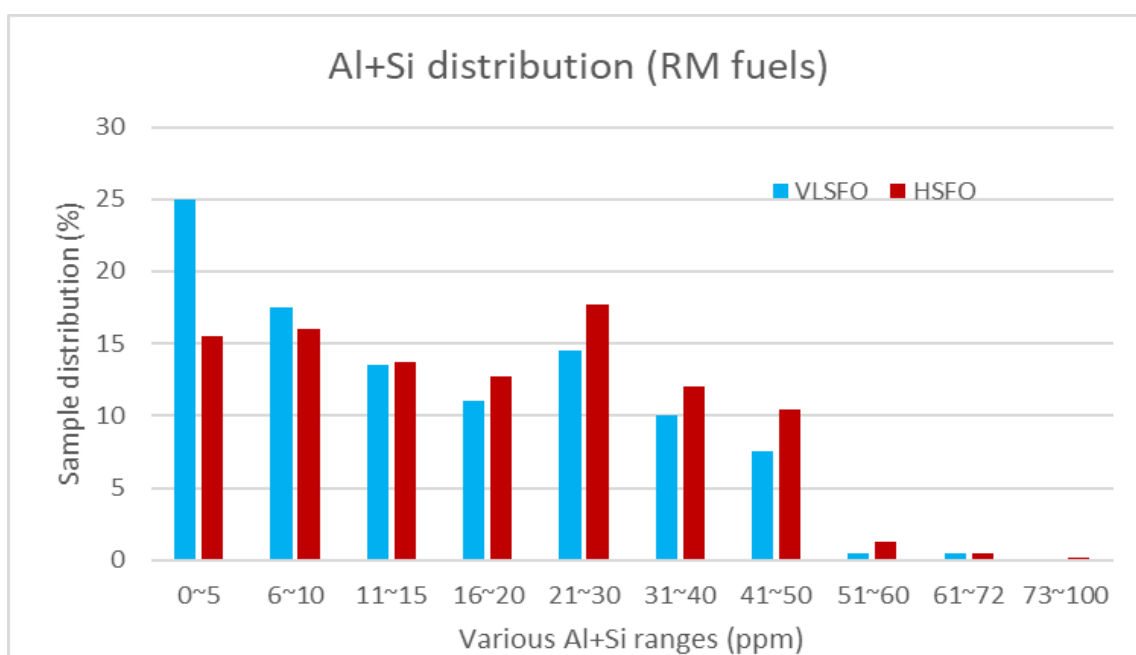
Figure 9 - Distribution of catalytic fines (Al+Si) in VLSFO and HSFO as bunkered (RM grades only). [11].

Table 4 show the number of fuels being on and off spec. for catalytic fines, when comparing VLFSO from 2020 and HSFO from 2018. The results show that the number of off spec. VLSFO's for catalytic fines are reduced compared to HSFO from 2018.

Table 4 - On spec/off spec Catalytic fines for VLSFO in comparison to pre-IMO 2020 legislation [9]

Al+Si, mg/kg	2020 RM VLSFO		2018 RM HSFO	
	≤ 60	> 60	≤ 60	> 60
% of samples	99.8	0.2	98.5	1.5

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9 IMO Document MEPC76/5 average Al+Si for VLSFO – reported as 18.2 ppm and for HSFO – reported as 22.3 ppm

10 Sample is off spec. The maximum specified catalytic fines content in ISO 8217:2024 is dependent on the fuel oil grade

11 Sample is off spec. The maximum specified catalytic fines content in ISO 8217:2024 is dependent on the fuel oil grade
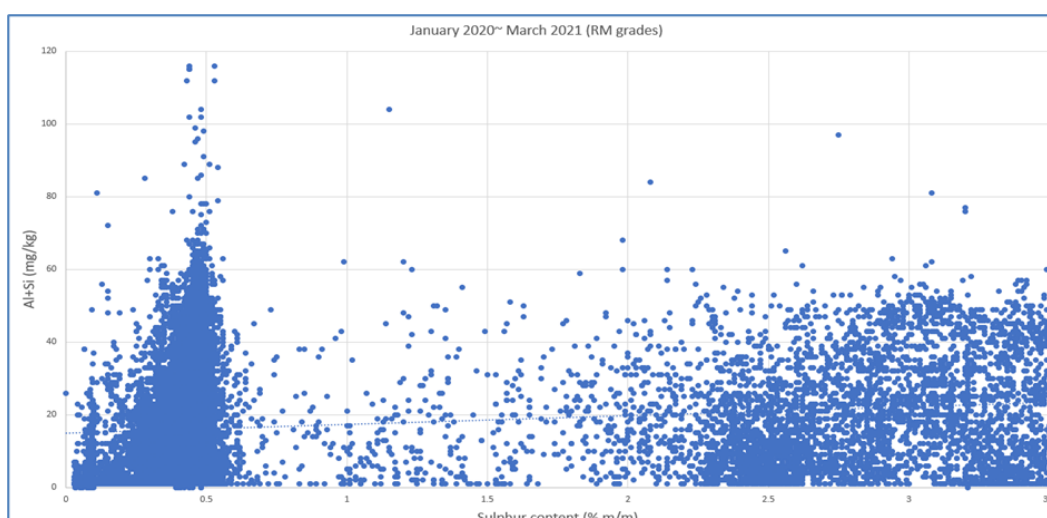
Figure 10 - Catalytic fines content in relation to sulfur content in fuel as bunkered. [11]

Figure 10 compares sulfur content against catalytic fines content. This demonstrates the persistent presence of catalytic fines in VLSFO, comparable with HSFO and equally catalytic fines are found in the RM ULSFO.

8.5. Pour Point

Pour point is an important cold flow fuel parameter requiring specific attention to each fuel as fuelled to ensure the fuel in the storage tank does not reach a condition by which it can no longer flow; essentially becoming solid in the tank and pipelines. Table 5 and Figure 11 show the distribution of average pour point for different fuel types. The data shows that the pour point is generally found to be higher for the VLSFO's and RM-ULSFO's than for HSFO.

Fuel temperature should be maintained at least 10 °C above the given pour point to avoid the fuel becoming unpumpable. As can be seen from Table 5 below, the maximum pour point for a residual-based fuel can be as much as 42 °C usually due to a specific geographical location or refinery processes, in which case the fuel in the tank will need to be heated to at least 52 °C to avoid solidification and ensure it remains pumpable. See also Section 7.3 for information on wax in fuels.

Noting that ISO 8217 provides limits of maximum of 30 °C for some residual grades and up to 6 °C for some distillate grades; pour point temperatures of fuels exceeding these limits remain acceptable providing the ship has the capacity to maintain such fuels at the recommended temperatures to avoid solidification.

Table 5 - Typical pour point data for HSFO, VLSFO, ULSFO (RM type only). [8]

Pour point, °C			
	Average[12]	Min	Max
HSFO	9	<6	33
VLSFO	16	<6	42
ULSFO	18	<6	36

---

12 Pour point results reported as < 6 °C (testing terminated at 6 °C) are not included in the average value

Very low pour points are generally reported as less than a given figure such as <6 °C as the actual pour point in these cases is not specifically needed. This, in practice, is to avoid unnecessary laboratory time and cost to find the exact figure which has little operational significance, as such temperatures already being for the most part within the normal operational temperature range.
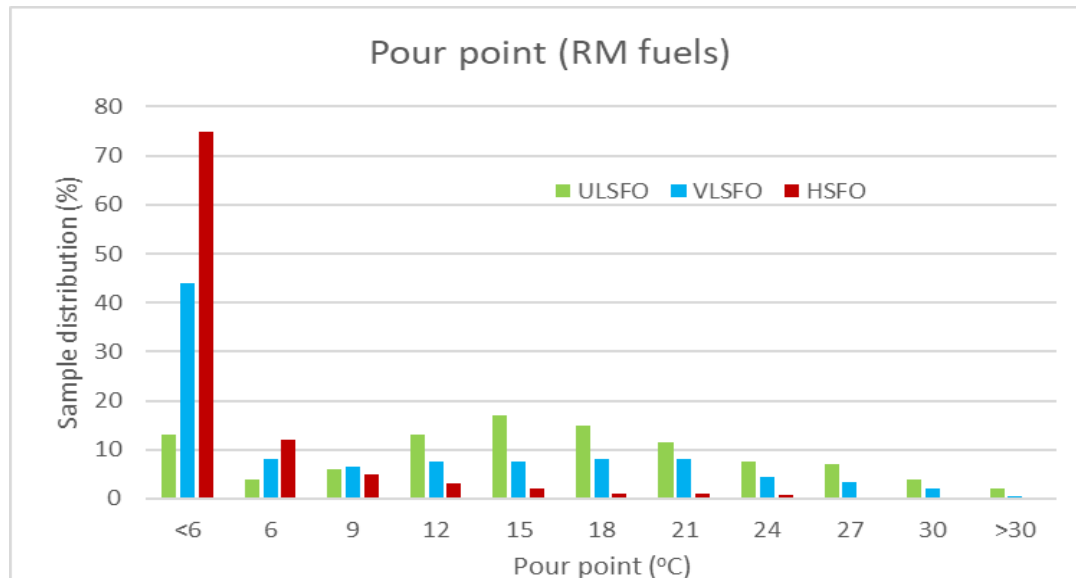

Figure 11 - Pour Point Distribution for HSFO, VLSFO, ULSFO (RM only). [11].

8.6. Sediment (fuel stability - sludge)

The measurement of the sediment content is a way to assess the thermal and mechanical stability of a marine residual fuel. ISO 8217 applies both ageing test methods, the chemical (TSA) and the thermal ageing (TSP), but in case of dispute, thermal ageing according to ISO 10307-2A is the reference test method.

These sediment methods are defined [4] [5] as follows:
- TSP is the total sediment after ageing a sample of residual fuel for 24h at 100°C under prescribed conditions. I.e. the amount of sediment after stressing the fuel through heating. This method is expected to show the maximum amount of sediment that is likely to form when applying thermal stress.
- TSA is the total sediment after dilution of a sample of residual fuel with a paraffinic solvent (hexadecane) under carefully controlled conditions, followed by storage for 1h at 100°C. i.e. the amount of sediment after stressing the fuel chemically and storage at high temperature. This method is expected to show the maximum amount of sediment that is likely to form when applying a combination of chemical and thermal stress.

In other words, TSP is representative of the resistance of the fuel against thermal stress whereas TSA represents the compatibility when comingling with a paraffinic fuel under limited thermal stress.

Table 6 and Table 7 show the distribution of sediment content of RM fuels according to thermal ageing (Total Sediment potential, TSP, ISO 10307-2A) and chemical ageing (Total Sediment Accelerated, TSA, ISO 10307-2B).

The comparison of the tables highlights that:
- HSFO are more sensitive to chemical ageing (% of HSFO with TSA > 0.10 much higher than TSP > 0.10) whereas
- VLSFO are sensitive to both ageing methods (reduced difference between % of VLSFO with TSA > 0.10 and TSP > 0.10).

Table 6 - Distribution of RM type fuels according to ISO 10307-2, procedure B (chemical ageing (TSA)). [8]

TSA (RM)	Sample distribution		
	≤ 0.05	>0.05 & ≤0.10	>0.10
HSFO	88.4	7.0	4.6
VLSFO	92.4	5.0	2.6
ULSFO	96.2	2.7	1.1

Table 7 - Distribution of RM type fuels according to ISO 10307-2, procedure A (chemical ageing (TSP)). [8]

TSP (RM)	Sample distribution		
	≤ 0.05	>0.05 & ≤0.10	>0.10
HSFO	92.2%	6.77%	1.1%
VLSFO	95.8%	3.2%	1.0%
ULSFO	98.8	1.5%	0.5%

Figure 12 shows the distribution of TSP versus TSA for HSFO and VLSFO. It clearly emphasises that for HSFO TSA is higher than TSP but for VLSFO, the trendline is very close to the parity line. This indicates that either TSP or TSA can be elevated with VLSFO.

Operationally this shows that for VLSFO or ULSFO RM type fuels a TSA of <0.10% m/m may result in a TSP >0.10% m/m giving a false negative to be in specification for the sediment being <0.10% m/m. Therefore, it is guided that for VLSFO both TSA and TSP should be measured.
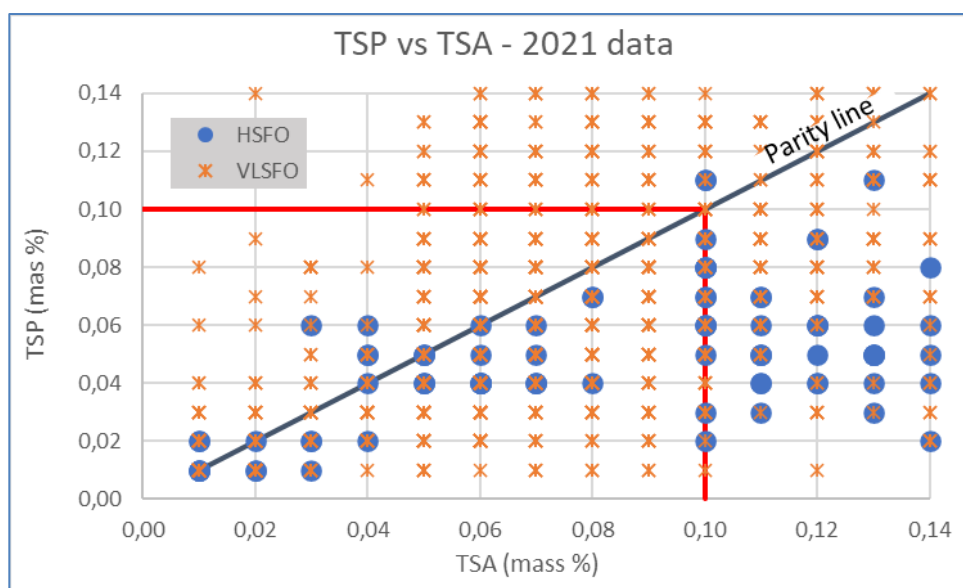
Figure 12 - TSP vs TSA distribution for HFO and VLSFO. [11]

8.7. Fuels properties summary section

This chapter has highlighted the change in terms of fuel quality after the 1st of January 2020 when almost 80% of the HSFO market switched to VLSFO. Some fuel characteristics or the testing thereof such as viscosity, density, total sediment testing, and pour point were highly impacted as they are directly linked to the need of a low sulfur blend component being required to adjust the sulfur content in the final fuel. On average, viscosity and density have decreased, and pour point has increased, but such parameters may vary considerably from fuel to fuel, supplier to supplier, port to port and geographical region to geographical region. Other characteristics such as amount of catalyst fines remained almost the same compared to pre-2020 fuels.

Any significant changes on fuel characteristics, in particular the decrease of viscosity, shall be considered in the fuel management system for loading and storage to handling and use.

Part 2 - Fuel system design

This section describes the updates of the fuel system design and builds on the CIMAC Rec. 25 [1].

9. General arrangement and tank design

The fuel system starts at the point of bunkering at the ship's side manifold and into the ship's storage tanks distributed throughout the ship either in double bottoms and or deep tanks.

For each storage tank, ensure, by design, that there will be sufficient heating capacity for the temperature of the fuel to be maintained at least 10 °C above this pour point. This is to avoid the fuel from becoming unpumpable. At the same time, avoid overheating excessively which may lead to thermal stability issues and reduce storage time.

On demand, fuel is pumped up to the settling tanks, directly from the storage tanks, where gross impurities and water can have time to gravitate and settle to the tank bottom aided by elevated temperatures. The fuel is then passed from the settling tank to the service tank through the separator plant, where the main fuel cleaning on board is performed to the point that the fuel is ready for use. As a last defence however, hot fine filters are placed in the fuel conditioning booster circuit to refine the cleaning process by further removing particles and by informing if the fuel cleaning process is not sufficient (see also CIMAC guideline for fuel filters [10]).

A ships fuel supply system consists of three sections:
- Storage tanks: Double bottoms or deep tanks.
- Fuel cleaning/treatment system: Settling tank to separator plant to service tank
- Fuel conditioning unit – from service tank to machinery plant including a final set of protective filters of recommended 10 μm.
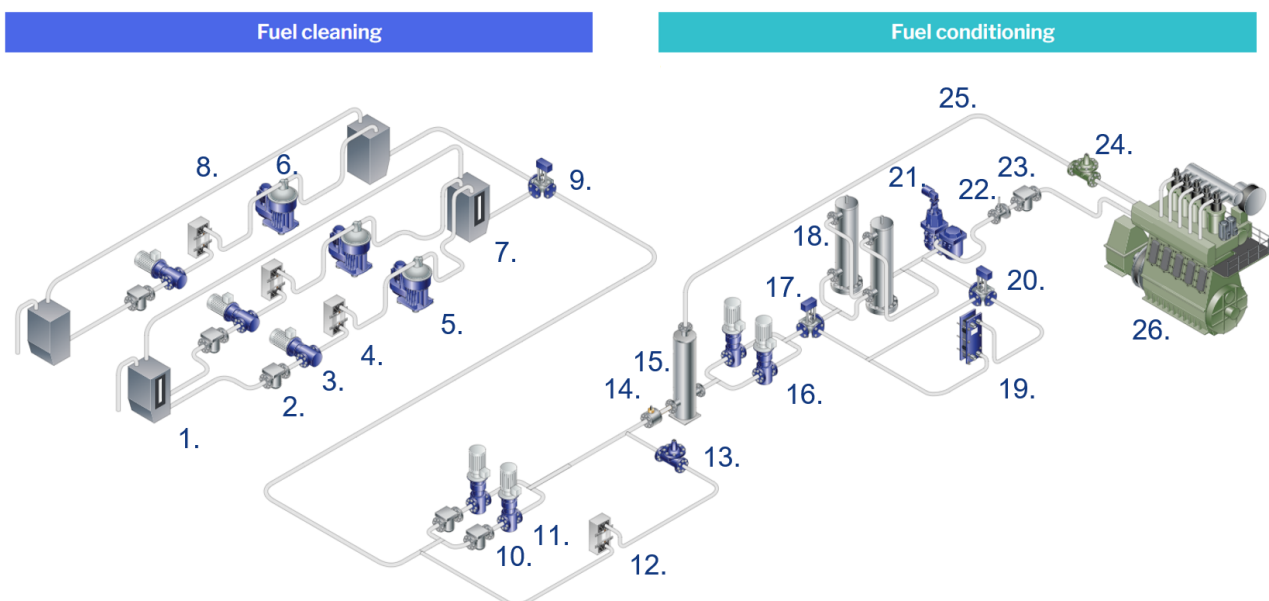

Figure 13 - Schematic overview of an adaptive dual fuel treatment system for VLSFO and ULSFO with separation, automatic flow control, fuel change-over, fuel conditioning and 10 μm filtration.

(1) Settling tank, (2) Strainers, (3) Feed pumps, (4) Heaters, (5) Fuel Oil Separators, (6) Distillate Separator, (7) Service tanks, (8) Recirculation pipe, (9) Changeover valve, (10) Strainers, (11) Supply pumps, (12) SPV Cooler, (13) Supply pressure valve, (14) Flow meter, (15) Mixing Tank, (16) Circulating pumps, (17) Heater bypass valve, (18) Fuel oil heaters, (19) Cooler, (20) Temperature regulating valve, (21) Fuel Oil self-cleaning filter, (22) Viscosity transmitter, (23) Indicator filter, (24) Pressure control valve, (25) Return pipe, (26) Engine

The schematic arrangement in Figure 13 shows a typical fuel cleaning and conditioning arrangement starting from the settling tank, of which there should be at least two, one for the residual fuel oils and the other for distillate fuel oils.

It is recommended that ships should be built to have greater flexibility to cope with one to four different sulfur fuel grades. This may include two settling tanks and two service tanks for the same residual grade to accommodate variation in fuel composition and thereby aid the cleaning process by segregation of different fuel types. In general, engine makers recommend at best a 10 µm filter prior to the fuel entering the engine fuel rail for best engine protection, although 50 µm are still being used today. Engine manufacturers manuals and service letters provide guidance as to their preferences for specific machinery plant.[13]

9.1. Main fuel storage tanks

Since the introduction of the VLSFO requirements in 2020, the industry has experienced wide ranging compositions including a higher degree of paraffinic fuels and more recently the trend is towards blending a percentage of biofuel in these fuels. Fuels that are characteristically diverse from one fuel to another are generally more susceptible to be incompatible when mixed/comingled.

It is therefore recommended that ships are designed with enough separate main fuel tanks to allow for newly bunkered fuels to be kept segregated from those already on board. This will enable greater fuel management flexibility and avoidance of the risk of de-stabilising fuels that are otherwise stable.

Heating coils, with sufficient capacity, should be fitted to ensure that fuels remain pumpable not only for their viscosity but also to be retained at least 10 °C above the pour point. To avoid fuel solidifying in transfer and fuel system conditioning pipes when no fuel transfer is in progress, heat tracing lines on piping and filters should also be fitted. Heating should also be considered not just for the residual fuel tanks but also for the distillate fuel tanks where some form of heating capability is advisable now with more paraffinic fuels with higher cold flow properties of cloud and cold filter plugging points which might require temperatures above 20 °C to be maintained in low temperature ambient operating conditions.

Fuel tank design safety requirements are covered under Classification design rules and should be adhered to. These include tank filling and suction piping arrangements; vent pipe fire traps and anti-static build up earthing requirements in IACS UI 151: [11].

Transfer pumps should be of positive displacement to minimise emulsification allowing for gross water separation in the settling tank and efficient water removal through the separators.

Consideration should also be given to the pumping capacity required for when in the rare likelihood that at a de-fuelling operation is required, that the transfer system has the capacity to discharge in a timely manner. This would normally mean a higher rate than the normal transfer rate on board is designed for.

9.2. Settling and service tanks

Best practice design for settling and service tanks is that they should have sloped bottoms to concentrate the sediment, extraneous dirt, and water towards the de-sludge cock to facilitate effective drainage. Also, inlet to overflow pipes for service tanks should extend to the bottom of the tank enabling the cleaning of the fuel in the bottom of the tank. See figure 14. Reference is also given in IACS UI 151: [11].

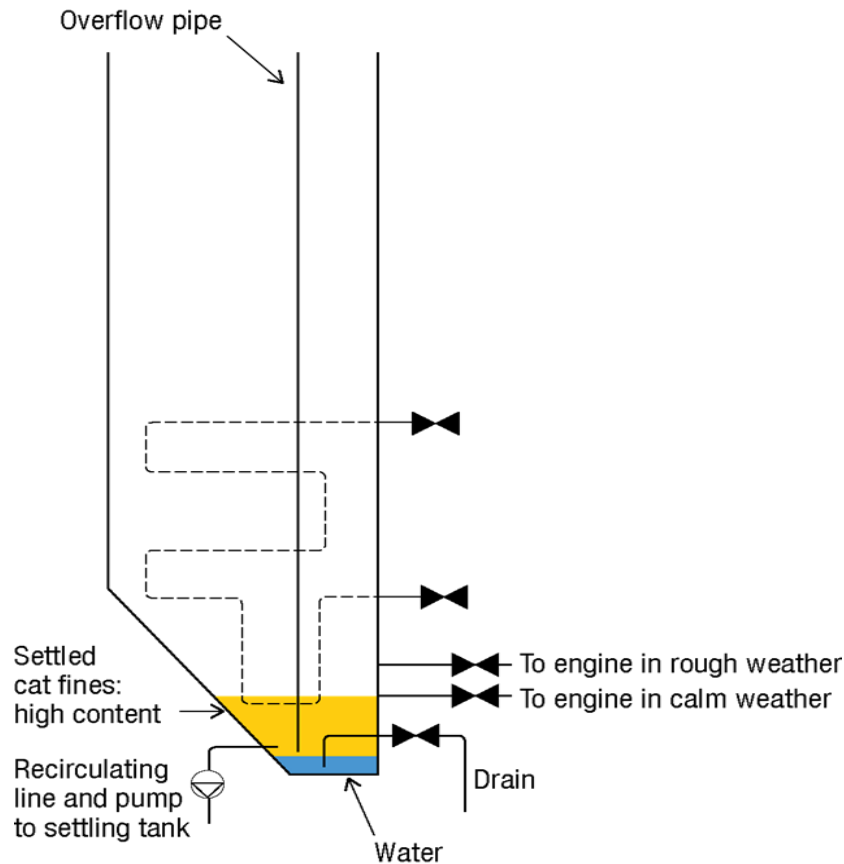13 See e.g. MAN ES service letter [3] or WinGD Fuel Guideline DTAA001522

Figure 14 - Schematic of fuel service tank – note the overflow to the bottom of the tank.

9.3. Tank design recommendations

- Settling and Service tanks with sloped bottom to facilitate routine de-sludging.
- Two settling and two service tanks for RM fuels adds increased flexibility to maintain fuel segregation and reduce change over times between fuel types.
- Design of fuel storage tanks, double bottom, or deep tanks, to facilitate tank cleaning, recirculating and transfer between tanks.
- Increased de-bunkering pump capacity should be considered in the event an unusable and untreatable fuel remaining on board.
- If equipment for tank cleaning is not installed, suitable procedures must be in place to avoid feeding sludge and fuel contaminants to the engine
- The capacity to heat all fuel tanks, both RM and DM types should be considered to manage the tendency for fuels to have higher cold flow temperature properties.

10. Centrifugal separators

This section outlines the theory for centrifugal separation and describes the method for separator sizing in the design of the fuel cleaning plant on board.

The focus here is on cleaning of residual fuel, but it is also customary practice to have separators installed on vessels using distillate fuels to remove water and abrasive particles. See also CIMAC recommendation No. 25 [1].

10.1. Theory

Separators are installed with the purpose of reducing the content of solids and water to a level that does not cause excessive wear or other related problems to the engine. Centrifugal separators have proven to be the most effective means of removing fuel contaminants, both water and solids, that are dangerous to engines.

Particles are removed from fuel oil in separators as well as in settling tanks based on the principle that particles have a greater density than the oil. In settling tanks, given enough time, most particles will settle to the bottom of the tank. However, if the particles are very small, there is invariably insufficient time for particles to settle in time due to the low settling rate.

The action of a separator increases the settling from 1g (9.8 m/s^2), as in gravitational settling in a tank, to many 1000 times this value. Catalytic fines and asphaltenic agglomerates are subject to the same principle when being separated in a disc stack separator as in a tank. The centrifugal force acts upon the particles, moving them to the periphery, whereas the flow of the oil brings the particles towards the centre of the bowl. If the flow reaches a rate that is exceeding the capacity of the separator, the catalytic fines particles will escape with the oil rather than being separated from it. In this case, the particles do not have time to settle. So the time the fuel has in the separator, known as "retention time", is critical.

The separation efficiency is strongly influenced by the size and density of the contaminants, and so the centrifugal separator has a natural bias towards removing the heaviest impurities. Thus, the centrifugal separators are the most important part of the treatment plant and good results very much depend on correct selection, installation, and operation.

10.2. Aspects and fuel properties affecting separation efficiency

Separation efficiency is dependent upon temperature (controlling both fuel viscosity and density), flow rate, particle size and proper separator care, maintenance and set up. A separator's ability to separate contamination from fuel is regulated by Stoke's Law (see equation below).

$$v_c = \frac{d^2(\rho_P - \rho_F)}{18\eta}\omega^2 r$$

Settling velocity (v_c) depends on: Particle size, d, Particle density, ρ_P, Fuel density, ρ_F, Dynamic viscosity of the fuel, η , Centrifugal acceleration, ω, Particle position on circular radius, r

Figure 15 illustrates the influence that the two fuel properties of viscosity and density, separator flow rate and particle sizes to be removed, have on the separator efficiency.
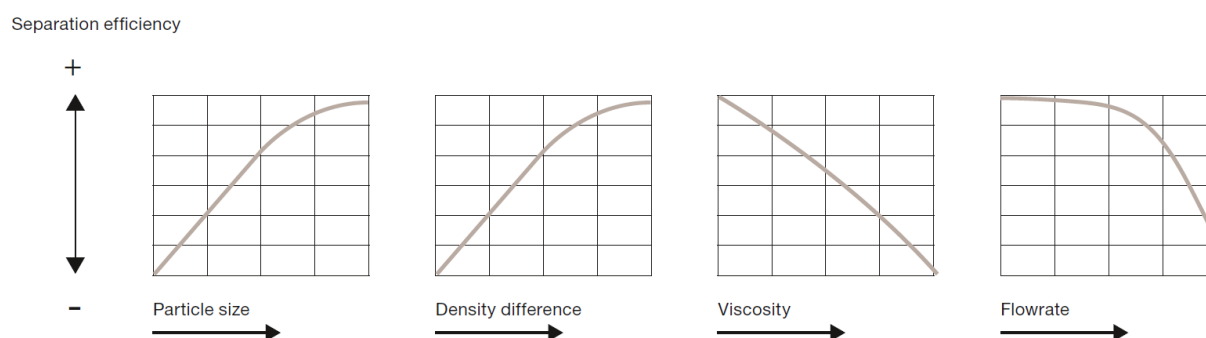
Separation efficiency

Figure 15 - Influencers on separator efficiency

10.2.1. Density and Viscosity

The greater the difference in density between the contaminating particles and the fuel oil, the higher the separation efficiency. The settling velocity increases inversely to viscosity, so the thinner the fuel, the higher the separation efficiency. Since both density and viscosity vary with temperature, separation temperature is the critical operating parameter, and the higher the temperature, the higher the separation efficiency. Recommendations for fuel oil separator temperature is given in Section 16.3.

VLSFO have in general lower viscosity and density than the traditional HSFO, but high fluctuation between high and low values for different fuels are seen in the field, and they are depending on the specific fuel blend in use. These large variations om viscosity can affect several aspects in the fuel treatment system, and care must therefore be given to understanding the characteristics of the fuel in use, amending the treatment settings to achieve the best possible fuel cleaning outcome.

Managing the fuel temperature is critical particularly for VLSFO treatment, due to a wider range of viscosity possibilities, to ensure safe operation and achieving both suitable fuel cleaning and maintaining the required viscosity at the fuel pump inlet.

Density

Density is a key property governing the ability of the centrifugal separators to remove contaminants and needs to be correctly handled to allow separation to occur. The density limit of ≤991 kg/m^3 is required to enable purifiers to work effectively in order to take into account the high operating temperatures of 98°C. For clarifiers, the limit of ≤1010kg/m^3 is required.

Density differences in fuel compounds and properties variations between fuels are critical to address for proper fuel cleaning. To safeguard efficient separation, it is of utmost importance to maintain the water-oil interface in a stable and correct position within the separator's disc stack. A high-density fuel will push the interface to the periphery of the bowl, whereas a low-density fuel will push the interface to the centre. The control of which is achieved either by automation or use of correct separator gravity discs.

Viscosity

Viscosity is a key to both fuel cleaning and for proper handling in the engine systems and for combustion. The separators' ability to remove water and solids from the fuel is dependent on the fuel's viscometrical properties, the thinner the fuel, the higher the fuel cleaning efficiency. Thus, fuel temperature needs to be properly controlled throughout the fuel treatment system.

Engine OEMs define the viscosity before engine inlet to support proper handling in the fuel pumps, and also to optimise flow and spray patterns for good atomisation in the combustion chamber to support good combustion. Therefore, care should be taken that both separator and engine inlet temperatures are followed.

10.3. Automatic and conventional separation systems

Separator systems can be either automatic or of gravity disc type. Automatic separator systems provide flexibility to handle a variety of viscosity and densities while continuously ensuring efficient fuel cleaning without any need for manual interference. Conventional separation systems (gravity disc type) require closer fuel monitoring, manual handling, and adequate actions to adjust the water-oil interface, commonly referred to as the water seal, in alignment with the actual fuel properties.

10.3.1. Automatic separator systems

Separators use advanced technology to remove water, catalytic fines and other impurities and particles in the fuel, where attention from crew is required to handle differences in density and viscosities. To enable efficient and optimal operation there are separator systems available in the market which include technology for monitoring and automatically adjusting settings according to fuel quality (see Figure 16 and Figure 17).
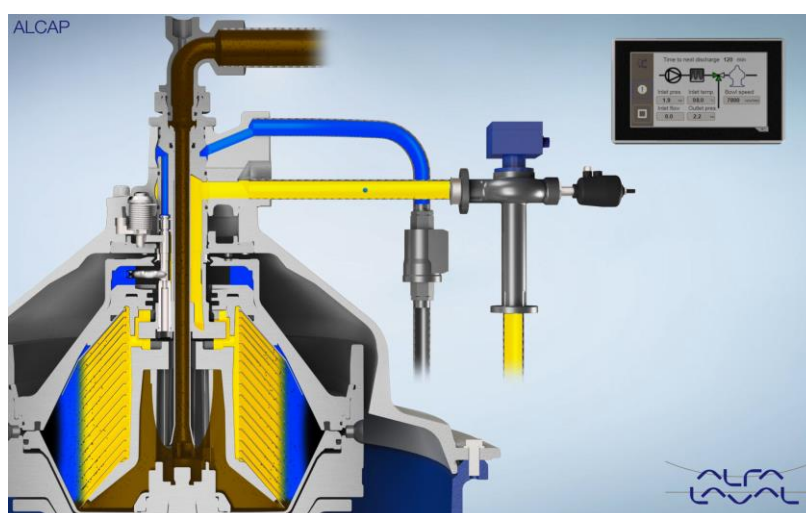
Figure 16 - Example of automated separator. ALCAP Separator (Alfa Laval).

By measuring capacitance on the clean oil outlet, an ALCAP separator can detect sludge build-up and water, and control discharge accordingly. The system automatically adjusts to different fuel viscosities and densities without the need to change gravity discs.
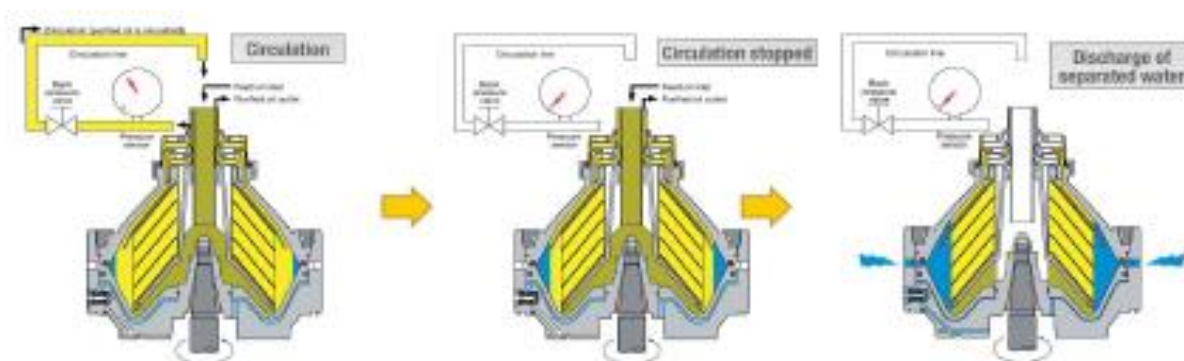
Figure 17 - Example for automated separator. An alternative technology for water detection system in centrifugal separators (MKK).

10.3.2. Conventional separator systems

Conventional separators use a manually fitted gravity disc for water removal and is adjusted based on properties of the fuel in use. Each gravity disc is sized according to the specific density of the fuel, to ensure the fuel/water seal interface is correctly positioned in the bowl. Thus, all fuel characteristics should be monitored as being constant and match the allowed density range of the selected gravity disc.

When a new fuel is put into use, the crew may have to change the gravity disc inside the separator to fit the water seal according to the new fuel density to ensure optimal fuel cleaning. If a lower density fuel is introduced without change of gravity disc, the water seal gets pushed inwards, severely compromising the fuel cleaning capabilities of the separator since the water seal blocks the disc stack where separation occur. A higher-density fuel will push the interface outwards, "breaking" the water seal resulting in the fuel is being discharged together with contaminants and waste components.

The risk of an improper chosen gravity disc is less with a higher density fuel, as the separator will then come into alarm and it will be more obvious that large amounts of fuel are passing into in the sludge tank – but rather with lower density fuel, as the separator appears to be working properly since it may not alarm, whereas it is actually just pumping the uncleaned fuel through the system without cleaning it.

10.3.3. Particle size

The settling velocity increases rapidly with particle size. Typically, this means the smaller the particles the more challenging the task of separation (see Figure 18). However, in a separator, centrifugal force enables the efficient separation of the particles of sizes detrimental to engine operation.
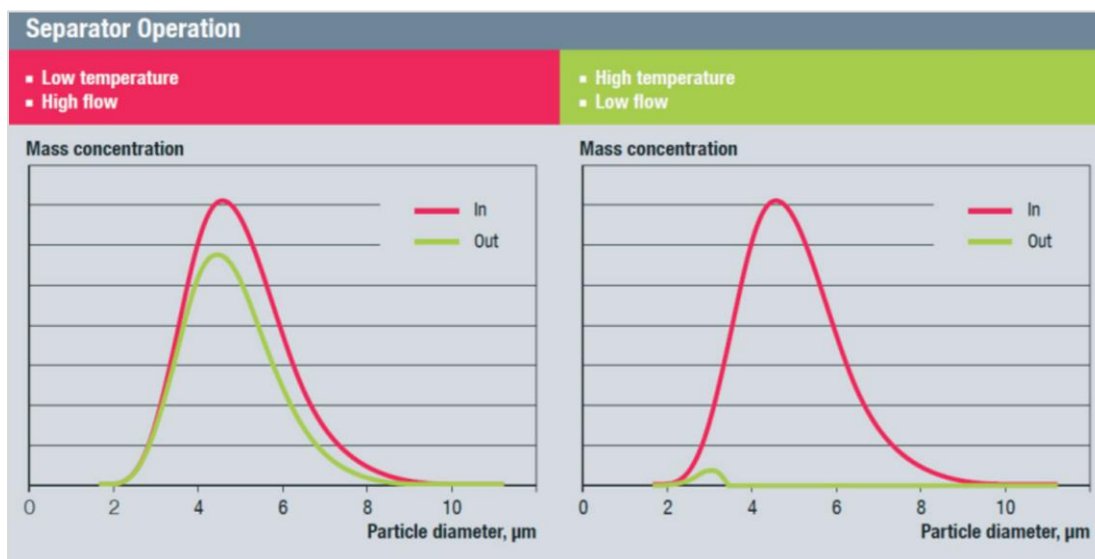
Figure 18 - Impact of fuel flow and temperature on particle size separation

10.3.4. Flow rate

The amount of retention time the fuel is in the separator makes a significant difference on the separation efficiency and the ultimate cleanliness of the fuel entering the service tank.

As the flow rate decreases, the fuel is allowed to spend more time in the separator bowl, which increases the separator's ability to remove smaller and lighter particles. Increasing fuel retention time in the separator bowl therefore improves the cleanliness of the fuel and thus reduces risk of wear and damage on fuel system and engine components. To have the best separation result, the flow through the separator should be as low as possible but must be controlled to meet the demand for fuel from the engines.

10.3.5. Automatic flow control systems

When slow steaming, adjusting to reduced flows can lead to a significantly improved separation performance.

Slow steaming refers to the practice of operating transoceanic cargo ships, especially container ships, significantly below their maximum speed. Normally, a fuel oil separator has a layout for 100% engine fuel consumption plus constant values for different margins. However, ships today rarely operate their engines at 100% load which implies that the amount of fuel being processed through the separator is greater than the fuel required from the service tank to the engine. This results in a significant amount of fuel recirculation. See also Section 16.3 guidance for temperature management.

With an automatic flow control system, the fuel feed rate to the separators can be matched to the actual engine load. The actual fuel consumption of the engine is measured by a flow meter, which is mounted on the fuel conditioning system. This value together with information from the tank level meter and three-way valve switch is processed in a control unit. When the feed rate to the separators is reduced, a variable frequency drive (VFD) controls the feed pump and only the fuel required by the engine plus 10% recirculation, a safety factor, is processed into the separators control unit. By that, separation becomes more efficient, and less energy is consumed by the feed pumps and separators.
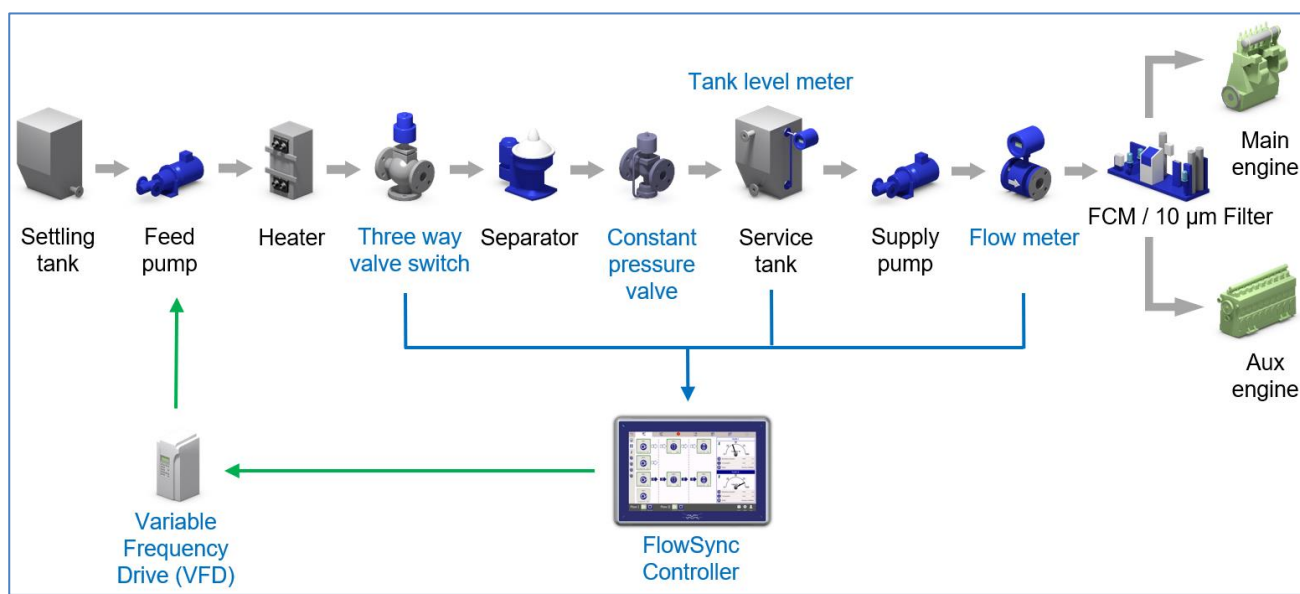
Figure 19 - Example of an adaptive fuel line with automatic flow control.

Figure 19 and Figure 20 are examples of using a system like Flow Sync to synchronize the oil feed to the separator with the actual engine load. Other solutions in other ways are available to control flow rate are available. By matching the flow of fuel to the engine's needs, it increases retention time in the separator bowl, giving the separators the best possible conditions for separation of solids, catalytic fines, and water. The result is lower engine wear, maintenance costs and energy savings from reducing the power required to operate the separators.

The separators' efficiency increases significantly because the fuel remains in the separator bowl for a longer period, enabling particles with a lower settling velocity to be removed from the oil. Therefore, there is a great potential to increase separation efficiency by applying automatic flow control in response to the actual fuel consumption (Figure 19, Figure 20).
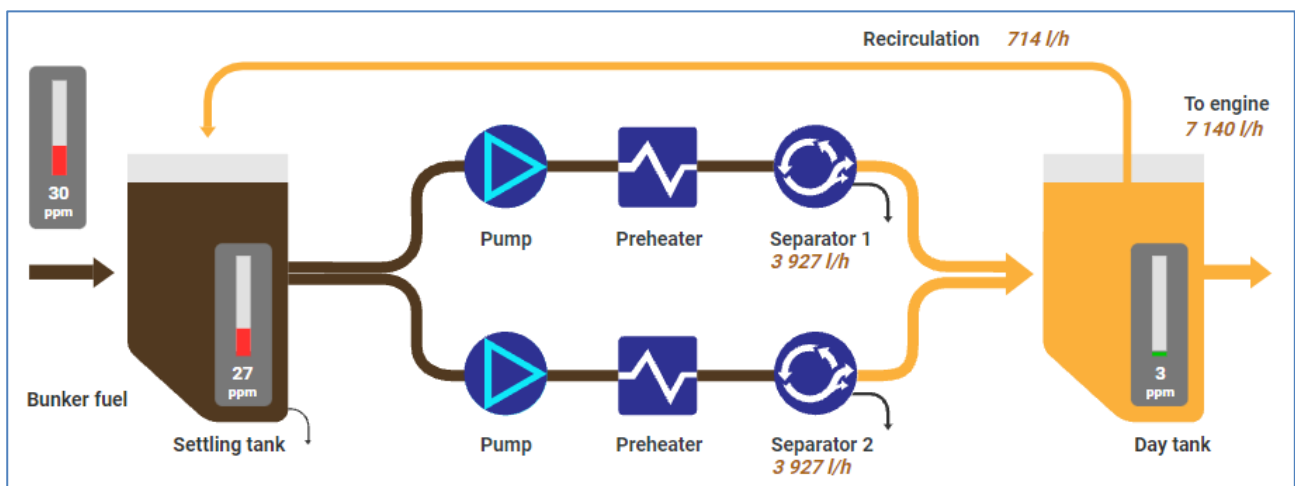
Figure 20 - Separators running in parallel mode with automatic flow control system. This setup can reduce the catalytic fines content from storage tank: 30 ppm Al+Si to 3 ppm Al+Si in service tank.

11. Separator sizing

Normally, a fuel separator has a design layout to meet the engine's fuel consumption at 100% load plus constant values for different margins. Sizing is based on MRC (Maximum Recommended Capacity) or CFR (Certified Flow Rate).

11.1. Maximum recommended capacity (MRC)

Suppliers of separators determine the maximum recommended capacity (MRC) for each unit according to mechanical design criteria and empirical knowledge. These factors are not commonly known and do not allow for equal comparisons of different separators.

11.2. Certified Flow Rate (CFR)

A separator's Certified Flow Rate (CFR) is defined by the industry standard CEN EN 17763:2022 [12] for a defined oil viscosity, density, and particle size. This test environment enables a measurement of the efficiency of the separation system in a standardised way. Spherical test particles of 5 µm in size are added to a fuel-like test oil. The CFR is defined as the flow rate when 85% of the particles are separated from the oil by the separator. Using CFR to specify a separator's capacity ensures the selection of the correct separator size for the performance required and thereby ensures safe engine operation.

The separation efficiency, η, is calculated as follows:

$$\eta = 100 \cdot (1 - C_{out}/C_{in})$$

where: η is separation efficiency in %; C_{out} is number of the test specific particles in cleaned test oil; C_{in} is number of the test specific particles in test oil before centrifuge.

The CFR standard for separators [12] ensures a common standard for benchmarking flow rate and allows ship designers to size the separator and obtain the correct cleaning efficiency.

Figure 21 shows, that generally CFR-rated separators (with a CFR-sizing factor of 0.23 L/kWh) have a higher separation efficiency than MRC-rated separators.
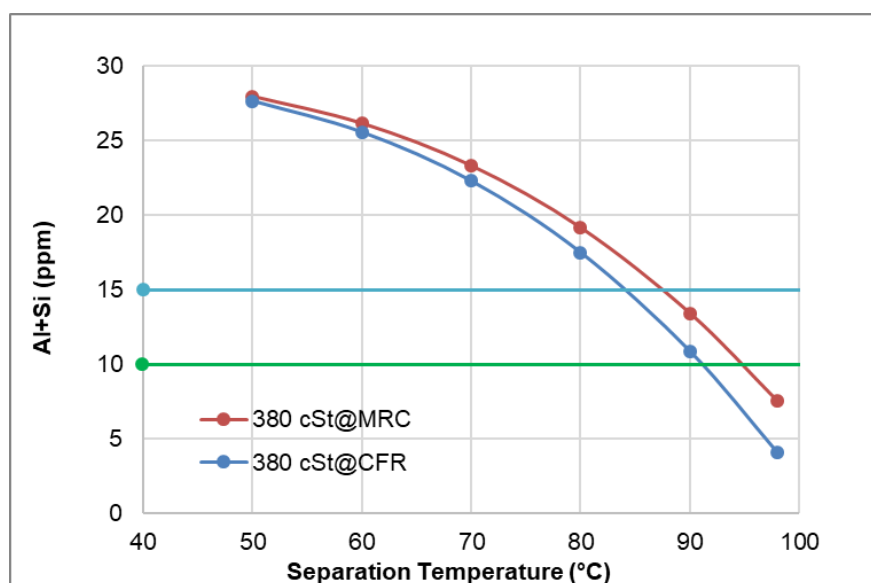
Figure 21 - Particle removal in MRC-rated separators vs. CFR-rated separators (according to sizing factor of 0.23 L/kWh).

11.3. Engine OEM recommendations for separator sizing

Engine OEM recommend that the size of the separator should be chosen according to the suppliers table valid for the highest selected viscosity fuel oil to be used, and in compliance with the CFR standard CEN EN 17763:2022. See Appendix I, Table 12 for specific engine requirements.

12.   Fuel conditioning system post cleaning

12.1. General layout

The main purpose of the fuel conditioning system is to ensure proper conditioning of the fuel oil fed from the daily service tank to the engines. The fuel conditioning system ensures that correct flow, pressure, and viscosity are matching the engine manufacturers specifications. These parameters are vital for the engine's performance.
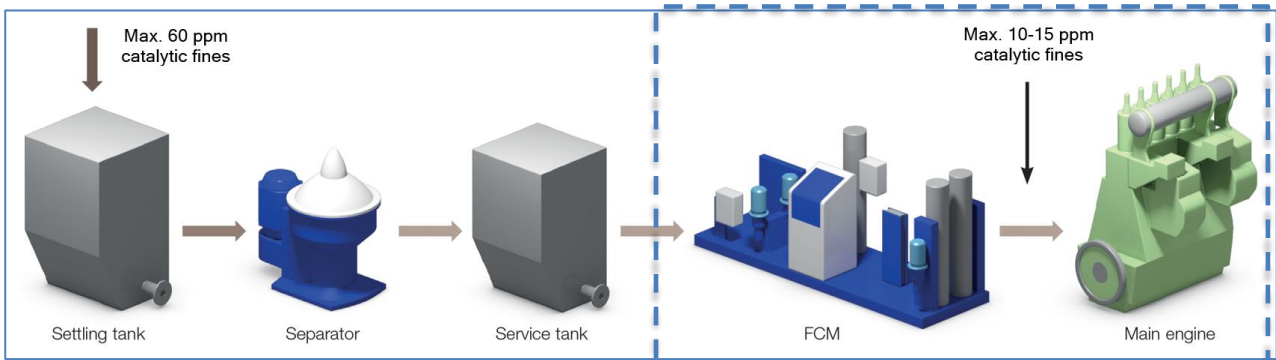
Figure 22 - A typical on-board fuel treatment plant (Adapted from Alfa Laval's Blue Book), FCM: Fuel Conditioning Module

The fuel conditioning system consists of the fuel supply system, which builds up the pressure to 8-10 bars, and the fuel circulating system, which heats or cools the fuel to the required viscosity / temperature at engine inlet. See Figure 23.
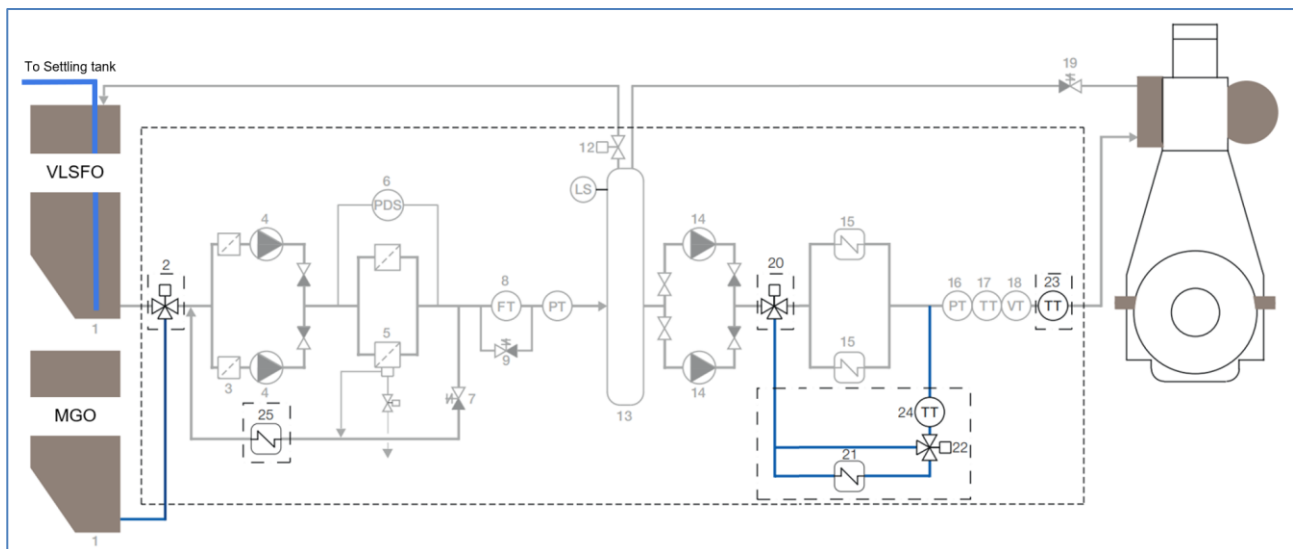
Figure 23 -Typical fuel conditioning system layout

1. VLSFO and MGO service tank 2. Three-way changeover valve (V1) 3. Pump strainers 4. Supply pump 5. Automatic backflushing filter 6. Filter pressure drop switch 7. Supply pressure control valve 8. Flow transmitter 9. Flow transmitter bypass 10. Pressure transmitter, supply pump 11. Level switch 12. Automatic deaeration valve 13. Mixing tube 14. Circulation pump 15. Heaters 16. Pressure transmitter, circ. pump 17. Temperature sensor 18. Viscosity sensor 19. Engine pressure control valve 20. Three-way changeover valve (V2) 21. ACS cooler 22. Three-way mixing valve (V3) 23. Temperature transmitter (TT2) 24. Temperature transmitter (TT3) 25. SPV Cooler 26. Three-way changeover valve (V4) 27. Heating media valve (V6) 28. Cooling media valve (V7)

Ships are very often operated on fuels with wide ranging properties, e.g. distillate and residual fuel and fuels having low and high viscosities respectively; this can pose operational and safety concerns when switching between them.

Low viscosity fuels are operated at much lower temperature than high viscosity fuels. So, when changing between fuels with such different properties, the fuel conditioning system must be designed to handle the temperature differences in a safe and controlled manner to ensure the fuel viscosity is maintained within the OEM recommended limits and the rate of change such that thermal shock and gasification is avoided in the engine fuel pumps (usually a rate of change of 2°C per minute).

The installation of coolers, as well with the normally fitted heaters, are recommended in both the high-pressure supply system and fuel circulating system, Figure 23.

The combination of both a heater and cooler will better manage between the higher temperature demand of the high viscosity fuels and the lower temperature demand for the low viscosity fuel, now more common for the ULSFO and VLSFO fuels.

12.2. Filters

Fuel separators are used to remove the substantial amount of dirt and catalytic fines present in the fuel as fuelled. However, as mentioned above, several factors may impact separation efficiency, and good results have been observed with the installation of a 10 µm (absolute) full-flow automatic back-flushing filter, positioned in the high-temperature fuel recirculation system, see Figure 19 and Figure 23. Alternatively, a fine filter can be positioned in the supply system.

Such a filter is by no means sufficient to remove all the catalytic fines from the fuel but can act as a final barrier and an indicator for insufficient operation of the separators. For example, an increased average pressure-drop across the filter indicates that the operation of the separators must be optimised.

In general, engine makers recommend at best a 10 µm filter, although 50 µm are still being used today prior to the fuel entering the engine fuel rail for best engine protection. Manufacturer's service letters provide guidance as to their preferences for specific machinery plant.[14]

In summary, increased reliability and low wear rates can be seen when:
- 10µm filter is installed on the "hot side" before entry into the engine fuel rail
- Pressure-drop across the filter and pressure drop alarms are logged
- An increase in the frequency of backflushing is also another indicator of possible poor separator performance

Filters are only considered as a final safeguard; installed to prevent substantially sized extraneous material from reaching the engine rather than a device for actual fuel cleaning. However, a more precise filtration process can protect the engines from potentially harmful material which may have slipped through other fuel treatment processes. Filters can be placed in suction and pressure lines and the design of filters depends on the viscosity of the fuel, operating temperature, operating pressure, volume of flow and filter sizing. For more information, reference is made to the [10].

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[14] See examples in MAN ES service letter [16] or Installation Manuals from WinGD or MAN ES

12.3. Sludge management

Fuel and lube oil sludge generated on ships needs to be treated and disposed of in a safe and compliant manner. To empty tanks and continue with safe operations, vessels must be able to contain the disposal of waste oil without damage to the environment.

Efficiently treating the waste oil on board can reduce the volume, frequency and growing costs associated with disposal on land. New fuels and tightening environmental legislation place higher demands on fuel treatment.

In general terms, the sludge or waste oil can be processed in a waste oil separator designed to separate:
- water and pass it into the bilge management system
- solids/asphaltenes and obtain a cleaner oil phase which may be burnt in a boiler or incinerated, alternatively disposed of on shore to a dedicated port reception facility.

Advanced waste oil separators combine decanter and disc-stack centrifuges to entirely dewater sludge volumes – while creating the potential to recover oil from the waste. These systems can treat waste lubricating oil (LO) as well as waste fuel oil (FO), enabling vessels and diesel power plants to take complete control of their sludge management. A system is shown in Figure 24.

Advanced waste oil separators present an effective solution to separate waste oil into three phases:
1. Clean water (low oil and solids content) - The water is suitable for further processing with an oily water (bilge) separator, allowing discharge at sea according to MEPC.107(49).
2. Clean oil (low water and solids content) - The oil is easily burnt in a boiler or incinerated without adding fuel. Reclaimed FO may be further cleaned with a multi-pass process and returned to the fuel tank for substantial fuel savings, please consult engine OEM recommendations.
3. Super-dry solids - The little waste volume remaining can be landed as dry waste at greatly reduced cost.

1	Three-way valve	6	Duplex strainer	11	Flow transmitter (water)
2	Three-way changeover valves	7	Shell-and-tube heater	12	Flow and density transmitter (fuel)
3	Demulsifier dosing unit	8	Temperature transmitters	13	EPC 60 control unit (not pictured below)
4	Feed pump with electric motor	9	Constant pressure valve		
5	Pressure transmitters	10	BX 50 high-speed centrifugal separator		

Figure 24 - System layout for on board sludge management

13.   Fuel cleaning design summary

When designing a fuel cleaning system, experience has shown that the following key points are recommended: Separators reduce content of solids and water to a level that do not cause excessive wear or other problems to the engine. Fuel cleaning quality and results depend on correct selection, installation, and operation.

- Separator efficiency is highly impacted by density differences, viscosity, particle size, retention time and flow rate. See Stokes law for more information.
- Automatic separator systems and features will assist crew and provide flexibility to automatically handle fuel variations compared to conventional separators.
- Install a fuel cleaning system above the minimum capacity required.
- Use separator sizing in relation to CFR-rating (Certified Flow Rate).
- Install fine filter (10-micron mesh size preferred) system prior engine fuel rail inlet.
- Install service tank system to be able to clean the fuel in the service tank.
- The fuel cleaning system should be able to handle worst case fuel quality scenarios of high catalytic fines and water content, higher capacity than base requirements should be considered to offer great operational flexibility.
- Include both fuel heating and cooling capability. The systems should be able to handle the actual fuel, and ideally be fully automated.
- Viscosity controller should be fully automated to viscosity control. Fuel change over design to control rate of temperature change should be automatically controlled. (Usually at 2 °C per minute).

Part 3 - Operational practices

This section describes best operational practices for fuel cleaning on board vessels:

14. Fuel treatment systems

The desired quality of the fuel at the machinery plant fuel rail is first determined by the fuel quality meeting the selected ISO 8217 [3] fuel grade for the bunker manifold and then the capacity of the fuel system to clean and condition the fuel before engine. The quality of the fuel at the engine inlet is directly related to the engineer's awareness and competence in machinery operations, performance of the fuel treatment system, storage arrangements and "as delivered" properties. If the recommendations for fuel grade, storage, settling and fuel tanks as well as fuel cleaning is not followed at anyone or more of these stages, the risk of poor-quality and incorrectly conditioned fuel at the engine inlet is increased.

The most important properties for fuel quality at engine inlet are viscosity, abrasives of catalytic fines (Al+Si) and water. The ranges for these can be seen in the table in Appendix I, however some typical ranges can be seen here:

- Viscosity at injection, which typically varies between 2–20 cSt.
- Levels of abrasives such as catalytic fines which typically should be below 15 ppm, and ideally as low as possible below this limit.
- Water which should be kept to a minimum ideally below 0.3% V/V.

Too often it is seen that the design of the fuel separator and preheater installations in the fuel cleaning system are too small and that the steam supply to the preheater is limited, or that the temperature control is too slow or flow rates through the separator are too high. These are all factors that reduce the ability to clean the fuel efficiently. Design guidance is given in Part 2 of this document, and further to this other guidelines CIMAC Rec. 25; [1] and IACS recommendations IACS UI no. 151 [11]. These are in addition to the separator manufacturers guidance for ship specific requirements for the design and installation of a ship fuel cleaning system. See also Section 19.

15.   Fuel cleaning performance and sampling

The analysis of bunker manifold fuel sample, correctly drawn, will provide the level of catalytic fines (Al+Si) and water content entering the storage tanks and indicate the degree of cleaning required to effectively reduce before entering the engine. It is important to ensure that the fuel cleaning systems on board are operating efficiently to reduce water and abrasives to the recommended levels to minimise the risk of engine damage.

The fuel oil cleaning system should have sampling points meeting the requirements of MEPC.1/Circ 864 in locations that ensure a representative sample of the fuel in use can be drawn to determine the efficiency of the separator cleaning process. Such knowledge is necessary to enable the required improvements to the fuel treatment plan.

The recommended sample points are listed as follows (see Figure 25):
1. As bunkered and sampled at the fuel manifold
2. Before the fuel cleaning equipment
3. After the fuel cleaning equipment
4. Before the fuel enters the oil fuelled machinery plant engine/boiler.
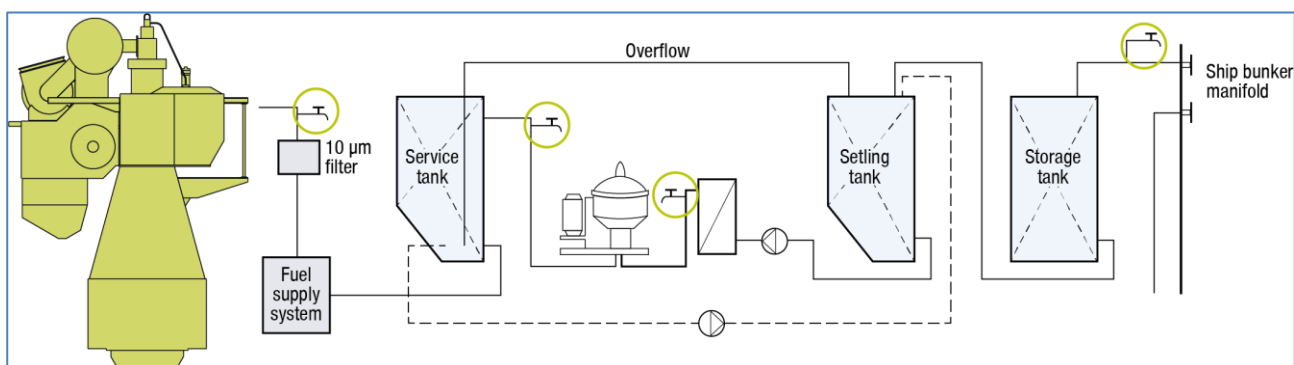
Figure 25 - Fuel sampling points are shown in the green circles.

Performance of fuel cleaning systems are complex to predict, and so to carry out a fuel system performance check on a regular basis is often straight forward and cost effective to run. The fuel parameters to be analysed in Table 8 should make the basis of any performance check for comparing results between the sampling points.

Table 8 - Requirements for fuel system performance assessment

Characteristic	Unit	Test Method Reference
Aluminium	mg/kg	IP 501 / IP 470 / ISO 10478
Silicon	mg/kg	IP 501 / IP 470 / ISO 10478
Water	Volume %	ISO 3733
Ash	Mass %	ISO 6245
Additional properties may be useful for identifying and fingerprinting the fuel entering the separator to understand the source product, other control parameters and correct settings are applied such as:		
Density at 15°C	kg/m^3	ISO 3675 / ISO 12185
Kinematic Viscosity at 50°C	mm^2/s	ISO 3104

We recommend that the fuel system performance checked by taking a full set of fuel system samples every four months, specifically checking the centrifuge efficiency when bunkering a fuel with more than 40 ppm catalytic fines (Al + Si) and or during a heavy weather when tank bottoms may be stirred up passing higher concentrations of settled catalytic fines. See Table 9.

Table 9 - Fuel sample requirements and position.

Sampling	Sampling positions
When Al+Si above 40 ppm in fuel as bunkered	1) At engine inlet 2) Before Separator 3) After Separator 4) Bunker manifold sample
Every 4 months	
During heavy weather	

Cases in the field have shown that even small amounts of catalytic fines can increase wear, so all measures must be taken to reduce the risk of introducing catalytic fines into the engine.

15.1. Examples of results for fuel cleaning in service

Averages taken from a fuel treatment system check programme, can be seen in Figure 26 and Table 10. The results show that most fuel cleaning happens in the separators, but also that the settling tank and service tank contribute to the cleaning. The general fuel cleaning efficiency is found to be approximately 68%.
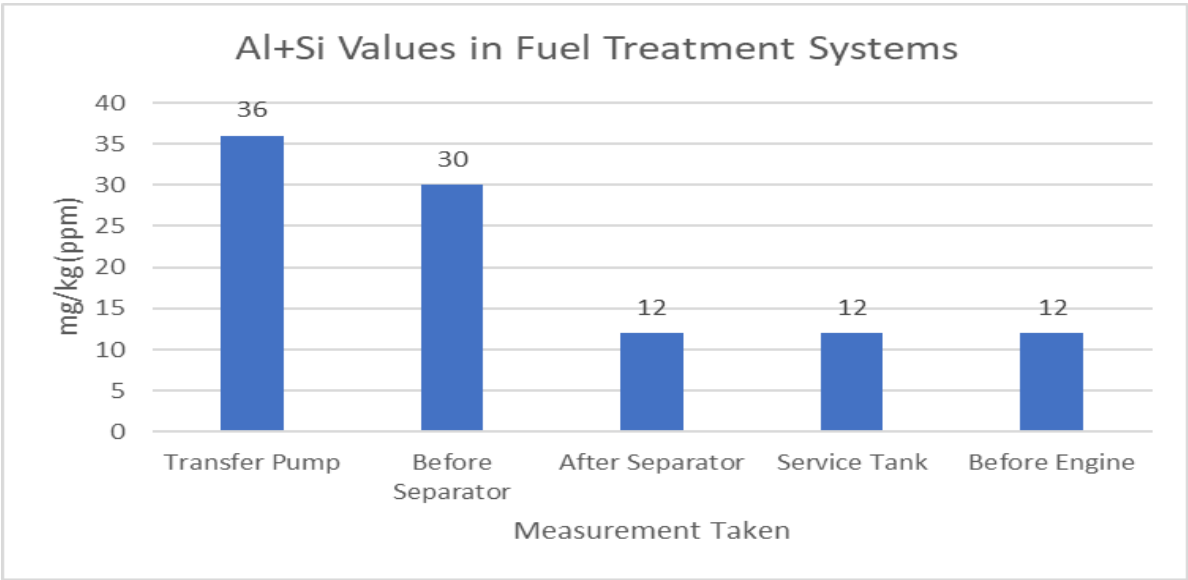
Figure 26 - Fuel treatment efficiency collected on fuel system check samples from service. The table is based on HSFO over 5 years (2018). [8]

15.2. Tank cleaning practice

Cleaning of the settling and service tanks, along with an inspection, should be carried out periodically (at least once per year), to mitigate against catalytic fines build up. In calm weather, water and abrasives will settle to the bottom of the tanks, but in high sea they can be churned up and transferred further on in the system in high concentrations.

From the settling tank, a high concentration of catalytic fines, water and other extraneous dirt could reach the separators, overloading the design capacity of the separators which may result in the carryover of the abrasives and water to the service tank above acceptable levels. This means that the service tank could be contaminated with excessive amounts of catalytic fines, which will go to the engine fuel rail where they will cause increased wear on the fuel pumps, injector nozzles and cylinder liners and piston rings.

Even a standard level of cleaning of the fuel will lead to a concentration of catalytic fines in the bottom of the service tank if the system is not designed and operated with measures for continuous cleaning in mind.

15.3. General best practice tank management

General best practice for fuel cleaning of the tanks can be summarised to:
1. De-sludge the settling and service tanks at the designated sludge drain cocks at regular intervals, normally this would be carried out daily.
2. Maintain cleanliness of fuel in the service tanks, in some cases the cleaning of the fuel in the service tanks can be enhanced by recirculating the fuel back to the settling tank. (e.g. if there are high catalytic fines present). This can be facilitated by design by ensuring that the service tank overflow pipe inlet is positioned close to the bottom of the service tank and then from the top of the settling tank by a separate line from service tank to settling tank with a recirculating pump. See Figure 14.
3. Cleaning all fuel in the service tank before use if the tank has not been in use for some time (e.g. 1-2 weeks).
4. inspecting the cleanliness of the service and settling tanks is recommended periodically such as during annual surveys.

16.   Guidelines for separator plant operation

To increase the efficiency of fuel cleaning in the separator plant and, thereby, remove more catalytic fines from fuel oil, there are two main points to consider when operating the plant:

- separation temperature: maintaining it as high recommended by OEM's for the viscosity of the fuel being cleaned.
- flow rate through the separator: keep the flow as low as practically possible to extend residence time in the separator.

It is recommended that operators use the entire installed separator capacity and run standby separators in parallel, and/or multiple separators when considered necessary. i.e. when it is known there is either high water content and or catalytic fine content.

16.1. General separator layout operation guidelines

The separator layout on board a vessel plays a critical role in optimizing separation efficiency with removal of water and abrasive particles.

Separators on board can usually be operated in single, series or parallel mode. Parallel operation is always the most efficient way to clean fuel as the fuel flow rate can be split in half, leading to an increased time for water and particles in the disc stack of a separator and thereby increased time for removal.

OEM and CIMAC recommendations are that the separator arrangement options for single, series or parallel mode operations should be made possible.

The theory is explained in Section 10.1, and examples can be seen in Figure 27.
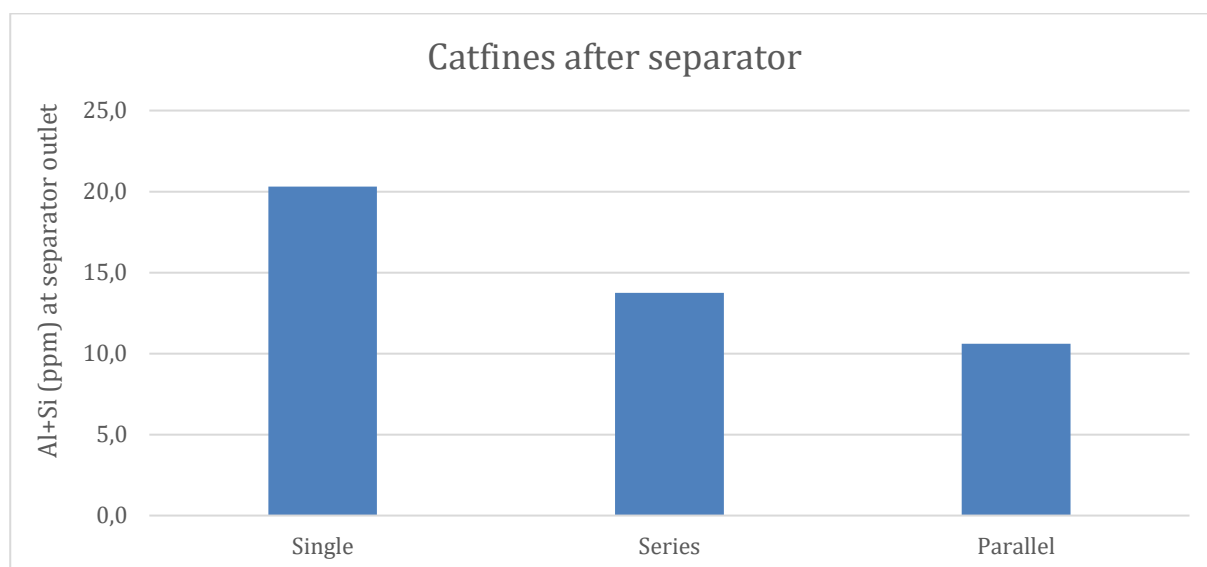
Figure 27- Calculated concentration of catalytic fines after the separator(s) when operating in single, series or parallel system arrangement, based on 30 ppm particles at separator inlet with a size of 3.5 µm.

16.2. Examples of fuel separator plant operation

Fuel systems on board ships are usually designed with a 10% recirculation flow from the service tank to the settling tank. This is to safeguard that the service tank is always full. Figure 29 visualize the impact of flow on particle concentration. An overview of the results is shown in Figure 28. The automated flow control is described in Section 10.3.5.

This example is based on a vessel with 50 MW installed engine power, a fuel feed temperature of 50 °C, a separator feed temperature of 98 °C, a particle concentration in the fuel of 30 ppm (Al+Si) and an average particle size of 2.8 µm.

ClassNK (Guidance for onboard use of Compliant Fuel Oil with SOx regulation from 2020)

Tested by Mitsubishi Kakoki Kaisha, Ltd. using the disc type centrifuge separator SJ35H.

Graph"X" Treatment flow rate of SJ35H purifier and separation efficiency by particle size distribution

Test conditions :
- Cat Fine (Al+ Si) concentration before purification 52 mg/kg
- Fuel Oil kinematic viscosity (50°C) : $265 mm^2/s$
- Fuel Oil flow-through temperture during test : *1
- Fuel Oil density (15°C) : $0.997 g/cm^3$

*1 : Temperature at which viscosity of sample fuel oil becomes $35mm^2/s$

Figure 28 - Sample of flow rate and separation efficiency test results. Data from NK (Nihon Kaiji Kyokai), March 2019. Flow rate capacity 3900 l/h according to MRC380 cSt corresponds to CFR380 cSt at 2900 l/h.

The results from this controlled test condition clearly shows that by reducing the flow of the fuel through put through the separator improves the fuel cleaning efficiency.
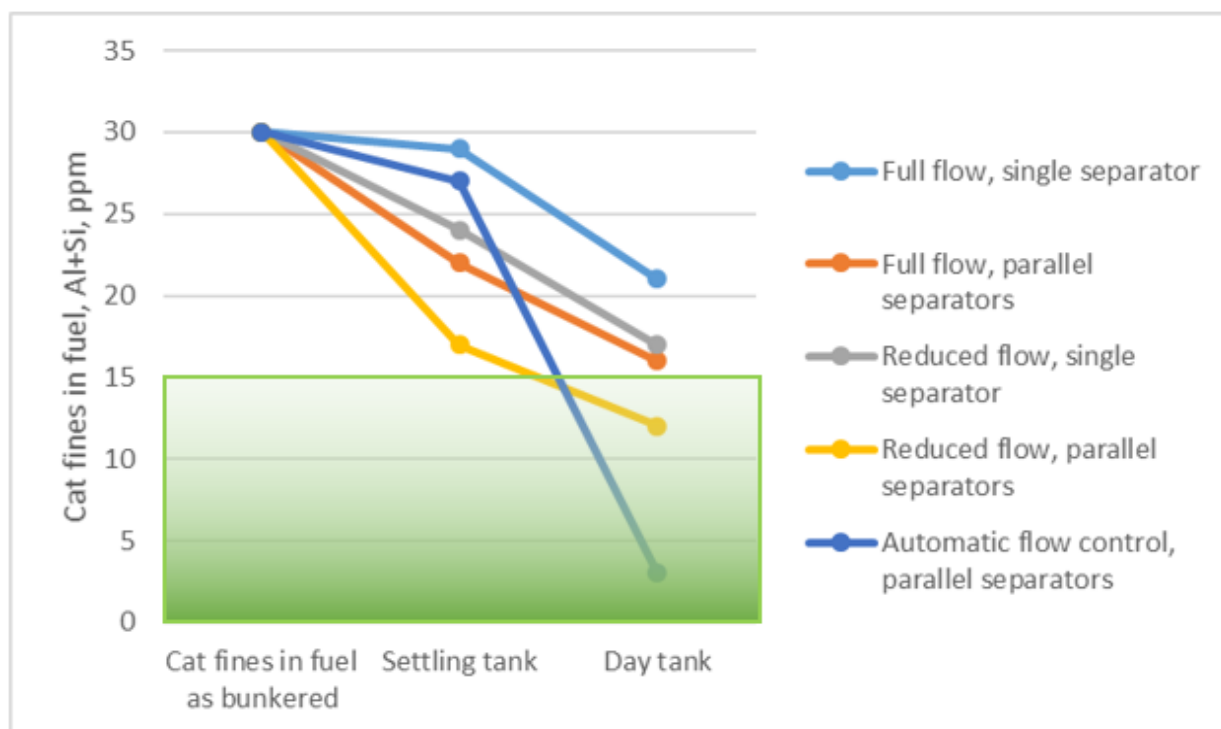
Figure 29 - Calculated concentration of cat fines after the separator when operating in different arrangements and flows.

Example of full flow, single separator

Figure 30 shows that the engine requires 11,900 L/h fuel. 1,190 L/h of cleaned fuel is transferred back to the settling tank via the recirculation line, resulting in a slight decrease of particle levels in the settling tank.
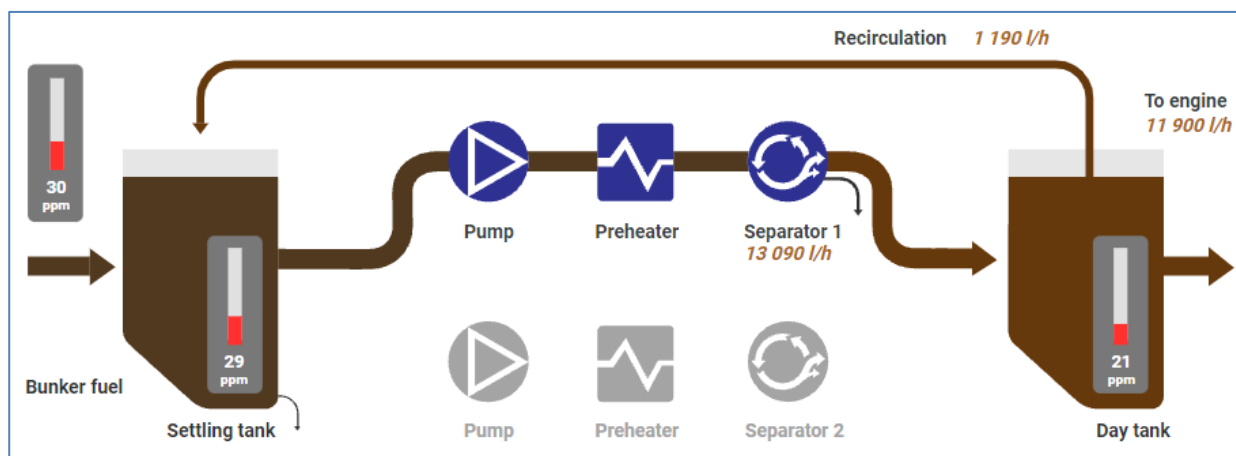
Figure 30 Flow = 100%, separator running in single mode

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However, full fuel flow through the separators at reduced engine load leads to a vast amount of fuel to be pumped from the service tank to the settling tank because it is not required by the engine. This process is not efficient in terms of energy usage and separation efficiency and can be significantly improved with an automatic flow control system, addressed in Part 2 of this document.

Example of full flow, parallel separators

If the standby separator is running in parallel mode, then twice the amount of fuel is cleaned, leading to a large recirculation flow of 14,280 L/h, adding more clean fuel to the settling tank and service tank. See Figure 31.
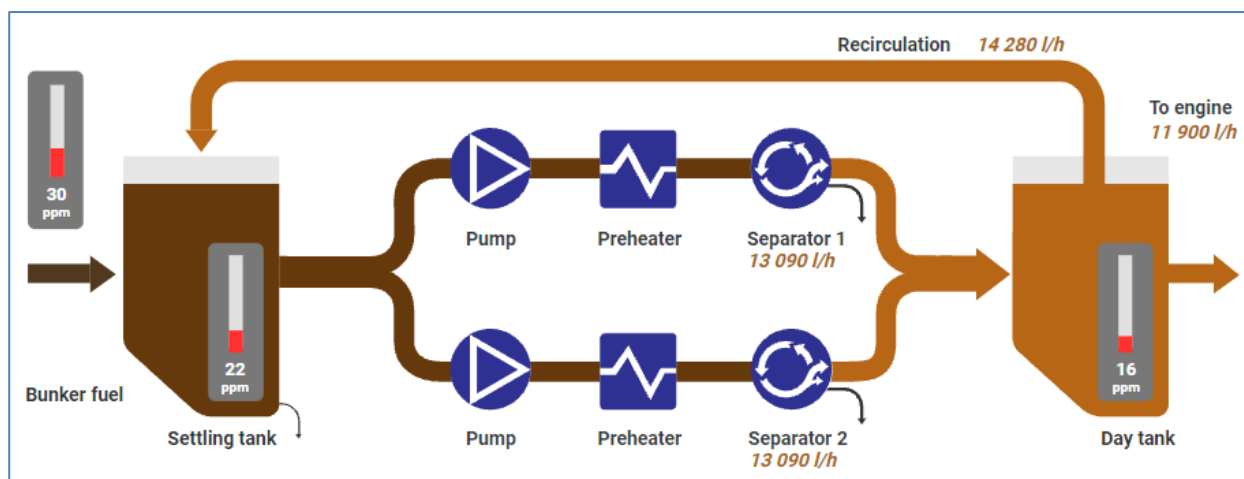
Figure 31 - 100%, separator running in parallel mode with full flow through each separator.

Example of reduced flow, single separator

If the vessel is slow steaming with reduced engine power and reduced fuel consumption, less fuel is required by the engine and more fuel needs to be transferred back via the recirculation line. This results in reduced particle concentrations in the service tanks (Figure 32 and Figure 33).
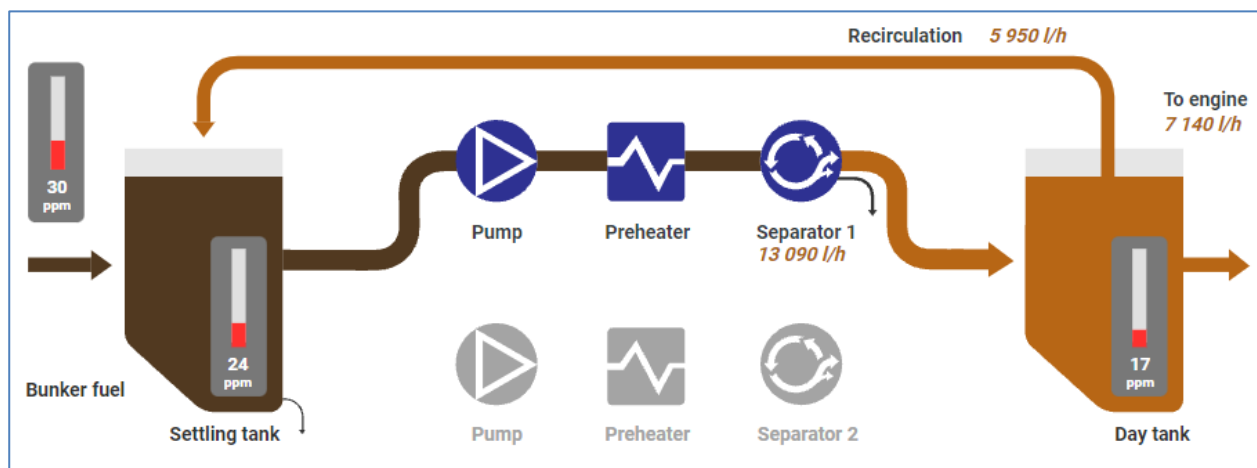
Figure 32 - Flow = 60%, separator running in single mode.

Example of reduced flow, parallel separators
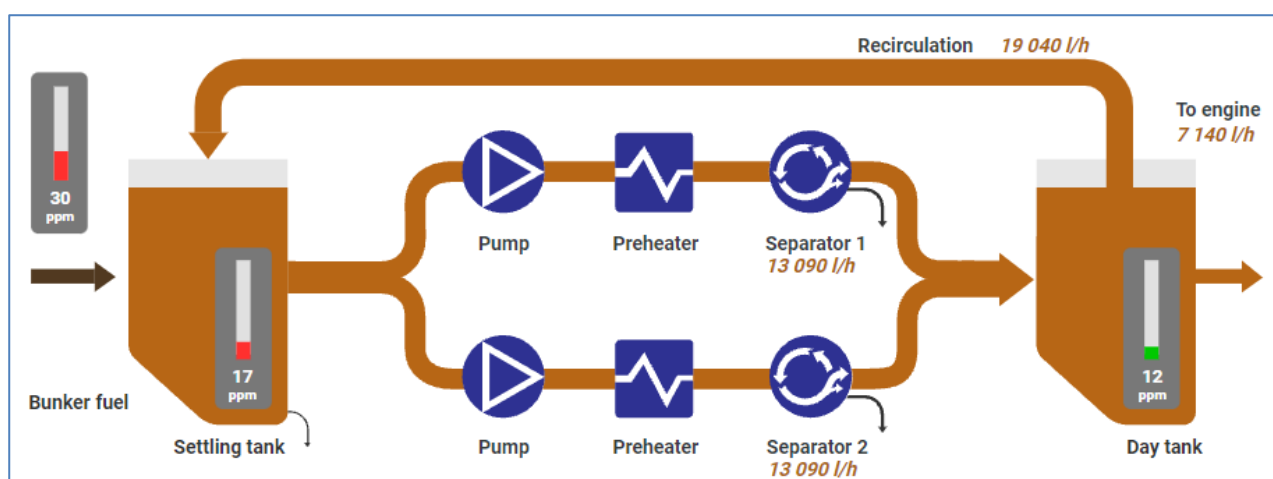
Figure 33 - Flow = 60%, separator running in parallel mode with full flow through each separator.

However, full fuel flow through the separators at reduced engine load leads to a vast amount of fuel to be pumped from the service tank to the settling tank because it is not required by the engine. This process is not efficient in terms of energy usage and separation efficiency and can be significantly improved with an automatic flow control system (see Part 2).

16.3. Separation temperature guidelines

The viscosity of the fuel is strongly dependent on the temperature. The higher the temperature, the lower viscosity, and the lower viscosity the higher the separation efficiency, according to Stoke's equation. (See section 10.2). An inlet temperature of 98°C with only small variations (maximum ±2°C) is recommended for high viscosity fuels. For different fuel types, it is advised to follow the recommendations of the separator manufacturers. An example is given in Table 10. Please note that MGO (2 – 6 cSt at 40°C) can be treated at lower temperature than below table suggests.

Table 10 - Guideline for fuel storage and cleaning temperatures based on viscosity (Source: Alfa Laval).

Viscosity at 50°C	Separation Temperature (°C)*
Up to 20 cSt	40°C
20 to 30 cSt	50°C*
30 to 40 cSt	60°C*
40 to 50 cSt	70°C*
50 to 70 cSt	80°C*
70 to 700 cSt	98°C

Separation temperature can be set up to 98°C. The higher the temperature the better the result will be. Consider the viscosity in the booster and adjust the temperature accordingly. Refer also to Figure 36.

In the event that the temperature of the fuel in the service tank after the separation process is higher than that corresponding temperature required to obtain the correct viscosity required by the engine, which can be the case of light VLSFOs, then cooling before injection into the engine will be required. (See also Section 12 for fuel conditioning). Some VLSFO's require careful thermal management when they have been shown to have a reduced thermal temperature stability and so may show increased formation of sludge if heated to high temperatures for prolonged periods.
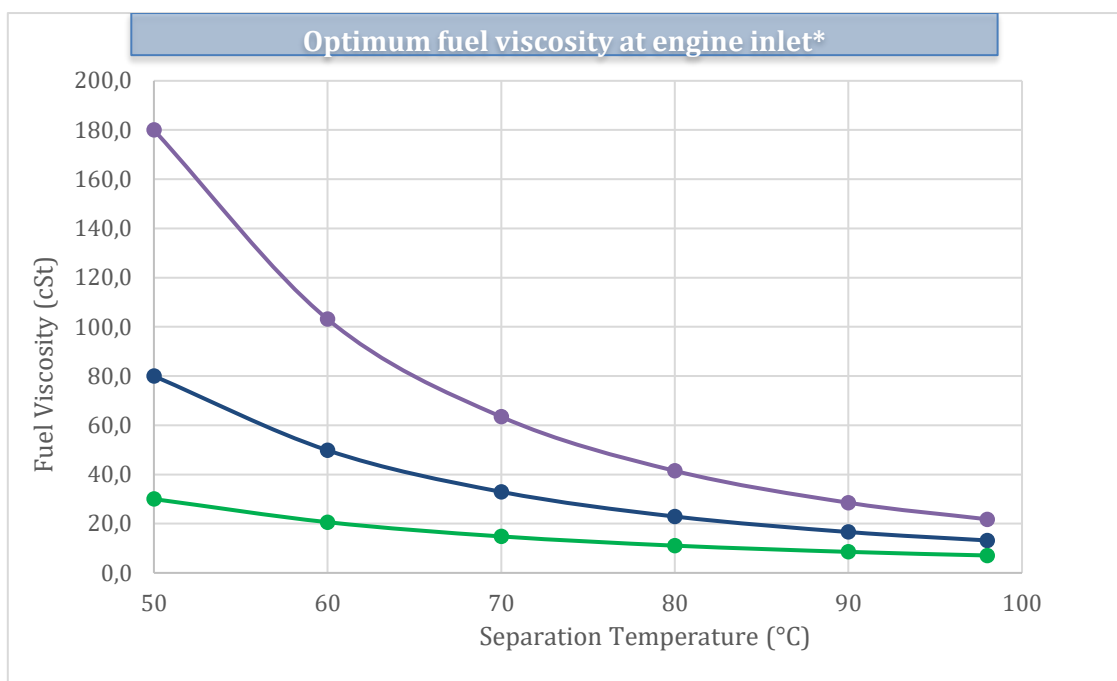
Figure 34 - Fuel viscosity vs separation temperature

Figure 35 shows the dependence of fuels with different viscosity, heated to different temperatures and the effect on cleaning. For example, a 30 cSt (at 50 °C) fuel should be heated to min. 60 °C to clean the fuel from 30 ppm Al+Si (catalytic fines) to 15 ppm Al+Si.
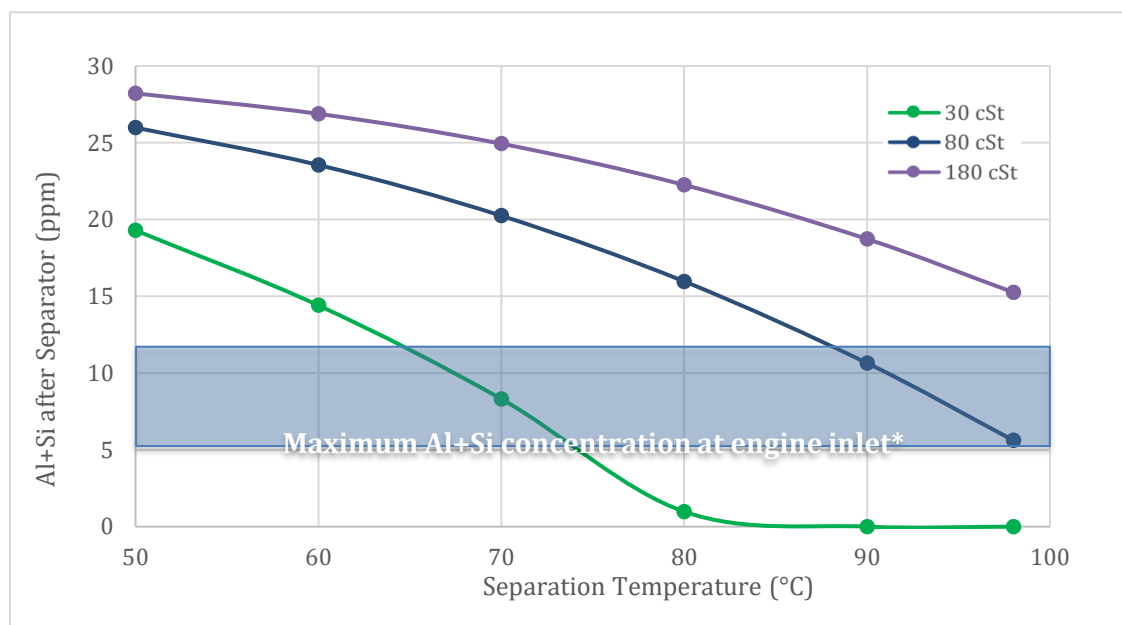
Figure 35 - Dependence of catalytic fine concentration (Al+Si) after separator to separation temperature for a fuel containing 30 ppm Al+Si with a particle size of 3 µm, in a CFR-rated separator.

16.4. Cold flow properties

Variations in cold flow properties have a significant impact on the fuel flow and fuel's ability to be pumped in the fuel treatment system. If the fuel becomes too cold, for example when stored in tanks, the paraffinic content can precipitate as wax, forming large sludge masses that accumulate in fuel tanks and block fuel filters and separators, damaging them and potentially resulting in engine shut down.

This makes it vital to keep the fuel temperature above the cold flow property temperatures in particular the pour point and the wax disappearance point when passing through the separators. Lack of attention to the fuel's cold flow properties can lead to sludge deposits at the separator and difficulties in transferring from storage to settling tanks especially in low temperature ambient conditions. Filters and pipelines should have the capability to be heated to avoid cold flow challenges.

Further information can be found in CIMAC guideline [6].

16.5. High-temperature separation

Raising the temperature above 100°C will increase separation efficiency. However, as this is above the boiling point for water, the separator systems must be designed for such operation. In most systems, HSFO and VLSFO can be heated to max. 98°C to prevent the water from boiling.

When increasing the temperature above 100 °C (max 110°C) (noting that additional safety considerations need to be considered), the pressure in the separator bowl prevents the water from evaporating, but if the systems are not designed for such operation, it can have serious consequences during a discharge, when the +100°C water may be released into atmospheric pressure and boil off instantaneously, leading to a large pressure increase inside the separator stand.

For further information, please consult with the ship specific separator manufacturer.

16.6. Fuel change-over from low viscosity fuel to high viscosity fuel and vice versa

Fuel change-over from low viscosity fuel to high viscosity fuel and vice versa should be carried out at the lowest practical rate to avoid the risk of thermal stress causing the fuel pumps to stick as the components will expand and shrink at different rates. The recommended rate is generally max. 2 °C/min. (See Section 18 and engine OEM recommendation).

Therefore, when the ship changes the fuel in use from a low viscosity fuel to a high viscosity fuel, or vice versa, the on-board fuel system should be able to:
- run a controlled temperature rise (or decrease) from the set point of the fuel in use to the set point of the new fuel.
- maintain the viscosity of the fuel at the engine inlet always within the optimal values as specified by the engine maker.

This can be secured by an integrated control of the heaters, the coolers, and the changeover valve, operated manually or automatically being controlled by the auto-viscosity controller.

16.7. Example of fuel change over

Figure 36 shows parameters measured in a fuel changeover procedure, performed according to the engine makers' recommendations.

Figure 36 - Fuel changeover diagram from HSFO to distillate fuel (Alfa Laval)

(a) Variable engine load - fuel changeover by mass flow consumption in real life conditions; (b) Temperature trend - Progressive fuel temperature change at engine inlet (set C°/minute); (c) Viscosity is kept within set limits (set high / low cSt value)

The upper curve (a) describes the actual load on the engine, while the following one (b) shows the transition of the temperature. Such transition proceeds with a constant pace of degrees per minute as set by the operator, without peaks or interruptions affecting the time to complete it. This is typically 2 °C/min. (refer to engine makers guidelines)

During the procedure, the viscosity of the fuels' blend is always kept within the upper and lower limits set by the operator and represented by the red dotted lines (c).

16.8. On-board monitoring of machinery condition

Successful optimisation of the fuel cleaning and the engine cylinder condition depends on the due diligence of the operators monitoring the condition of the cylinder and piston ring condition and acting on the information obtained.

It is recommended to check the fuel regularly for catalytic fine content, use cylinder lube drain oil analysis (two-stroke engines), and inspect the engine for wear. For two-stroke engines, the wear will mainly be found in the combustion chamber parts, i.e., piston rings, pistons, and cylinder liners, and for four-stroke engines, the wear will mainly be found in the fuel equipment. See Section 19.

16.9. Preventative measures

This section outlines some key preventative measures to protect against the impact of catalytic fines on the machinery plant:
1. In the case that catalytic fines damage is suspected, the first step should be to check the performance of the on-board fuel cleaning process, this can best be done by carrying out a fuel system performance check (see Table 8 and Table 9) as well as checking the engine room log for the separator settings and arrangement / status and whether fully optimised.
2. As earlier advised routinely take samples for to assess the fuel system performance (see Table 8 and Table 9)
3. For two-stroke engines, use the on-board analysis tools for checking the cylinder condition:
    a. High iron (Fe) in the cylinder lube drain oil means high wear. If BN is also high, the wear is likely caused by catalytic fines.
    b. Make regular scavenge port inspections and wear measurements, and follow the wear development
    c. Make liner surface examination, e.g., with replica analysis. The analysis may show elevated levels of catalytic fines in the graphite lamellas

17. Summary: Fuel cleaning operational practises

Experience shows that special attention must be drawn to the following regarding fuel cleaning operational practices:

- Be aware of the key characteristics of the fuels as loaded.
- Keep you separator temperature as high as possible in line with fuel viscosity, according to separator maker guidelines (see 16.3).
- Keep your separation temperature as high as possible.
- Keep the flow rate through the separator as low as possible. Single separator operation is not as effective as parallel separator set up, where flow is reduced and retention time increased, resulting in better separator and fuel characteristics.
- Have a high standard of daily operations.
- Check results from fuel system performance checks.
- Act on the results when needed.
- Apply daily de-sludge operations on the service and settling tanks.
- Ensure there is an inspection schedule on tank cleanliness – particularly settling and service tanks.

There are numerous other best practice documents available, some of which are listed in our reference section 21.

Appendices, Listings and References

18. Appendix I – OEM listing fuel properties

The Table 11 below gives an overview of some of the major OEM requirements for fuel quality before the engine and for fuel cleaning systems. *Note: Always refer to newest, relevant OEM recommendations.*

Table 11 - Overview of requirements from some major OEM's. Always refer to latest information from OEM's

OEM	Engine type	Fuel filter before engine	Separator sizing: CFR (Certified Flow Rate)	Kin. Visc.	Fuel Change-over Rate (°C / Min.)	Catalytic fines, Al+Si, ppm	Combustion	Other? E.g. elements for SCR, Water
MAN ES two-stroke	Single fuel, e.g., MC, ME-B, ME-C. Duel-fuel (diesel-side), e.g. ME-GI, ME-LGIM, ME-LGIP, ME-GIE	Full flow: 10 µm filter	0.23 litres/kWh	2-20 cSt	2	<15 ppm for shorter periods	No special requirements	SCR: Refer to SCR manufacturer. No free water.
WinGD	Single fuel, RTA, RT-flex and X Dual Fuel: X-DF, XDF-A, X-DF-M	An automatic self-cleaning filter of maximum 10 µm absolute sphere passing mesh size		2-20 cSt	2	<15 mg/kg at engine inlet	No special requirement	SCR: Refer to SCR manufacturer. No free water / less than 0.2%w/w. See OEM guidelines.
Japan Engine	All UE engines	50 µm 5-10 µm (Recommendation)	n.a.	2-18 cSt	1-2	<30ppm (As fuelled) <7ppm (Engine inlet)	CCAI < 850 (Recommendation)	SCR: Refer to SCR manufacturer Water: <0.2%
Wartsila four-stroke	Wartsila branded medium-speed diesel and dual-fuel engines	Engines with jerk injection pumps: 34 µm sphere passing mesh. Engines with common rail fuel injection system: 6 µm sphere passing mesh.	$Q = (P * 1{,}15 * SFOC * 24)/(\delta * t)$ P = output [kW] SFOC [g/kWh] δ = fuel density [kg/m³] t = daily separation time [h], typically 23-24 h	DM: 2.0-24 cSt for most engine types. RMA10 – RMD80 fuels: typically, 6-16 cSt, RME 180 – RMK 700 fuels: 16-24 cSt		Max. 15 mg/kg bef. engine	CCAI: max. 870	Fuel quality to be taken into account in SCR design. Cl, P, Zn and organic Si are harmful for catalyst material.
MAN ES 4S – large engines	Single & Dual Fuel (for main Injection System)			2-14 cSt		<15 ppm	ECN > 20	MGO: Zn, Ca: < 0.2 ppm, P, V, Na: < 5 ppm Water: No free water, HFO: < 0.2%, MGO: < 0.02%. If Asphaltenes: > 8%: Asphaltenes/MCR < 0.66
MAN ES 4S – gensets	Single fuel (cetane)			2-18 cSt		Max 15 mg/kg before engine	Cetane >35 Recommend ECN >20	Refer to SCR maker to comply with IMO Tier III.

				Some engine types approved for 21 cSt in special cases		Max 60 mg/kg in fuel (before separator)	Recommend CCAI <880	
Himsen 4S	-			HFO: 12 ~ 18 cSt MGO/MDO: 3 ~ 14 cSt		<15mg/kg	No special requirement	
Caterpillar (MaK) 4S	Liquid Fuel Engine	MDO: Primary filter: 320 µm. Fine filter: 25 µm (on engine). HFO: Primary filter: 320 µm. Automatic filter: 10 µm. Fine filter: 34 µm (on engine).	V = 0.28 [L/kWh] * P V = Volume [L/h] P = Engine power [kW]	2-12 cSt	2	< 15 ppm	CCAI < 870 CCAI < 850 (recommended) ECN > 20	No free water, max. 0.2% at engine inlet See OEM recommendation with further requirements for fuel
Rolls Royce	Only DMX, DMA; DMZ and for one engine series also DMB			1.5 - 4.5 cSt		0	CN > 45 CI > 42	See OEM recommendation with further requirements for fuel

19. Appendix II – Service experience on engine wear

This appendix includes influencing factors for wear in engines, an overview of the wear and case studies with damage and mitigation.

19.1. Influencing factors for wear in two-stroke engines

The quality of fuel at the engine inlet impacts the performance of the engine and directly or indirectly affects the level of wear-rate of various critical engine components. Below is an overview influencing factors for two-stroke engines, Figure 37. Factors relating to catalytic fines are marked with blue squares.
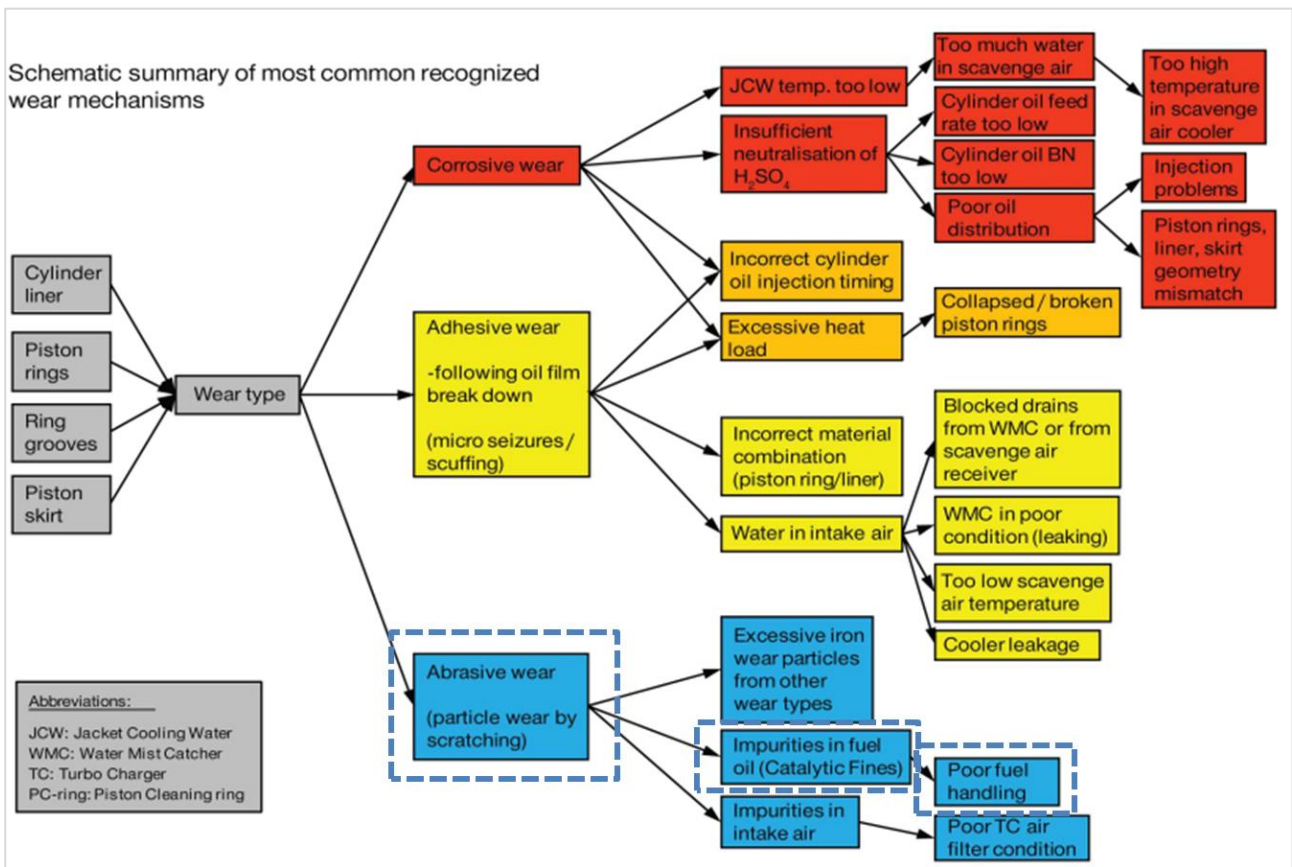
Figure 37 - Factors influencing wear of cylinder liner, piston rings, piston ring grooves and piston skirt. Factors relating to catalytic fines are marked with blue squares. [13]

19.2. Wear in engines - overview

Wear, and possible scuffing, in two-stroke engines are mainly found in the combustion chamber zone on cylinder liners, piston rings and piston ring grooves.

Whereas wear in the small four-stroke auxiliary engines are found primarily in the fuel system, where the fuel atomiser holes are damaged. They holes become too large for effective atomisation of the fuel resulting in poor combustion and thereby increasing deposits in the post combustion spaces,

including exhaust valves and turbocharger nozzle and rings. This further results in a worsening combustion profile that could eventually lead to engine failure and breakdowns.

An overview of the damages found in two-stroke engines and small four-stroke auxiliary generator sets (Holeby engines in this case) can be found in Figure 38.
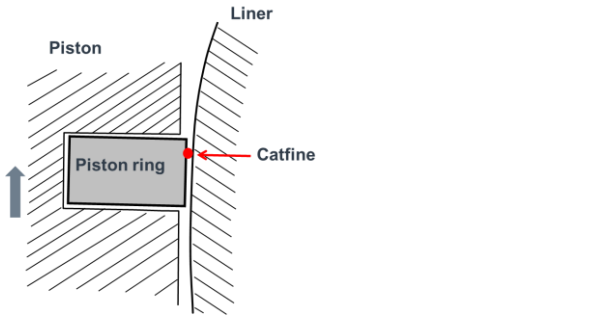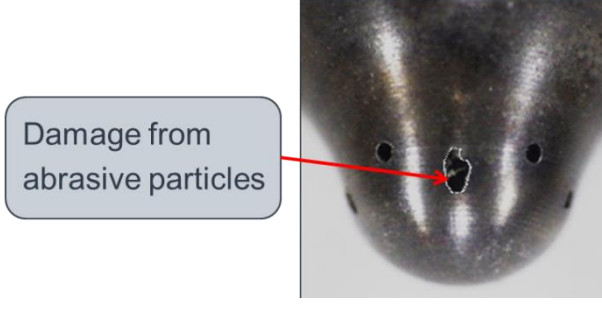
Damages found in two-stroke engines	Damages found in small four-stroke Gensets
Wear in combustion chamber parts	Wear in fuel equipment
Resulting in high wear	Resulting in poor combustion

Figure 38 - Overview of damage found in two-stroke engines and small four-stroke Gensets.

19.3. Erosion/cavitation (four-stroke engines only)

Erosion and cavitation are seen in fuel pumps and injectors in four-stroke engines and can result in the loss of material due to mechanical and/or physicochemical reactions under high temperatures and pressures or fuel contamination. This can cause issues with injector precision and fuel atomisation.

Figure 39 - (ref: Chai, J; Chahine, G.L. (2016) Relationship between material pitting and cavitation field impulsive pressures. Wear Vol. 352-353 pp 42–53)

19.4. Case studies remedial and preventative actions

There are many case studies illustrating the effects of contamination and engine issues in the field. The table below provides a short guide to some of the main failures reported, the possible causes and what remedial action or preventative measure can be taken.

Table 12 - Case studies from field experience

Case	Failure mechanism	Potential cause	Remedial action	Preventative measure
1	High engine wear and scuffing (liner surface and piston rings). Not caused by off spec fuel.	Build up to high catalytic fines levels in the service tank over time. Catalytic fines swirled suddenly up in the fuel e.g., at rough seas.	Service tanks cleaned. Effective fuel cleaning and treatment.	Regular cleaning of the service tanks. Tracking of magnetic iron in the cylinder drain oil. If the failure was caught in time and continuous feeding of contaminated fuel was halted, the recovery period may be short, and overhaul may not be needed.
2	High engine wear and possible scuffing (liner surface and piston rings).	Fuel not cleaned for catalytic fines. Temperature in separator too low.	Effective fuel cleaning and treatment.	Make sure that the fuel temperature in the separator is sufficiently high and the flow rate at the lowest practical. Clean the fuel heaters regularly. Design system cacity to maintain stable high fuel temperature in separator. Fuel system performance check samples should be taken
3	High engine wear. Catalytic fines identified in liner and piston rings	Low S fuel led to a decision that it was not necessary to clean the fuel.	Effective fuel cleaning and treatment.	Always clean the fuel. Correct operation of the fuel cleaning equipment on board. Measurements of catalytic fines entering the engine Fuel system check samples should be taken
4	Elevated levels of magnetic iron detected in used oil analysis	Initially treated as cold corrosion and lube oil feed rate increased. Iron levels lowered via dilution, but wear continued.	Effective fuel cleaning and treatment.	Diagnose issue correct and take appropriate actions. Fuel system check samples should be taken
5	Increased catalytic fines in fuel found via fuel condition monitoring	Constant high level of catalytic fines was maintained – potential wear issues from this source	Through monitoring – changes were made to lower catalytic fines pre-engine to approx. 5 mg/kg from 15 mg/kg	Monitoring systems and effective use of separators can be used to prolong engine life and eliminate potential issues before they arise. Check the separator function regularly by taking samples both before and after separator.

Case	Failure mechanism	Potential cause	Remedial action	Preventative measure
6	High engine wear (liner surface and piston rings)	Catalytic fines are hydrophilic. Therefore, if a homogeniser the equipment is installed before separator, catalytic fines cannot be removed effectively	Change the location of the homogeniser to after separator.	Do not install a homogeniser before separator.
7	High sludge formation	Asphaltenes in fuel get unstable by changing the fuel matrix	Monitor separator operation closely, and if sludge is excessive, decrease the interval between sludge discharges. In case sludging blocks system, stop using the fuel.	Avoid mixing different fuel batches without checking for compatibility.
8	High sludge formation	In case TSP is high as fuelled, increased sludge formation may occur.		Avoid prolonged storage at high temperatures. Use the fuel as soon as possible.
9	High sludge formation	Fuel may become unstable after long storage at high temperature		Avoid prolonged storage at high temperatures.
10	High sludge (wax) formation	Wax formation when fuel temperature is below wax formation temperature	It is required that the fuel temperature in the storage tanks is maintained at least 10 ºC above pour point. Heat the fuel above wax formation temperature in settling tanks and entering separators	Avoid cooling the fuel below wax formation temperature. For low viscosity paraffinic fuels check the wax liquifying temperature and maintain above this at inlet to the separator plant for effective treatment.
11	High sludge formation	Sludge shows differing behaviour	In case sludge found is very sticky or shows resinous behaviour (polymerised) or is not manageable,	Consider not using the fuel and collect evidence, such as sample of fuel entering separator's and that of the sludge from separator and or filters.
12	High sludge in separators	Fuel may become unstable after repeated fuel heating and motion in separation step	Adjust feed rate to meet engine consumption rate Stop recirculation from service tank (after confirming that the fuel is affected by thermal/physical stress)	Good monitoring of fuel management and performance will help to mitigate In case of the fuel as delivered having higher TSP, this may be a consideration as to its unstable condition

20. Appendix III – Wear mechanisms

There are several wear processes that can occur in the engine depending on the conditions. Wear in two-stroke and four-stroke engines can be categorised into four main types:

- Corrosive wear
- Abrasive wear
- Adhesive wear
- Erosion/cavitation

20.1. Corrosive wear

Corrosive wear is the result of chemical corrosion and mechanical wear acting simultaneously on the same surface. See schematic in Figure 40.

| **Schematic of corrosive wear** | **Schematic of material loss from corrosive wear** |
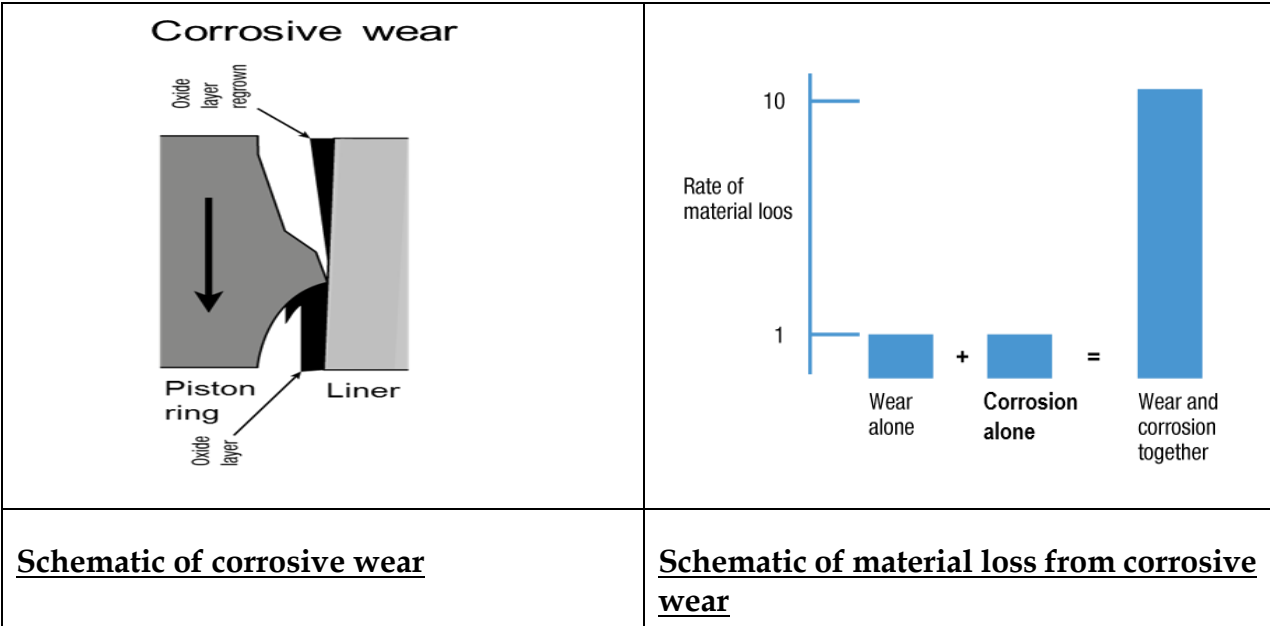
Figure 40 - Schematics of corrosive wear [14] [15]

Wear will remove the protecting oxide layer exposing the unprotected surface to corrosion. Wear and corrosion with each acting alone may induce low wear but when acting together, the wear can increase to very high level.

Chemical corrosion will result in formation of corrosion products on the surface. These products will normally protect the surface against further corrosion, but when they are removed by either an abrasive (e.g., catalytic fines) or an adhesive wear process, the surface is left un-protected, and the chemical corrosion process can continue. This leads to a high increase in the rate of material loss (wear).

Corrosive wear will be almost completely absent if either the corrosion factor or the wear factor is removed. Likewise, if either of the factors are increased, e.g., heavy wear from catalytic fines, corrosive wear will also increase.

20.2. Abrasive wear

Abrasive wear is displacement or removal of material caused by hard protrusions or hard particles which are forced against and moving along a solid surface. In case of protrusion or asperity contact, the wear is called two body abrasion while it is named three body abrasion in the case of hard particle (e.g., catalytic fines) involvement.

Abrasive particles cause wear when they enter the combustion become trapped between sliding surfaces such as the piston ring and liner, or the piston ring and ring groove.
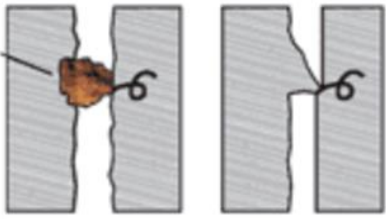
Catalytic fines (examples at red arrows) embedded in the soft graphite lamellas in a cylinder liner surface	**Abrasive wear, 3-body, and 2-body abrasion - Wear from catalytic fines is 3-body abrasion**

Figure 41 - Replica print showing catalyst fines and Schematic of abrasive wear [14]

The particles are trapped either rolling freely between the sliding surfaces, or partially embedded in one of the surfaces - see Figure 41 where catalytic fines are being trapped between the piston ring and the liner. The wear process is 3-body abrasive wear. The more and bigger the particles are, the higher the wear will be. The amount of wear depends primarily on the hardness of the two materials in contact. If a surface has a hardness of more than half of the abrasive particle or protrusion, it is normally regarded as sufficiently wear resistant. Catalytic fines abrasive wear can happen quickly and can lead to escalating replacement, installation and dry dock costs if not dealt with in a timely manner.

Abrasive wear will only occur when the lube oil is insufficient to separate the two components from each other. Polishing, scratching, and grinding are all a result of abrasive wear. This is the most common type of wear in industrial equipment.

20.3. Adhesive wear

Adhesive wear is the result of the high mechanical load of two opposing, sliding surfaces leading to increased duration of contact and/or increased temperature in the contact. This can lead to plastic deformation or micro welding and will lead to tearing of material and/or transfer of material from one surface to the other. See schematic in Figure 42 below.

Load force, material hardness, crystal structure, affinity of the applied materials and material oxidation are key factors affecting the level of adhesive wear. Typical adhesive wear will start at the top of an asperity, where the local load can be very high, and can then form micro-seizure spreading quickly to neighbouring surfaces in a self-accelerated manner. This is then known as scoring, galling, seizure, or scuffing.

Lack of a lube oil film will not necessarily result in adhesive wear, depending on the affinity of the materials.

Figure 42 - Schematic of adhesive wear [14]

20.4. Erosion/Cavitation

Cavitation is a form of erosive wear where a material surface erodes over time due to local high amplitude short duration and small footprint loads from repeated individual and collective cavitation bubble collapse. Cavitation initiates from bubble nuclei in the liquid, which when exposed to low pressures grow explosively then collapse violently when the pressure recovers, thus generating very high local pressures and shock waves. When a bubble collapses onto a material surface, a re-entrant micro jet forms in the deformed bubble, vectors towards the material and impacts its surface with shock waves forming in the subsequent dynamics. The flow due to the bubble collapse and the re-entrant jet impact generate high impulsive stress into the material. When these exceeds the elastic limit of the material, permanent deformation occurs, and a microscopic pit is generated.

21. References

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[13] MAN Energy Solutions, Instruction Manuals.

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22. Abbreviations/definitions

Al+Si – Aluminium and Silicon

CFR – Certified Flow Rate

Deleterious material – material causing harm or damage

DM – Distillate Marine (fuel)

EGCS – Exhaust Gas Cleaning System

FCC – Fluidised catalytic cracking

FO – Fuel Oil

HSFO – High Sulfur Fuel Oil (>0.50%S)

LO – Lube Oil

MCR – Maximum continuous rating

OEM – Original Equipment Manufacturer

PP – Pour Point

RM - Residual Marine (Fuel)

S - Sulfur

SEM – Scanning Electron Microscope

TSA – Total sediment accelerated

TSP – Total sediment potential

ULO – Used Lube Oil

ULSFO – Ultra Low Sulfur Fuel Oil (≤0.10%S)

VFD - Variable frequence drive

VLSFO – Very Low Sulfur Fuel Oil (≤0.50%S)

WAT – Wax Appearance Temperature

WDT – Wax Disappearance Temperature

WG7 – Working Group 7 (CIMAC)

DF

RF

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