Evolution of Fuels with the Advancement of Powertrains

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Abstract The primary source of energy in all engines and powertrains is the "Fuel". This term includes a range of different types from gas to distillate or synthetics and to heavy liquid fuels. The primary function of a fuel is to offer the requested amount of energy to the powertrain in all conditions and in all domains (land, sea, and air). Additionally, fuel is an important source of emissions that strongly impact air quality but also a pollutant for land and marine environments. The continuous effort to impose stricter limits led to the alteration of the fuel characteristics. Simultaneously, compatible advance alternative fuels (ex. biofuels such as biomethane, biodiesel, bioethanol, etc.) and renewable and synthetic fuels entering the market. This chapter presented an overview of Fuel characteristic associated with the development of different standards (both civil and military) for different kind of fuels which are associated with different propulsion systems. The continuous development of the fuel standards for compressed ignition engines in association with the biofuel standards will be analyzed. For spark ignition engines, unleaded petrol in association with ethanol fuel as blending components for petrol will be examined. The development of marine fuels including the biofuels and the new synthetic fuels from synthesized hydrocarbons will be presented. The Liquefied Petroleum Gas (LPG) will be examined. An important analysis will be presented for the aviation turbine fuels through the development of synthesized hydrocarbons.

Keywords Diesel · Biodiesel · Petrol · Ethanol · Marine fuel · Aviation fuel · Synthetic hydrocarbons

Abbreviations

ASTM	American Society for Testing and Materials
ATJ-SPK	Alcohol-To-Jet synthetic paraffinic kerosene

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BTL	Biomass-to-Liquid
CCAI	Calculated Carbon Aromaticity Index
CFPP	Cold Filter Plugging Point
CHJ	Catalytic Hydrothermolysis Jet
COS	Carbonyl Sulfide
cSt	Centistokes (1cSt = 1 mm^2/s)
CTL	Coal-to-Liquid
DPFs	Diesel Particulate Filters
DNV	Det Norske Veritas
EGD	European Green Deal
FAME	Fatty Acid Methyl Esters
FT	Fischer–Tropsch
CEN	European Committee for Standardization
GHG	Green House Gas
GND	Green New Deal
GTL	Gas-to-Liquid,
HC	Hydrocarbons
HEFA	Hydroprocessed Esters and Fatty Acids
HRD	Hydroprocessed Renewable Diesel
HVO	Hydrotreatment Vegetable Oils
IMO	International Maritime Organization
ISO	International Organization for Standardization
JP	Jet Propulsion
l	Liter
LNG	Liquefied Natural Gas
LPG	Liquefied Petroleum Gas
Max	Maximum
Min	Minimum
mg	Milligram
MON	Motor octane number
NCV	Net Calorific Value
NOx	Nitrogen Oxides
OECD	Organization for Economic Cooperation and Development
PAH	Polycyclic aromatic hydrocarbons
PGND	Pact for a Green New Deal
PM	Particulate Matter
ppm	Parts per million (1 mg/l = 1 ppm)
pS/m	Measure of electrical conductivity
1 pS/m	$1 \times 10^{-12}\ \Omega^{-1}\ M^{-1}$
PTL	Power-to-Liquid
RED	European Renewable Energy Directive
RON	Research Octane Number
SIP	Synthesized Iso-Paraffins
SPD	Synthesized Paraffinic Diesel
SPK	Synthesized Paraffinic Kerosine

SPK/A	Synthesized Paraffinic Kerosine plus Aromatics
TEU	Twenty-foot equivalent unit
ULO	Used Lubricating Oils
UN	United Nations
vol	Volume
wt	Weight
wsd	Wear scar diameter

1 Introduction

The members of the Organization for the Economic Cooperation and Development (OECD) are trying to limit the CO_2 emissions and to reach net zero emissions by 2050. Attempting to meet this challenge they "baptize" their programs' "Green Deal".

Examples are:

- the resolution in the US called "Green New Deal—GND" [1],
- the program in Canada "Pact for a Green New Deal—PGND" [2] and,
- in Europe "European Green Deal—EGD" [3].

The Global GNDs, while attempting to achieve their targets, they are pushing for the increment of the use of alternative fuels. The introduction of any fuel can be efficient only through the standardization process.

The energy challenges are not simply political challenges. Policy must be in line with technological change in order to be efficient and effective [4]. This is not always self-evident. The fact that European Renewable Energy Directive (RED) II has to be amended before even it could be transposed into National law shows that it has several shortcomings although it was adopted less than three years ago. Despite that the renewable fuels sector to date has realized the majority (>95%) of Green House Gas (GHG) emission savings in the transport sector, the lack of support and unfocused policy measures has resulted in that the fuel, the biofuel and alternative fuel industry has not been mobilized to its full capacity [5].

As the transportation platforms get more complicated, the equipment manufacturers face the challenge of adopting and constructing complex systems for their propulsion. The powertrains options have expanded beyond conventional fuels. Alternative powertrains may rely on alternative fuels from different primary sources or feedstocks from many different production paths with different degrees of efficiency.

This chapter will focus on the fuels which have been standardized to be commercially available. It will try to present the current state of the art of the fuel properties, which are responsible for the powertrain's continuous operability. In this attempt, the guide will be the international available standardization documents which are necessary first to establish the market and second to resolve any market failures.

The fuel technology influences the machines and powertrains design development and their environmental performance. Fuel is one of the pillars that helps powertrains be efficiently productive. Fuel characteristics depend on the specifications of the engine operating at different loads, in order for this cooperation to be efficient. It must always be borne in mind that the working environment of each powertrain determines its performance. On the other hand, the fuels must have sustainable characteristics. As a result of the above approach, the fuels used in the three domains (land, sea, and air) will be examined.

2 Land Domain

The fuel quality affects vehicle and engine operation, durability, and emissions. Fuel quality harmonization allows the introduction of common powertrain design worldwide. All the discussed advanced technologies will perform better when using a standard fuel of high quality [6]. Powertrain technology and certain fuel quality parameters influence not only the vehicle's fuel consumption but also its overall performance. The land-based powertrains, vehicle mainly, consumes liquid fuels which they have high energy density [7].

This chapter intends to cover the fuels for the transportation used in the land domain. Additionally, the housekeeping practices are essential to maintain the desired end use fuel quality. Chemical additives are very often used which aim to improve some quality characteristics of the fuel without having a holistic overview to the fuel-engine cooperation. The addition of additives must not affect the fuel standardized quality characteristics. The environmental requirements under the legislation in force must not reduce fuel efficiency and performance. The GHG emissions from the transportation sector are greater than the 90 s in the European Union [8, 9]. Unleaded Petrol and Diesel will be examined in this section as long with their bio replacements fuel Bioethanol and Fatty Acid Methyl Esters (FAME) well known as biodiesel, respectively.

2.1 Petrol

The current European quality requirements for the unleaded petrol specified mainly two types of unleaded petrol depending on the maximum ethanol content 5 or 10% vol. [10]. In Table 1 the main characteristics of unleaded petrol with 5–10% vol. ethanol are presented. The minimum requirements of the octane rating remain unchanged for at least the last two and a half decades. The octane number has impact to the engine performance, fuel efficiency, emissions and is associated with the resistance to auto ignition.

From 2008 until today the following changes have been made [10–12]:

- The introduction of bioethanol into the market [13]. This leads to the separation of the specifications into two categories with different bioethanol content. The

Table 1 European petrol specification based on [10]

Property	Units	Limits	5% ethanol	10% ethanol
Research Octane Number (RON)		Min	95	
Motor Octane Number (MON)		Min	85	
Density (at 15 °C)	kg/m^3	Max	775	
		Min	720	
Sulfur content	ppm	Max	10	
Manganese content	ppm	Max	2	
Oxidation stability	minutes		360	
Final boiling point (FBP)	°C	Max	210	
Distillation residue	% vol	Max	2	
Hydrocarbon type content	% vol			
Olefins		Max	18	
Aromatics		Max	35	
Oxygen content	% wt	Max	2.7	3.7

introduction of a higher percentage by volume of ethanol in the gasoline (10% vol.) has an impact on the refining and blending processes of the fuel as it influences the performance of the vehicle as the oxygenated organic compound increases the octane number. The first category contains bioethanol 5% vol. with a maximum oxygen content by weight of 2.7% wt., and the second 10% vol. with a maximum oxygen content of 3.7% wt.

- The addition of bioethanol changes the maximum volume of oxygenates in the petrol. This limit is important because the addition of ethanol (mainly bioethanol) change the volatility of the fuel and its distillation characteristics. The effect of this change is to affect the tailpipe and evaporative emissions. Car manufactures have introduced vehicles on the market that can use ethanol in greater amounts than 10% vol. [14, 15]. The current European specification for bioethanol is presented in Table 2.
- The change in the permittable manganese content is limited to 2 ppm. Manganese is the replacement of the lead in the petrol, and it was used as octane additive (octane booster). Its addition may affect the emission control systems and increase the low-speed pre-ignition in turbocharged engines. Car manufactures are strongly opposed the use of manganese and other metal additives such as Ferrocene which contains iron. The reason is that these metals poisoned the vehicle's catalyst and generating deposits in the spark plug.

- Sulfur reduced from 50 parts per million (ppm) to 10 ppm as result of stricter environmental legislation to reduce the sulfur oxides emissions [16–18]. Additionally, the sulfur in the fuel affects the lifetime of the catalyst and the sensors in the modern vehicles.

Table 2 Specification of bioethanol based on [14]

Property	Unit	Limits	Value
Ethanol plus higher saturated alcohols content	% wt	Min	98.7
Higher saturated (C3–C5) mono-alcohols content	% wt	Max	2
Methanol content	% wt	Max	1
Water content	% wt	Max	0.3
Total acidity (expressed as acetic acid)	% wt	Max	0.007
Electrical conductivity	pS/m	Max	2.5×10^6
Inorganic chloride content	ppm	Max	1.5
Sulfate content	ppm	Max	3
Copper content	ppm	Max	0.1
Phosphorus content	ppm	Max	0.15
Involatile material content	mg/100 ml	Max	10
Sulfur content	ppm	Max	10

It must be noticed that the unleaded petrol has a small amount of lead concentration (max. 5 ppm). Lead is a physical substance in the petrol. It has good lubrication performance but in amounts greater than 5 ppm contaminates the emission control system reducing the catalyst efficiency. The result of this is the increase of Hydrocarbons (HC) and Nitrogen Oxides (NO_x) emissions. The concentration of inorganic chlorine content in bioethanol is most of importance because chlorine forms highly corrosive acids during the combustion process which can damage the engine and destroy the fuel injection system.

2.2 Diesel

This section is trying to present the diesel fuel quality requirements reflecting the changes of standards in combination with the powertrains needs. The current diesel fuel standardization characteristics are presented in Table 3 [19]. The climate requirements are playing important role in the formulation of diesel characteristics because they influence the behavior of the hydrocarbon composition (paraffins, naphthene, aromatics). The property of the Cold Filter Plugging Point (CFPP) characterizes the cold flow performance of the fuel. The paraffinic hydrocarbons will come out of the fuel as waxes in low temperatures. Wax in the tank prevent the starting of the ignition process and is a source of operating problems. FAME is another parameter which can influence the cold flow performance of the finished fuel. It is important that FAME will be fully compliant with its standardized quality requirements.

Additionally, the climate regions are divided in two main categories, one is the temperate climate, and the other the arctic and severe climates.

Table 3 European diesel fuel specification based on [19]

Property	Unit	Limit	Value
Cetane number		Min	51
Cetane index		Min	46
Density at 15 °C	kg/m^3	Max	845
		Min	820
Viscosity at 40 °C	mm^2/s	Max	4.5
		Min	2
Distillation parameters			
% vol. recovered at 250 °C	% vol	Max	<65
% vol. recovered at 350 °C		Min	85
95% vol. recovered at	°C	Max	360
Polycyclic Aromatic Hydrocarbons (PAH)	% wt	max	8
Sulfur content	ppm	Max	10
Manganese content	ppm	Max	2
Carbon residue (on 10% distillation residue)	% wt	Max	0.3
Ash content	% wt	Max	0.01
Water content	ppm	Max	200
Total contamination	ppm	Max	24
FAME content	% vol	Max	7
Oxidation stability	Hours	Min	20
Lubricity, corrected wear scar diameter (wsd 1.4) at 60 °C	µm	Max	460

Arctic climates have been divided into four classes. Fuel flow and distillation properties are also different. The main characteristics of these classes are the lowest minimum value for density (800 kg/m^3) and the minimum viscosity (1.5 mm^2/s) to ensure the flow rate requirements of the powertrains.

The differences between the 2009 specifications and the current are the reduction of Polycyclic Aromatic Hydrocarbons (PAH) content from 11 to 8% wt. and the manganese content which is limited to 2 ppm. The PAH content is defined as the total aromatic hydrocarbon content minus the mono-aromatic-hydrocarbon content. The aromatic content of the diesel fuel is responsible for the formulation of the PAH and nitrogen oxide emissions because they influence the flame temperature during the combustion process into the chamber. The aromatic content is influencing the particulate matter emissions from the diesel engine. This reduction is in combination with the lower sulfur content of the fuel from 50 ppm, until the end of 2008, to 10 ppm.

Additionally, the new vehicle technology uses Diesel Particulate Filters (DPFs) in order to minimize the Particulate Matter (PM) emissions from the combustion of diesel fuel. The higher aromatic content of the fuel is shortening the regeneration interval of the filter and the result of this process is the plugging of the filter. Plugging of the filter not only increases the fuel consumption but also causes a backpressure in the exhaust system [6].

2.3 *Fatty Acid Methyl Esters (FAME)*

The current European specification for the FAME widely known as biodiesel is presenting in Table 4. The standard reference number is EN 14214 [20–22]. From 2009 until today the major changes are:

- the withdrawn of the carbon residue specification and
- the decrement of the maximum level of the finished fuel monoglycerides content.

The quality of the finished fuel has been improved throughout the years. The requirement to have minimum cetane number of 51 in combination with the limiting value of the carbon residue achieve the goal to reduce the excess amount of ignition improvers additives into the finished fuel.

The monoglyceride content along with the di- and tri- glyceride content is affecting the cold flow properties of the biodiesel. Car manufactures through the last decade

Table 4 FAME standardized characteristics based on [21]

Property	Unit	Limit	Value
FAME content	% wt	Min	96.5
Density at 15 °C	kg/m^3	Max	900
		Min	860
Viscosity at 40 °C	mm^2/s	Max	5
		Min	3.5
Cetane number		Min	51
Acid value	mg KOH/g	Max	0.5
Linolenic acid methyl ester	% wt	Max	12
Methanol content	% wt	Max	0.2
Monoglyceride content	% wt	Max	0.7
Diglyceride content	% wt	Max	0.2
Triglyceride content	% wt	Max	0.02
Water content	% wt	Max	0.05
Total contamination	ppm	Max	24
Sulfated ash content	% wt	Max	0.02
Sulfur content	ppm	Max	10
Sodium (Na) plus Potassium (K) content	ppm	Max	5
Calcium (Ca) plus Magnesium (Mg) content	ppm	Max	5
Phosphorus content	ppm	Max	4

introduced dedicated sophisticated vehicles for using 100% FAME fuel. If pure FAME diesel fuel is distributed in the market, then the fuel must have the same cold flow performance as the conventional diesel fuel. A computational guide has been introduced in order to help the producers to predict the performance of the fuel in cold weather conditions.

FAME is a good lubricity additive for the diesel fuel to avoid operation failures of the powertrains. It is important to have a good oxidation stability and for this reason additives were used to secure it, before the storage of the fuel. The amount of Sodium (Na), Potassium (K), Calcium (Ca) and Magnesium (Mg) must be between the referred limits because otherwise the fuel system of the vehicles will be poisoned.

2.4 Paraffinic Diesel

The paraffinic diesel fuels have been introduced into the European market from 2009. Through the last decade they have developed rapidly, and the standardization process has followed this development conducting a Common Workshop Agreement (CWA) on 2009 [23], a technical study on 2012 [24] and finally publishing the first European standard in 2016 [25]. The characteristics of the paraffinic diesel are illustrated in Table 5. The word "paraffinic" includes all the processes (everything to liquid) under the acronym XtL such as:

Table 5 Paraffinic fuel standardized characteristics based on [25]

Property	Unit	Limit	Fuel class A	Fuel class B
Cetane number		Min	70	51
Density at 15 °C	kg/m^3	Max	800	810
		Min	765	780
Flash point	°C	Min	>55	
Viscosity at 40 °C	mm^2/s	Max	4.5	
		Min	2	
Distillation parameters:				
Recovered at 250 °C	% vol	Max	<65	
Recovered at 350 °C	% vol	Min	85	
95% vol. recovered at	°C	Max	360	
Lubricity, wsd at 60 °C	µm	Max	460	
FAME content	% vol	Max	7	
Manganese content	ppm	Max	2	
Total aromatics content	% wt	Max	1.1	
Sulfur content	ppm	Max	5	
Total contamination	ppm	Max	24	

- BTL: Biomass-to-Liquid,
- GTL: Gas-to-Liquid,
- PTL: Power-to-Liquid and
- CTL: Coal-to-Liquid.

The Hydrotreatment can be used for the treatment of various vegetable oil feedstocks and produces the Hydrotreatment Vegetable Oils (HVO) which are covered by the same specifications. The distillation curve of the paraffinic diesel is different from the conventional as described above and covered by the EN 590 standard. Paraffinic fuels are divided into two (2) classes which are basically the same with only two differences:

- the cetane number and
- the range of the density.

These parameters are interconnected. The density is lower than the diesel fuel and this characteristic may affect the fuel economy of the powertrains.

This category of the fuel has good oxidation stability similar with the conventional diesel fuel, but they have, especially the class A fuels, high cetane number which can help the conventional fuel to have a clean burn. Paraffinic fuels have low concentrations of sulfur and aromatics. The cold flow properties are similar with the conventional replacement. They can be used securely as drop-in fuels.

On the other hand, the paraffinic fuels have low lubricity performance. Lubricity is one of the important parameters which always must be taken into consideration because it affects the performance of the engines and the powertrains. Not appropriate lubricity can cause:

- excessive pump wear leading to a catastrophic failure of the fuel pump,
- a fatal breakdown, and
- increased tailpipe emissions.

As mentioned above the FAME fuel has a very good lubricity and one of the reasons that this specification includes its addition is to improve the lubrication performance of the paraffinic fuels covered by this specification.

2.5 Liquefied Petroleum Gas (LPG)

The LPG is one of the products of the distillation process of the crude oil. LPG defined as low pressure liquefied gas composed of one or more light hydrocarbons. The LPG which consists mainly of propane, propene, butane, butane isomers, butenes with traces of other hydrocarbon gases and it is normally stored under pressure [26]. If the pressure is released, large volumes of gas will be produced which form flammable mixtures with air over the range of approximately 2–10% vol. The current standardization of the LPG is presented in Table 6. During the 2020 this specification is under amendment debating about the propane content of the fuel. The concentration

Table 6 LPG standardized characteristics based on [26]

Property	Unit	Limit	Value
MON		Min	89
1,3 butadiene	% wt	Max	<0.1
Propane content (debating)			
Until 30-04-2022	% wt	Min	20
From 01-05-2022	% wt	Min	30
Total sulfur content (after odorization)	ppm	Max	30
Evaporation residue	ppm	Max	60
Vapor pressure, gauge, at 40 °C	kPa	Max	1550
Vapor pressure, gauge, min. 150 kPa *(or* 200 kPa *debating), for different climate requirements:*			
Grade A	°C	Max	−10
Grade B			−5
Grade C			0
Grade D			10
Grade E			20

of propane is critical because is helping the cleaner combustion of the fuel and ensuring the ignition at very low temperatures in winter period. High vapor pressure is important for clean burning and for lean operation of the modern turbocharged engines.

The developments during the last decade in the LPG standardization are:

- the inclusion in the standard of the propane content of the fuel which as explained is important for the operational behavior of the gas engines.
- lower the limit for sulfur concentration of the fuel in order to be align with the environmental regulation and
- define separate limit for the 1,3 butadiene concentration because of the chemical safety legislation. The proposed concentration for 1,3 butadiene for the upcoming years will be 0.09% wt.

Table 7 Biomethane standardized characteristics based on [27]

Property	Unit	Limit	Value
Hydrogen	% wt	Max	2
Oxygen	% wt	Max	1
Sulfur	ppm	Max	30
$H_2S + COS$	mg/m^3	Max	5
Lower heating value (LHV)	MJ/kg	Min	39
		Max	48

2.6 Natural Gas - Biomethane

The use of natural gas and biomethane in the transport sector standardized in Europe with the technical standard document EN 16723-2 [27].

The concentrations of impurities are of importance of the fuel quality because they can harm the fuel system of the powertrains. Additionally, Biomethane contains silicon (Si) in amounts greater than 0.5 ppm. The current production methods cannot produce biomethane with concentration in silicon lower than this concentration. Great efforts of research are ongoing because higher concentrations than 0.1 ppm can harm many of the lambda oxygen sensors which are being available on the market today [28]. The biomethane must contain (Table 7):

- low concentrations of lubricating oil because otherwise they can harm the injection system.
- limited concentration of hydrogen because it can corrode the steel fuel tanks.

The hydrogen sulfide and the carbonyl sulfide (COS) used for safety purposes (odor mask) and contribute to the total sulfur of the fuel.

3 Maritime Domain

The world trade is depending on maritime transportation. According to United Nations (UN) in January 2020 [29] the world fleet reached the total carrying capacity of 2.1 billion dead-weight tons (dwt). 11.1 billion tons of cargo shipped globally in 2019, while the 7.9 billion tons of them were dry cargo [30].

Most of these ship vessels burns liquid fuels. In 2019 the total annual global marine fuel demand is more than 400 million tons. The containerships with more than 4,000 Twenty-foot Equivalent Unit (TEU) are responsible for the consumption of approximately 20% of all marine fuel. The fuel represents more than the 50% of the ship's total running costs [31].

The marine fuels classification is standardized by International Organization for Standardization (ISO) under the ISO 8216-99 standard document, in two categories. The one category contains the distillate marine fuels which are having the letter "D" in their definition and the other contains the residual marine fuels which are having the letter "R". For both categories, the letter "M" from the marine environment is used. The residual marine fuels accompanied by a number which defined the maximum kinematic viscosity of the fuel in square millimeters per second (mm^2/s) or centistoke (cSt) at 50 °C [32, 33]. The new era in marine fuel composition established in 2017. In the present state, the fuel shall contain hydrocarbons from synthetic or renewable sources such as HVO, GTL or BTL fuel and co-processed renewable feedstock which can be blended at the refineries with petroleum derived hydrocarbons.

3.1 Distillate Marine Fuels

The family of the distillate marine fuels currently includes seven categories of fuels as depicted in Table 8 based to the current standardization documents ISO 8216:2017 and ISO 8217:2017 [33, 34].

The characteristics of the DMX fuel remain unchanged during the last 12 years. As emergency fuel has lower flash point (>43 °C), has greater cetane index (>45) and its kinematic viscosity is between the range of 1.4–5.5 mm^2/s. Although, DMX is fuel for emergency purposes, in 2010 lubricity characteristic (max 520 μm at 60 °C) was added in order to provide the same lubrication performance with the other distillate marine fuels. The marine fuels for general purposes are mainly the DMA (DFA) and DMZ (DFZ). The difference between DFA and DMA is that the DFA marine fuel contains FAME (biodiesel). The same difference exists between DFZ and DMZ marine fuels. The characteristics of DMA are presented in Table 9. Through the last 12 years the major changes are the introduction of lubricity characteristic during 2010

Table 8 Classification of distillate marine fuels based on [33]

Category						
DMX	DMA	DFA	DMZ	DFZ	DMB	DFB
Fuel for emergency purposes	Fuel for general purposes. DFA can contain FAME up to 7% vol		Fuel for general purposes. DFZ can contain FAME up to 7% vol		Fuel for general purposes which may contain traces of residual fuel. DFB can contain FAME up to 7% vol	

Table 9 DMA fuel characteristics based on [34]

	Unit	Limit	ISO 8217:2017
Density at 15 °C	kg/m^3	Max	890
Kinematic viscosity at 40 °C	mm^2/s	Min	2
		Max	6
Flash point	°C	Min	60
Sulfur	% wt	Max	1
Cetane index		Min	40
Ash	% wt	Max	0.01
Hydrogen sulfide	ppm	Max	2
Acid number	mgKOH/gr	Max	0.5
Oxidation stability	gr/m^3	Max	25
Lubricity, corrected wear scar diameter (wsd 1,4) at 60 °C	μm	Max	520
Fatty acid methyl ester (FAME)	% vol	Max	7 (DFA)

to prevent the failure of the rotary mechanics and the reduction of sulfur concentration in 2017 due to lower the emissions of sulfur oxide in the marine sector. DMA (DFA) has a kinematic viscosity gradient of 4 mm^2/s while the DMZ (DFZ) has 3 mm^2/s.

The DMB (DFB) grades can include residual fuel, and this is the reason that the viscosity is limited between 2.0 and 11.0 mm^2/s. The other characteristics that are necessary and depend on the nature of the fuel are: the concentration of water that has a maximum of 0.3% vol. and the total sediment having a maximum limit of 0.1% wt. In addition, the cetane index has a minimum value of five points lower than other marine distillation fuels, which indicates that this category does not have the same combustion efficiency as DMA and DMZ marine fuels.

For distillate marine fuels the amount of energy which the fuel can contribute during the combustion process can be expressed by the Gross Specific Energy (Q_{Dgv}) and the Net Specific Energy (Q_{Dnp}), both expressed in megajoules per kilogram (MJ/kg). These standardized equations must be used in the marine domain instead of Net Heating Value (NHV) and the Higher Heating Value (HHV) of the fuel.

The above-mentioned parameters can be calculated through the Eqs. 1 and 2 respectively [34]:

$$Q_{\mathrm{Dnp}} = \left(46.423 - 8.792\rho_{15}^2 \cdot 10^{-6} + 3.170\rho_{15} \cdot 10^{-3}\right) \cdot [1 - 0.01(w_w + w_a + w_s)] + 0.094\,2w_s - 0.024\,49w_w \tag{1}$$

$$Q_{\mathrm{Dgv}} = \left(51.916 - 8.792\rho_{15}^2 \cdot 10^{-6}\right) \cdot [1 - 0.01(w_w + w_a + w_s)] + 0.094\,2w_s \tag{2}$$

where:

- ρ_{15} = the density at 15 °C, $\mathrm{kg/m}^3$.
- w_w = the water content, %wt.
- w_a = the ash content, %wt. and
- w_s = the sulfur content, %wt.

Fleets around the world have issued their minimum quality requirements for Naval Distillate Fuel. The specifications change through the last decade are depicted in Table 10 [35–37]. The requirements are stricter than the distillate marine fuel according to ISO 8217.

Lubricity requirement of 460 μm, established in order to predict the wear on engine components, particularly the fuel pump in order to prevent engine breakdown. With the advent of low Sulfur marine diesel, lubricity became a requirement in most fuels for predictive maintenance purposes. In Fig. 1 a measurement of Lubricity parameter using the High Frequency Reciprocating Rig (HFRR) method for a distillate marine diesel fuel with sulfur concentration 0.092% wt. is illustrated [38]. From 2014 a minimum requirement for Aromatics content is added. This need is because of the introduction of Synthesized Paraffinic Diesel (SPD). Aromatics improve the

Table 10 Naval distillate fuel properties based on [37]

	Unit	Limit	Distillate marine fuel	Synthesized marine diesel
Density, at 15 °C	kg/m^3	Max	876	805
		Min	800	770
Distillation parameters:				
10% vol	°C		Record	191–290
50% vol			Record	Record
90% vol			Max. 357	Max. 357 Min. 290
Distillation end point			Max. 385	Max. 385 Min. 300
Residue + Loss	% vol	Max	3	3
cloud point	°C	Max	−1	−1
Flash point	°C	Min	60	60
Particulate contamination	ppm	Max	10	1
Viscosity, at 40 °C	mm^2/s	Max	4.3	4.3
		Min	1.7	1.7
Acid number	mg KOH/g	Max	0.3	0.08
Ash	% wt	Max	0.005	–
Aromatics	% wt		Min. 8.1	Max. 0.5
Carbon residue on 10% bottoms	% wt	Max	0.2	–
Hydrogen content	% wt	Min	12.5	14.5
Derived cetane number			Min. 42	Max. 80 Min. 42
Storage stability	mg/100 ml	Max	3	–
Sulfur content	% wt	Max	0.0015	0.0015
Trace metals:				
Calcium	ppm	Max	1	0.1
Lead	ppm	Max	0.5	0.1
Sodium plus Potassium	ppm	Max	1	0.2
Vanadium	ppm	Max	0.5	0.1
Lubricity, at 60 °C	µm	Max	460	–

stability of the fuel, but they have negative impact on ignition properties of the diesel fuel.

From 2014 the naval distillate marine fuel can be blended at a maximum of 50% vol. with SPD which is derived from Hydroprocessed Renewable Diesel (HRD) or Fischer–Tropsch (FT) produced SPD. The remaining 50% vol. of the blending

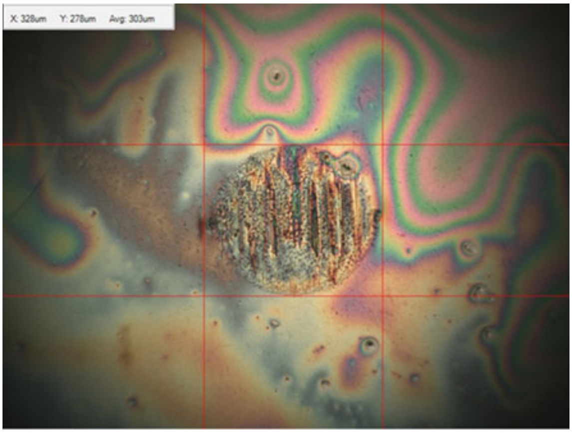

Fig. 1 Lubricity measurement of distillate marine fuel having 0.092% wt. Sulfur concentration

fuel must be from crude petroleum source derived hydrocarbons. The FT Hydroprocessed Synthetic Paraffinic Diesel (FT-SPD) and HRD derived blend components shall conform to the requirements presented in Table 10. It is defined that FT blending components shall be wholly derived from synthesis gas via the FT process using iron or cobalt catalyst and HRD blend components shall be comprised of hydrocarbon fuel obtained from hydrogenation and deoxygenation of fatty acid esters and free fatty acids. The processing of the product shall include hydrotreating, hydrocracking, or hydro-isomerization operational refinery processes such as polymerization, isomerization, and fractionation. On the contrary FAME are limited to 0.1% vol.

The synthesized paraffinic marine diesel has the limitation of 0.1 ppm per metal, in the content of various metals. This is because due to the current processes various metals can be included into the fuel. More specifically, this limitation applies to Aluminum (Al), Calcium (Ca), Cobalt (Co), Chromium (Cr), Copper (Cu), Iron (Fe), Magnesium (Mg), Manganese (Mn), Molybdenum (Mo), Nickel (Ni), Phosphorus (P), Lead (Pb), Palladium (Pd), Platinum (Pt), Tin (Sn), Strontium (Sr), Titanium (Ti), Vanadium (V) and Zinc (Zn). Additionally, the total concentration of alkali metals and metalloids which are Boron (B), Sodium (Na), Potassium (K), Silicon (Si) and Lithium (Li) must not exceed the 1 ppm. All the above limitation is because the metals in the fuel can:

- damage the fuel systems,
- create corrosive environment in the chamber and
- increase the wear in the moving parts of every marine engine.

3.2 Residual Marine Fuels

The family of the residual marine fuels currently includes eleven categories of Fuels as depicted in Table 11 based to the current standardization documents ISO 8216:2017 and ISO 8217:2017 [39]. In order to predict the combustion characteristics of the residual fuel an indicator for the ignition performance was developed. This is the Calculated Carbon Aromaticity Index (CCAI), an index which is associated with the viscosity and the density of the fuel as illustrated in Eq. 3 [39].

$$\mathrm{CCAI} = \rho_{15} - 81 - 141 \cdot \log_{10}\left[\log_{10}(\nu + 0.85)\right] - 483 \cdot \log_{10}\frac{\mathrm{T} + 273}{323} \qquad (3)$$

where:

- ρ_{15} = is the density at 15 °C, kg/m^3,
- ν = is the kinematic viscosity at temperature T, mm^2/s (cSt) and
- T = is the temperature, at which the kinematic viscosity is determined.

The CCAI is an important index because fuel with long ignition delays and bad combustion properties may contribute to an excessively high rate of pressure rise and thermal overload in the combustion chamber. This causes what is known as hard, knocking, or noisy engine running, especially at low load operation. The effects which are likely to follow, are poor fuel economy, loss of power, buildup of carbonaceous deposits and a possible engine damage from fatigue failure or metal-to-metal contact of shock loaded components. Examples of CCAI calculation, using Eq. 3, are illustrated in Fig. 2.

The residual marine fuels could be a potential place of discharging Used Lubricating Oils (ULO). This is inappropriate environmental behavior which can damage the heavy-duty marine engines. Thus, the residual fuels shall be free of ULO. In

Table 11 Classification of general-purpose residual marine fuels based on [33]

Category	Maximum kinematic viscosity at 50 °C (mm^2/s)
RMA	10
RMB	30
RMD	80
RME	180
RMG	180
RMG	380
RMG	500
RMG	700
RMK	380
RMK	500
RMK	700

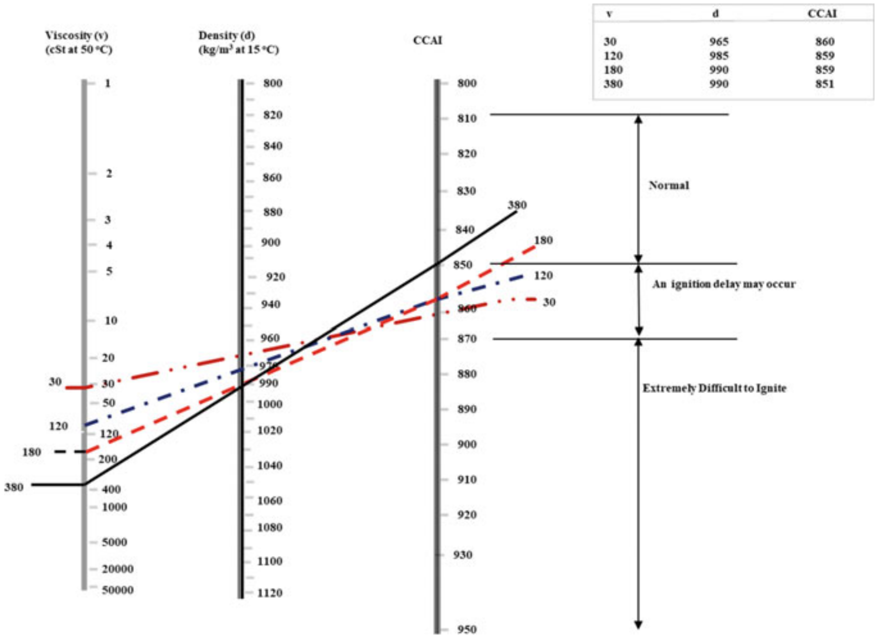

Fig. 2 Examples of CCAI calculation

order to identify the existence of ULO in the marine fuel the following Eqs. 4 and 5 must be considered.

$$\mathrm{K} > 30\mathrm{ppm} + \mathrm{Zn} > 15\mathrm{ppm} \tag{4}$$

or

$$\mathrm{K} > 30\mathrm{ppm} + P > 15\mathrm{ppm} \tag{5}$$

The lubricating oils contain significant amounts of detergent and anti-wear additives. Calcium as well as calcium compounds are the base of the detergent additives of lubricating oils. Zinc and Phosphorus compounds are in high concentrations in the anti-wear additives. If the Eqs. 4 and 5 are not satisfied, then the residual marine fuel assumed to be free of ULO. The current characteristics of the RMA 10, RMB 30 and RMD 80 residual fuels are illustrated in the Table 12.

The limit of Vanadium and Sodium in the fuel is of great importance. Vanadium exists in the fuel oils as part of complex hydrocarbon molecules which also contain other metals and elements. The Sodium can be entered either into fuel through its contamination with sea water or into the combustion zone in a form of sea water aerosol entrained in the charging air. The limit in the water is a key parameter in order to avoid the entrance of sea water into the fuel. The concentration of these two

Table 12 Characteristics of residual fuel for the categories of RMA 10, RMB 30 and RMD 80 based on [34]

	Unit	Limit	RMA 10	RMB 30	RMD 80
Density at 15 °C	kg/m^3	Max	920	960	975
Viscosity at 50 °C	mm^2/s	Min	10	30	80
Flash point	°C	Min	60	60	60
Carbon residue	% wt	Max	2.5	10	14
Ash	% wt	Max	0.04	0.07	0.07
Water	% vol	Max	0.3	0.5	0.5
Vanadium	ppm	Max	50	150	150
Aluminum plus silicon	ppm	Max	25	40	40
Sodium	ppm	Max	50	100	100
CCAI		Max	850	860	860
Hydrogen sulfide	ppm	Max	2	2	2
Pour point (upper)					
Winter quality	°C	Max	0	0	30
Summer quality	°C	Max	6	6	30
Acid number	mgKOH/g	Max	2.5	2.5	2.5

elements is very important because the formulation of the extremely corrosive, for the cylinder metals, Na_2SO_4/V_2O_5 complex into the ash, can cause severe damage to the engine. The empirical knowledge has established the ratio of Na/V = 1/3 as very important in order to avoid a Vanadium rich ash.

The concentration of all the metals is important because they can formulate ash deposits which can cause severe damage to components (piston crowns, exhaust valves and turbocharger blade surfaces) [40].

For residual fuels, net specific energy, Q_{Rnp}, and gross specific energy, Q_{Rgv}, both expressed in megajoules per kilogram, can be calculated with a degree of accuracy acceptable for normal purposes from Eqs. 6 and 7, respectively. There is a difference in the calculation of the energy content of the fuel using the Lower Heating Value instead of the Net Specific Energy The examination of this difference for a gas turbine saws that it does not affect the calculations of the operating stages of the gas turbine except for the estimated specific fuel consumption which is greater [41].

$$Q_{\mathrm{Rnp}} = \left(46.704 - 8.802\rho_{15}^2 \cdot 10^{-6} + 3.167\rho_{15} \cdot 10^{-3}\right) \cdot [1 - 0.01(w_w + w_a + w_s)] + 0.094\,2w_s - 0.024\,49w_w \tag{6}$$

$$Q_{\mathrm{Rgv}} = \left(52,190 - 8,802\rho_{15}^2 \cdot 10^{-6}\right) \cdot [1 - 0,01(w_w + w_a + w_s)] + 0,094\,2w_s \tag{7}$$

where:

- ρ_{15} = the density at 15 °C, kg/m^3,
- w_w = the water content, %wt.,
- w_a = the ash content, %wt. and
- w_s = the sulfur content, %wt.

3.3 Liquefied Natural Gas (LNG) and Methanol

The use of Liquefied Natural Gas (LNG) increased during the last two decades. The ISO undertake considerable effort to issue a standard for this fuel. As a result, during 2020 the ISO 23306 specification of LNG was issued [42]. The limited standardized characteristics will be the standard quality of the fuel. Basically, the Nitrogen concentration must not exceed the 1% mol. The theoretical mixture of the LNG has the composition of 99% mol methane and 1% mol nitrogen. The knock resistance of the fuel depends on its composition and for prediction the method of Propane Knock Index developed by Det Norske Veritas (DNV) was presented. The Net Calorific Value (NCV) of the fuel must be at least 33.6 MJ/m^3. The energy output of the fuel when it is not used in reciprocating powertrains must be calculated using the Wobbe index which is the division of the calorific value with the square root of relative density of the fuel. Existence of the same impurities (siloxanes and ammonia) as mentioned in biomethane above can be found in LNG.

Also, the use of methanol as bunkering fuel has been increased. The use of methanol as a fuel introduced as a potential solution for the shipping industry to reduce the GHG emissions by 2050. Methanol powertrains are already available in the market. During the 2020 the first step in standardization of the fuel became available with the publication of a CWA 17540 from CEN [43]. This is the first approach for standardization of the use of methanol as marine fuel incorporating the guidelines for the safety of ships using methanol as fuel from International Maritime Organization (IMO).

4 Aviation Domain

The aviation fuel is synonym with the power. The combustion quality in association with the energy content are the dominant parameters which must ensure stable power production. Even though, the consumption of the global aviation fuel was decreased during the last eight years, while the need for high quality fuel increased [44].

The fuel has important roles in the engine control and in the cooling of engine's fuel system components. Other key parameters are the stability, lubricity, cleanliness, non-corrosivity and fluidity [45]. The years before 2020, the aviation sector was steadily growing. The forecast for the global aircraft fleet was 39,000 aircrafts [46, 47]. Jet fuel is the main cost for the global airline industry [48, 49]. Traditionally, the global specifications of the civil aviation turbine fuels are issued and maintained by the American Society for Testing and Materials (ASTM). The compositions of jet fuel are main hydrocarbons from 8 to 16 carbon atoms, in various chemical compounds such as alkanes, iso-alkanes, naphthenics or naphthenic derivatives and aromatic compounds [50, 51]. Napthenes and Isoparaffines with less than 12 carbon atoms, help to reduce the freezing point which is critical in high altitude flying [49]. Additionally, the jet engines rely on the aviation turbine fuel to lubricate the moving parts in fuel pumps and in the flow control units. The production process influences the fuel's lubricity behavior. The "straight-run" fuels have good lubricity behavior because they contain trace amounts of certain oxygen, nitrogen, and sulfur compounds. Hydrotreatment of the fuel reduces sulfur and aromatic content and removes the natural provide lubricity.

No change has been observed for the properties of the Jet A-1 during the last 5 years [52–55]. During 2018, a blend of conventionally produced kerosene with synthetic iso-paraffinic kerosene produced by SASOL, has been acceptable for use in the civil aviation sector. Only the Co-processed mono-, di-, and triglycerides, free fatty acids, and fatty acid esters producing co-hydroprocessed hydrocarbon synthetic kerosene is recognized as being acceptable for manufacturing jet fuel. All other feedstocks are excluded from the jet fuel processing [56]. There is also the restriction that the refinery units, where the processed streams are used for aviation fuel production, shall not exceed 5% vol. of mono-, di-, and triglycerides, free fatty acids, and fatty acid esters in feedstock.

The main changes in the extended requirements of aviation turbine fuels which are containing co-hydroprocessed esters and fatty-acids is the limit on the viscosity at -40 °C. The maximum value must be 12 mm^2/s and the maximum content of unconverted esters and fatty acids will not exceed the 15 ppm. The fuel performance enhancing additives and the fuel handling and maintenance additives maintained their dosage ratings.

One important safety parameter in all the aviation turbine fuels is the electrical conductivity. The generation of static electric charge when fuel moves through a pipe, hose, valves, or filters, must be avoided. The aviation turbine fuel can be a conductor because it contains trace amount of ionizable compounds like water, phenols and napthenic acids. The potential initiation of a spark must be avoided, and this is the reason why the use of electrical conductivity additive is a requirement. If electrical conductivity additive is used, the conductivity shall not exceed 600 pS/m at the point of use of the fuel. When electrical conductivity additive is specified by the user, the conductivity shall be between 50 and 600 pS/m under the conditions at point of delivery.

Simultaneously, the evolution of the standard specification for the Aviation Turbine Fuel Containing Synthesized Hydrocarbons has undergone [57–60]. The term Synthetic Paraffinic Kerosene (SPK) usually used for describing all the synthesized aviation fuels. The basic requirements of the aviation kerosene continue to be active but additional batch requirements for each of the production process have been established. These processes are the:

- Fischer–Tropsch (FT) hydroprocessed synthesized paraffinic,
- Synthesized Paraffinic Kerosine produced from Hydroprocessed Esters and Fatty Acids (HEFA),
- Synthesized Iso-Paraffins (SIP) produced from Hydroprocessed Fermented Sugars,
- FT Synthesized Paraffinic Kerosine plus Aromatics (SPK/A),
- Alcohol-To-Jet Synthetic Paraffinic Kerosene (ATJ-SPK)
- Catalytic Hydrothermolysis Jet (CHJ) and
- Bio-derived Hydroprocessed Hydrocarbons (BHH), esters and fatty acids.

The comparison of the detailed requirements for the finished fuel from various synthesized hydrocarbon processes are illustrated in Tables 13 and 14. From 2016 no alteration has been observed for the FT hydroprocessed SPK. For SPK produced by the HEFA process, from 2016 the only change was the slight increment of the upper limit of density to 772 kg/m^3 the rest of the properties remained unchanged.

FAME is considered as incidental contaminant for the aviation fuels which can be picked up during fuel conveyance. FAME like water can be the source of microbial growth. The organism can be either aerobic or anaerobic or both. They use the fuel as “food”, but jet fuel can provide also other element nutrients, except for phosphorus content. The best approach to microbial contamination is prevention.

The fuel specifications trying to control the properties which are having dependency with each other. If the total aromatics content increases, density, final boiling point temperature, and freezing point increases, on the other hand the smoke point decreases. The properties of the fuel influence the thermal stability of the fuel. In all engines the fuel is also used to remove heat. In aircrafts the fuel removes heat from the engine oil, the hydraulic fluid, and the air conditioning system. The uncontrolled thermal increment of the fuel can accelerate the reactions which can that lead to the formation of gum and particulates matters. These two unwanted products may clog fuel filters and deposit on the surfaces of aircraft fuel systems or/and restricting flow in small diameter passageways causing faults in fuel flow. These deposits may lead to operational problems and increased maintenance.

For all synthesized paraffinic fuels there is a limitation of 0.1 ppm in the content of various metals. More specifically, this limitation applied to Aluminum (Al), Calcium (Ca), Cobalt (Co), Chromium (Cr), Copper (Cu), Iron (Fe), Potassium (K), Lithium (Li), Magnesium (Mg), Manganese (Mn), Molybdenum (Mo), Sodium (Na), Nickel (Ni), Phosphorus (P), Lead (Pb), Palladium (Pd), Platinum (Pt), Tin (Sn), Strontium (Sr), Titanium (Ti), Vanadium (V) and Zinc (Zn).

Almost in all the synthetic kerosene production routes the maximum Halogen presence, which is the sum of the Fluorine (F), Chlorine (Cl), Bromine (Br), Iodine (I), and Astatine (At) content, will not exceed 1 ppm. On the contrary, if the fuel produced following the Synthesized Iso-Paraffins (SIP) process from hydroprocessed fermented sugars, each element of the halogen group will not exceed 1 ppm.

These limits are important because the fuel can corrode any of the materials which were used in the construction of aircrafts fuel systems including sealants, coatings, and elastomers. Additionally, these elements can form solid particulates which can

Table 13 Detailed requirements for synthetic kerosene produced by different synthesized hydrocarbons processes based on [55, 60]

Property	Unit	Limit	SPKA	HEFA	SIP	SPK/A	ATJ-SPK
Distillation parameters:							
10% vol	°C	Max	205	205	205	205	205
50% vol		Max	Report	Report	Report	Report	Report
90% vol		Max	Report	Report	Report	Report	Report
Distillation end point		Max	300	300	255	300	300
T90–T10		Min	22	22	5	22	21
Distillation residue	% vol	Max	1.5	1.5	1.5	1.5	1.5
Distillation loss	% vol	Max	1.5	1.5	1.5	1.5	1.5
Flash point	°C	Min	38	38	100	38	38
Density at 15 °C	kg/m^3	Max	770	772	780	800	770
		Min	730	730	765	755	730
Freezing point	°C	Max	−40	−40	−60	−40	−40
Cycloparaffins	% wt	Max	15	15	Not specified	15	15
Saturated hydrocarbons	% wt	Min	Not specified	Not specified	98	Not specified	Not specified
Farnesane	% wt	Min	Not specified	Not specified	97	Not specified	Not specified
2,6,10-trimethyldodecane	% wt	Max	Not specified	Not specified	1.5	Not specified	Not specified
Aromatics	% wt	Max	0.5	0.5	0.5	20	0.5
Paraffins	% wt		Report	Report	Not specified	Report	Report
Carbon and Hydrogen	% wt	Min	99.5	99.5	99.5	99.5	99.5
Nitrogen	% wt	Max	2	2	2	2	2
Water	ppm	Max	75	75	75	75	75
Sulfur	ppm	Max	15	15	2	15	15
FAME	ppm	Max	Not specified	5	Not specified	Not specified	Not specified

cause plug of the fuel filters and wear increment in all the moving parts, especially fuel pumps. Contamination from trace amounts of sodium, potassium, and other alkali metals in the fuel can cause corrosion in the turbine section of the engine [45].

The routes of the Catalytic Hydrothermolysis Jet (CHJ) and the production of synthesized paraffinic kerosene produced from bio-derived hydroprocessed hydrocarbons, esters and fatty acids are added as standardized procedures in 2020. These processes include combination of hydrotreating, hydrocracking, or hydroisomerization, and other conventional refinery processes, and shall include fractionation [60].

Table 14 Detailed requirements for synthetic kerosene produced by catalytic hydrothermolysis jet (CHJ) and bio-derived hydroprocessed hydrocarbons (BHH), esters and fatty acids based on [55, 60]

Property	Unit	Limit	CHJ	BHH
Distillation parameters:				
10% vol	°C	Max	205	205
50% vol		Max	Report	Report
90% vol		Max	Report	Report
Distillation end point		Max	300	300
T90–T10		Min	40	22
Distillation residue	% vol	Max	1.5	1.5
Distillation loss	% vol	Max	1.5	1.5
Flash point	°C	Min	38	38
Density at 15 °C	kg/m^3	Max	840	800
		Min	775	730
Freezing point	°C	Max	40	40
Cycloparaffins	% wt	Max	Report	50
Aromatics	% wt	Max Min	21.2 8.4	0.5 –
Paraffins	% wt		Report	Report
Carbon and Hydrogen	% wt	Min	99.5	99.5
Nitrogen	% wt	Max	2	2
Water	ppm	Max	75	75
Sulfur	ppm	Max	15	15
FAME	ppm	Max	5	5

- The Kerosene type aviation turbine fuel (Jet Propulsion-JP) which is used from fighter jets categorized as follows [61–65]:
- JP-8: Kerosene type turbine fuel which will contain a static dissipater additive, corrosion inhibitor/lubricity improver, and fuel system icing inhibitor, and may contain antioxidant and metal deactivator.
- JP-8 + 100: JP-8 type kerosene turbine fuel which contains thermal stability improver additive.
- JP-8 + static dissipater additive: Kerosene type turbine fuel which will contain a static dissipater additive, may contain antioxidant, corrosion inhibitor/lubricity improver, and metal deactivator but will not contain fuel system icing inhibitor.
- JP-5: High flash point (>60 °C), kerosene type turbine fuel.
- Jet A-1 and JP-8 having high similarity because most of the properties are identical. There are two differences as shown in Table 15. The one is the sulfur mercaptan content higher in the Jet-A1 and the other is the smoke point level which is higher in the JP-8.

Table 15 Existing differences between Jet A1 and JP-8 based on [55, 63]

Property	Unit	Limit	Jet A1	JP-8
Sulfur, mercaptan	% wt	Max	0.003	0.002
Smoke point	mm	Min	18	19

The maximum height of the flame that can be achieved without smoking is the smoke point definition. The difference in smoke point unveils the use (commercial fuel or fighter jets fuel). Another difference is that not all the synthetic routes, which used to produce synthetic kerosene, have been standardized and approved as drop-in fuels of JP-8. The routes that were standardized is the FT Process and the Hydroprocessed Esters and Fatty Acids (HEFA) synthetic kerosene.

The JP-5 is a high flashpoint kerosine-type fuel which is used for navy application (basically for air powertrains used from ships) because of safety considerations. The fuel has the same flash point (>60 °C) like the marine diesel fuels which were used for ships. In order to achieve this safety property, its composition is different than the JP-8 or/and Jet-A1. These differences are illustrated in the Table 16.

When the JP-5 contains synthesized hydrocarbons the additional requirements which are illustrated in Table 17 must be followed. The Derived Cetane Number, the

Table 16 Existing differences between Jet A1 and JP-5 based on [55, 65]

Property	Unit	Limit	Jet A1	JP-5
Sulfur, mercaptan	% wt	Max	0.003	0.002
Sulfur, total	% wt	Max	0.3	0.2 from 2013
Flash point	°C	Min	38	60
Density at 15 °C	kg/m^3	Max	840	845
		Min	775	788
Viscosity −20 °C	mm^2/s	Max	8	7 (until 2013 was 8.5)
Freezing point	°C	Max	−47	−46
Net heat of combustion	MJ/kg	Min	42.8	42.6
Hydrogen content	% wt	Min	Not specified	13.4
Smoke point	mm	Min	18	25 (until 2016 was 19)

Table 17 Additional requirements of JP-5 containing synthesized hydrocarbons based on [65]

Property	Unit	Limit	Value
Aromatics	% vol	Min	8
Distillation parameters:			
T50–T10	°C	Min	15
T90–T10	°C	Min	40
Derived cetane number		Min	40
Viscosity at −40 °C	mm^2/s	Max	12

viscosity and the distillation gradient were established from 2016. The net heat of combustion is usually predicted by fuel density, which is also a function of composition. The flow rate of the fuel in the fuel systems has close relationship with density [66].

A fuel for fighter jets applications, must have a high volumetric energy content because it is a way to maximizes the energy that can be stored in a fixed volume (fuel tanks) and thus provides the longest flight range. A fuel for commercial applications must have high gravimetric energy content giving the advantage to the aircraft to have lower fuel weight [67].

5 Conclusion

The range of the fuels used by engines with different "missions" for the road transport, shipping and the aviation transport sector was examined and presented in this chapter. There is no "silver bullet" fuel but fuels produced from different technologies and raw materials.

The different properties that influence their performance examined and illustrated. The future progress of the energy transition from the three transport domains will not be feasible without the use of conventional and alternative gaseous and liquid fuels. Fuels with greater energy densities and lower carbon footprint are likely to be required to achieve the transportation goals of every load in each domain.

References

1. Galvin, R. Healy, N.: The green new deal in the United States: what it is and how to pay for it. Energy Res. Soc. Sci. **67** (2020). https://doi.org/10.1016/j.erss.2020.101529
2. MacArthur, L.J., Hoicka, E.C., Castleden, H., Das R., Lieu, J.: Canada's green new deal: forging the socio-political foundations of climate resilient infrastructure? Energy Res. Soc. Sci. **65** (2020). https://doi.org/10.1016/j.erss.2020.101442
3. European Commission: A European green deal: striving to be the first climate-neutral continent (2019). https://ec.europa.eu/info/strategy/priorities-2019-2024/european-green-deal_en (Accessed 3 Jan 2020)
4. Sovacool, B.K.: How long will it take? Conceptualizing the temporal dynamics of energy transitions. Energy Res. Soc. Sci. **13**, 202–215 (2016). https://doi.org/10.1016/J.ERSS.2015.12.020
5. Maniatis, K., Landälv, I., Waldheim, L., van den Heuvel, E., Kalligeros, S.: REDII-revision: an opportunity to build on SGAB's 2017-recommendations and significantly increase the Renewable Fuels targets in EU transport (2020)
6. ACEA, Auto Alliance, EMA, JAMA: World Wide Fuel Charter 6th Edition. European Automobile Manufacturers Association (ACEA) Avenue des Nerviens 85, B-1040 Brussels, Belgium (2019)
7. Paoli, L. Teter, J. Tattini, J. Raghavan, S.: Fuel consumption of cars and vans. international energy agency (IEA) (2020). https://www.iea.org/reports/fuel-consumption-of-cars-and-vans. (Accessed 28 March 2021)

8. Gray, N. McDonagh, S. O'Shea, R. Smyth, B. Murphy, D. J.: Decarbonising ships, planes and trucks: an analysis of suitable low-carbon fuels for the maritime, aviation and haulage sectors. Adv. Appl. Energy **1** (2021). https://doi.org/10.1016/j.adapen.2021.100008
9. Transport & Environment. How to decarbonise European transport by 2050. Square de Meeûs, 18, 2nd floor, B-1050, Brussels, Belgium (2018)
10. EN 228:2012+A1:2017: Automotive fuels—unleaded petrol—requirements and test methods. European committee for standardization. Rue de la Science 23, B-1040 Brussels, Belgium (2017)
11. EN 228:2008: Automotive fuels—unleaded petrol—requirements and test methods. European committee for standardization. Rue de la Science 23, B-1040 Brussels, Belgium (2008)
12. EN 228:2012: Automotive fuels—unleaded petrol—requirements and test methods. European committee for standardization. Rue de la Science 23, B-1040 Brussels, Belgium (2012)
13. EN 15376:2011: Automotive fuels—ethanol as a blending component for petrol—requirements and test methods. European committee for standardization. Rue de la Science 23, B-1040 Brussels, Belgium (2011)
14. EN 15376:2014: Automotive fuels—ethanol as a blending component for petrol—requirements and test methods. European committee for standardization. Rue de la Science 23, B-1040 Brussels, Belgium (2014)
15. ACEA: E10 compatibility list. European automobile manufacturers association (ACEA) Avenue des Nerviens 85, B-1040 Brussels, Belgium (2018).
16. Directive 98/70/EC of the European parliament and of the council of 13 October 1998 relating to the quality of petrol and diesel fuels and amending council directive 93/12/EEC, OJ L 350, 28 Dec 1998
17. Directive 2003/17/EC of the European parliament and of the council of 3 March 2003 amending Directive 98/70/EC relating to the quality of petrol and diesel fuels, OJ L 76, 22 March 2003
18. Directive 2009/30/EC of the European parliament and of the council of 23 April 2009 amending directive 98/70/EC as regards the specification of petrol, diesel and gasoil and introducing a mechanism to monitor and reduce greenhouse gas emissions and amending council directive 1999/32/EC as regards the specification of fuel used by inland waterway vessels and repealing Directive 93/12/EEC, OJ L140, 5 June 2009
19. EN 590:2013+A1:2017: Automotive fuels—diesel—requirements and test methods. European committee for standardization. Rue de la Science 23, B-1040 Brussels, Belgium (2017)
20. EN 590:2009: Automotive fuels—diesel—requirements and test methods. European committee for standardization. Rue de la Science 23. B-1040 Brussels, Belgium (2009)
21. EN 14214:2012+A2:2019: Liquid petroleum products—fatty acid methyl esters (FAME) for use in diesel engines and heating applications—requirements and test methods. European Committee for Standardization. Rue de la Science 23, B-1040 Brussels, Belgium (2019)
22. EN 14214:2012: Liquid petroleum products—fatty acid methyl esters (FAME) for use in diesel engines and heating applications - Requirements and test methods. European Committee for Standardization. Rue de la Science 23. B-1040 Brussels, Belgium (2012).
23. CEN/CWA 15940:2009: Automotive fuels—paraffinic diesel fuel from synthesis or hydrotreatment—requirements and test methods. European committee for standardization. Rue de la Science 23. B-1040 Brussels, Belgium (2009)
24. CEN/TS 15940:2012: Automotive fuels—paraffinic diesel fuel from synthesis or hydrotreatment—requirements and test methods. European committee for standardization. Rue de la Science 23. B-1040 Brussels, Belgium (2012)
25. EN 15940:2016+A1:2018+AC:2019: Automotive fuels – Paraffinic diesel fuel from synthesis or hydrotreatment – Requirements and test methods. European Committee for Standardization. Rue de la Science 23. B - 1040 Brussels, Belgium (2019).
26. EN 589:2018: Automotive fuels—LPG—requirements and test methods. European committee for standardization. Rue de la Science 23, B-1040 Brussels, Belgium (2018)
27. EN 16723–2:2017: Natural gas and biomethane for use in transport and biomethane for injection in the natural gas network—part 2: automotive fuels specification. European committee for standardization. Rue de la Science 23. B-1040 Brussels, Belgium (2017)

28. ACEA, Auto Alliance, EMA, JAMA: World wide fuel charter, methane—based transportation fuels, 1st Edn. European automobile manufacturers association (ACEA) Avenue des Nerviens 85, B-1040 Brussels, Belgium (2019)
29. UNCTAD Handbook of Statistics 2020—maritime transport: fact sheet no. 14: Merchant fleet. United Nations development statistics and information branch, Palais des Nations, 1211 Geneva 10, Switzerland (2020)
30. UNCTAD Handbook of statistics 2020—Maritime transport: fact sheet no. 13: World seaborne trade. United Nations development statistics and information branch, Palais des Nations, 1211 Geneva 10, Switzerland (2020)
31. IHS Markit Ltd.: IMO 2020: what every shipper needs to know. (2019)
32. ISO 8216-99:2002: Petroleum products—fuels (class F)—classification—part 99: general. International organization for standardization (ISO), Chemin de Blandonnet 8. CP 401-1214, Vernier, Geneva, Switzerland (2002)
33. ISO 8216-1:2017: Petroleum products—fuels (class F) classification—part 1: categories of marine fuels. International organization for standardization (ISO), Chemin de Blandonnet 8. CP 401-1214 Vernier, Geneva, Switzerland (2017)
34. ISO 8217:2017: Petroleum products—fuels (class F)—specifications of marine fuels. International organization for standardization (ISO), Chemin de Blandonnet 8. CP 401-1214 Vernier, Geneva, Switzerland (2017)
35. MIL-DTL-16884L: detail specification fuel naval distillate. Naval sea systems command, 1333 Isaac Hull Avenue, SE, Stop 5160, Washington Navy Yard, DC, 20376–5160 (2006)
36. MIL-DTL-16884M: detail specification fuel naval distillate. Naval sea systems command, 1333 Isaac Hull Avenue, SE, Stop 5160, Washington Navy Yard, DC, 20376–5160 (2012)
37. MIL-DTL-16884N: detail specification fuel naval distillate. Naval sea systems command, 1333 Isaac Hull Avenue, SE, Stop 5160, Washington Navy Yard, DC, 20376–5160 (2014)
38. Krivokapic, M.: The effect of using aviation fuel JP8 in mixtures with F76 on the injection profile of MTU 538, MTU 232 engine burners. Diplomatic Thesis, Hellenic Naval Academy, Piraeus, (2019)
39. The International Council on Combustion Engines (CIMAC): fuel quality guide—ignition and combustion. CIMAC e. V. Lyoner Strasse 18, 60528 Frankfurt, Germany (2011)
40. The International Council on Combustion Engines (CIMAC): Recommendations regarding fuel quality for diesel engines. CIMAC e. V. Lyoner Strasse 18, 60528 Frankfurt, Germany (2003).
41. Savvakis, A.C., Venardos, T., Roumeliotis, I., Kalligeros, S., Aretakis, N.: The influence of the synthetic fuels use in the operation of naval gas turbine. Hellenic Institute of Marine Technology, Book of Marine Technology, pp. 35–45, Athens, Greece (2017)
42. ISO 23306:2020: Specification of liquefied natural gas as a fuel for marine applications. International organization for standardization (ISO), Chemin de Blandonnet 8, CP 401-1214 Vernier, Geneva, Switzerland (2020)
43. CWA 17540:2020: Ships and marine technology—specification for bunkering of methanol fueled vessels. European committee for standardization. Rue de la Science 23. B-1040 Brussels, Belgium (2020)
44. IEA, Global aviation fuel consumption, 2013–2021, IEA, Paris. https://www.iea.org/data-and-statistics/charts/global-aviation-fuel-consumption-2013-2021. Last Accessed 09 March 2021
45. Chevron Corporation: Aviation Fuels Technical Review. Chevron Global Aviation, Chevron Products Company, 1500 Louisiana Street, Houston, TX 77002 (2006)
46. Cooper, T., Reagan, I., Porter, C., Precourt, C.: Global fleet & MRO market forecast commentary (2019)
47. Gray, N., McDonagh, S., O'Shea, R., Smyth, B., Murphy, J. D.: Decarbonising ships, planes and trucks: an analysis of suitable low-carbon fuels for the maritime, aviation and haulage sectors. Adv. Appl. Energy **1** (2021). https://doi.org/10.1016/j.adapen.2021.100008
48. International Air Transport Association: Annual Review 2020. 76th Annual General Meeting, Amsterdam (2020)

49. Weia, H., Liua, W., Chen, X., Yanga, Q., Li, J., Chen, H.: Renewable bio-jet fuel production for aviation: a review. Fuel. **254** (2019). https://doi.org/10.1016/j.fuel.2019.06.007
50. Hileman, J.I., Stratton, R.W.: Alternative jet fuel feasibility. Transport. Policy **34**, 52–62 (2014). https://doi.org/10.1016/j.tranpol.2014.02.018
51. ASTM: Physical constants of hydrocarbon and non-hydrocarbon compounds. ASTM International, West Conshohocken, PA (1991). https://doi.org/10.1520/DS4B-EB
52. ASTM D1655-16c: Standard specification for aviation turbine Fuels. ASTM International, 100 Barr Harbor Drive, PO Box C700, West Conshohocken, PA 19428–2959. United States (2016)
53. ASTM D1655-17: Standard specification for aviation turbine fuels. ASTM International, 100 Barr Harbor Drive, PO Box C700, West Conshohocken, PA 19428–2959. United States (2017)
54. ASTM D1655-18a: Standard specification for aviation turbine fuels. ASTM International, 100 Barr Harbor Drive, PO Box C700, West Conshohocken, PA 19428–2959. United States (2018)
55. ASTM D1655-20d: Standard specification for aviation turbine fuels. ASTM International, 100 Barr Harbor Drive, PO Box C700, West Conshohocken, PA 19428–2959. United States (2020)
56. Defence Standard 91-091: Turbine fuel, Kerosine type, Jet A-1; NATO code: F-35; Joint Service Designation: AVTUR. UK Defence Standardization, Kentigern House, 65 Brown Street. Glasgow, G2 8EX (2018)
57. ASTM D7566-16b: Standard specification for aviation turbine fuel containing synthesized hydrocarbons. ASTM International, 100 Barr Harbor Drive, PO Box C700, West Conshohocken, PA 19428–2959. United States (2016)
58. ASTM D7566-17a: Standard specification for aviation turbine fuel containing synthesized hydrocarbons. ASTM International, 100 Barr Harbor Drive, PO Box C700, West Conshohocken, PA 19428–2959. United States (2017)
59. ASTM D7566-18: Standard specification for aviation turbine fuel containing synthesized hydrocarbons. ASTM International, 100 Barr Harbor Drive, PO Box C700, West Conshohocken, PA 19428–2959. United States (2018)
60. ASTM D7566-20c: Standard specification for aviation turbine fuel containing synthesized hydrocarbons. ASTM International, 100 Barr Harbor Drive, PO Box C700, West Conshohocken, PA 19428–2959. United States (2020)
61. MIL-DTL-83133G: Detail specification turbine fuel, aviation, kerosene type, JP-8, and JP-8+100. US Department of Defense, AFPET/PTPS, 2430 C Street, Building 70, Area B, Wright-Patterson AFB OH 45433–7631 (2010)
62. MIL-DTL-83133H (AMENDMENT 2): Detail specification turbine fuel, aviation, kerosene type, JP-8, and JP-8+100. US Department of Defense, AFPET/PTPS, 2430 C Street, Building 70, Area B, Wright-Patterson AFB OH 45433–7631 (2013)
63. MIL-DTL-83133J: Detail specification turbine fuel, aviation, kerosene type, JP-8, and JP-8+100. US Department of Defense, AFPET/PTPS, 2430 C Street, Building 70, Area B, Wright-Patterson AFB OH 45433–7631 (2015)
64. MIL-DTL-5624V: Detail specification turbine fuel, aviation, grades JP-4 AND JP-5. Naval air warfare center, Aircraft division Lakehurst, Code 4.1.2, Mail Stop 120–3, Route 547, Joint Base MDL, NJ 08733–5100 (2013)
65. MIL-DTL-5624W: Detail Specification Turbine Fuel, Aviation, Grades JP-4 AND JP-5. Naval Air Warfare Center, Aircraft Division Lakehurst, Code 4.1.2, Mail Stop 120-3, Route 547, Joint Base MDL, NJ 08733–5100 (2016).
66. Wang, X., Jia, T.,·Lun Pan, L., Liu, Q., Fang, Y., Zou, J-J., Zhang, X.: Review on the relationship between liquid aerospace fuel composition and their physicochemical properties. Trans. Tianjin Univ. **27**, 87–109. https://doi.org/10.1007/s12209-020-00273-5
67. Chevron Corporation: Aviation fuels technical review, 1500 Louisiana Street, Houston, TX 77002, (2006)