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CIMAC Guideline

Alternative fuels for stationary and marine 4-stroke engines

The first edition of this CIMAC Guideline was approved by the members of the CIMAC WG17 'Gas engines' at its meeting on March 2026

Content

1 Introduction

This CIMAC guideline is intended for customers, owners, operators, and regulators. It provides a high-level overview of alternative fuel options beyond conventional fuels such as HFO, VLSFO, and natural gas for power generation and marine applications. The fuels considered in this guideline are primarily carbon-free gaseous fuels (e.g., hydrogen, ammonia) and methanol and ethanol.

These alternative fuels, especially those produced from non-fossil sources are gaining attention and their use in reciprocating engines is seen as a key enabler of energy decarbonization. The properties of these fuels vary widely and therefore require different modifications of existing engines, different storage conditions and safety concepts.

The focus of this guideline is to support operation of engines using such gaseous or low flashpoint fuels, together with providing information on the required safety concepts, applicable rules and regulations and the engine technology modifications, including retrofit capability. Presentation in the form of overview tables allows a simple comparison of the options. Detailed descriptions of engine performance and emissions are the subject of future guidelines.

The production, transport and availability of alternative fuels as well as their costs and their life cycle assessment are out-of-scope of this guideline.

2 Properties of different fuels

In Table 1 some important properties for natural gas (NG) and selected alternative fuels (e.g., e-fuels or fuels from biogenic origin) are shown. There is a large difference in some key parameters. Hydrogen for example has a very low minimum ignition energy and a very high laminar flame speed compared to natural gas, it is the opposite as ammonia. Methanol has comparable parameters as natural gas.

Table 1: Properties of different fuels (Source: INNIO Jenbacher [1][2][3][4])

		NG[1]	SNG	H_2	Ammonia	Methanol	Ethanol
CH_4	Vol-%	97.5	100	0	0	0	0
C_xH_x	Vol-%	2.5	0	0	0	0	0
H_2	Vol-%	0	0	100	0	0	0
NH_3	Vol-%	0	0	0	100	0	0
Alcohol	Vol-%	0	0	0	0	100	100
LHV (volumetric)	MJ/Nm^3	36.7	35.8	10.8	13.7	15’820	23’447
LHV (gravimetric)	MJ/kg	49.0	50.0	120.0	18.7	19.9	29.7
Heat of evaporation/temp.	kJ/kg/ °C	~510/ -161.5	510/ -161.5	454/ -252.9	1’370/ -33.4	1’100/64.6	879/78.4
Specific thermal capacity cp	kJ/kg/K	2.17	2.17	14.24	2.06	2.47	2.5
Heat of evaporation and heating to 40°C	kJ/kg	~950	~950	~4’600	~1’500	N/A	N/A

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[1] The composition and properties of natural gas vary widely (mostly) depending on its origin. Values shown here are intended to serve as a frame of reference for the properties of the alternative fuels.

Auto-ignition temperature	°C	~ 595	595	585	657	439	425
Minimum ignition energy	mJ	~ 0.29	0.29	0.017	8	0.14	0.28
Adiabatic flame temperature	K	~ 2'223	2'223	2'483	1'850	1'910	2'355
WI	MJ/Nm^3	49	50	41	~25	N/A	N/A
Methane / Octane number		92 / -	100 / 130	0 / -	- / 130	- / 114	- / 111
Stoichiometric air req.	Nm^3/Nm^3	9.7	9.5	2.4	3.6	N/A	N/A
Stoichiometric air req.	kg/kg	~16	17.2	34.2	6.13	6.24	9
Laminar flame speed (stoichiometric)	cm/s	38	38	350	7	36	45
Density (273.15 K 0.1013 MPa)	kg/Nm^3	0.75	0.72	0.09	0.77	795	790
Lower flammability limit	Vol-%	~5	5	4	14.8	7.3	3.5
Upper flammability limit	Vol-%	~15	15	75	33.5	36	15
AEGL 1 (10 min)	ppm	N/A	N/A	N/A	30	670	N/A
EC Occupational exposure limit value[2] (8 hours)	ppm	N/A	N/A	N/A	20	200	260 (NL)

For more detailed fuel specifications see CIMAC WG publications, contact CIMAC WG 7 Fuels, CIMAC WG 17 Gas Engines, CIMAC WG 2 Classification, CIMAC WG 8 Marine Lubricants or check ISO Standards. For methanol, industry is using IMBCA Standard [5] and specifications are covered in the ISO marine fuel standard for methanol ISO 6583:2024 [6].

3 Applicable standards, rules & regulations

For the use of alternative fuels in marine engine applications the following standards, rules and regulations apply:

- General: For all alternative fuels, having a flashpoint of less than 60 °C, basic requirements are set in SOLAS[3] Chapter II-1, Part G. This part makes reference to IGF Code[4] which defines mandatory requirements for the use of gases or other low flashpoint fuels on seagoing ships, except for gas carriers. For gas carriers the mandatory requirements of the IGC Code[5] apply.
- Major requirements are always a secondary barrier for all fuel systems, provided with leak detection, and automatic shutoff systems for the fuel supply in case of leakages.

In addition to the general requirements of the IGF Code and the IGC Code, specific requirements apply for specific fuels:

- Natural gas: Specific requirements as set in IGF Code Part A-1, and IGC Code Chapter 16 for gas carriers, apply.

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[2] EC Occupational exposure limit according to Directive 2000/39/EC

[3] International Convention for the Safety of Life at Sea

[4] International Code of Safety for Ships Using Gases or Other Low-flashpoint Fuels

[5] International Code of the Construction and Equipment of Ships Carrying Liquefied Gases in Bulk

- Methanol and ethanol: Specific requirements as set in MSC.1/Circ.1621 apply [7]. For the time being these regulations are interim guidelines only, but they are clearly intended to be added to the IGF Code as an additional part in the future.
- Ammonia: Specific requirements as set in MSC.1/Circ.1687 apply [8]. For the time being these regulations are interim guidelines only, but they are clearly intended to be added to the IGF Code as an additional part in the future.
- Hydrogen: Specific requirements are under development at IMO[6] CCC[7]11. The work plan foresees publication of interim guidelines for ships using hydrogen as fuel in December 2025.

In addition to the above statutory requirements of IMO, most marine classification societies have developed own rules for classification of ships which use gas or other low flashpoint fuels. Furthermore, classification societies collaborate to develop Unified Requirements, Unified Interpretations to IMO mandatory instruments and IACS (International Association of Classification Societies) Recommendations [9].

For land-based applications consolidated standards similar to the marine sector do not exist. The engines must comply with the regulations that apply in the respective regions to which the engines are delivered. These regulations are diverse and need to be considered on a case-by-case basis.

4 Safety concepts

The utilization of alternative fuels for stationary and marine engines necessitates a comprehensive safety concept for the facility. A consistent set of safety measures/requirements for the engine and fuel supply is crucial to ensure secure operation. Particularly in marine applications, redundancy is one of the means for maintaining propulsion and power generation availability. To avoid an unacceptable loss of power various arrangements might be required included but not limited to safety functions for the engine, the engine room, and the fuel supply, but also for the engine operation itself. The fundamental elements of a safety concept can be summarized as follows:

- Given the properties of fuel such as material embrittlement and corrosiveness, appropriate materials should be employed for all fuel-carrying systems.
- The toxicity and flammability of the fuel necessitate specialized training for the staff, and suitable personal protective equipment is required.
- Fuel storage: The fuel tank should be safeguarded from external events that could cause damage, and the location of the tank should be chosen accordingly.
- Fuel piping system: Depending on the rules, regulations, and safety concept applied (stationary, marine), either double-walled or single-walled fuel piping systems are needed. Single-walled piping systems require special handling rules in case of leakage purging and inerting measures are integral elements of the safety concept for fuel piping, and provisions for purging with a suitable fluid should be installed in both cases.
- Machinery space: Emergency shutdown and gas-safe machinery space concepts are applicable. Therefore, a secondary barrier against leakages should be installed where double-walled piping is not applicable. Well-defined concepts for leakage handling (in the case of the emergency shutdown concept) are necessary.
- Ventilation (if applicable): Spaces for tank connections, fuel preparation rooms, double-walled piping systems, and ducts should be ventilated. Depending on the design, the crankcase and other

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[6] International Maritime Organization
[7] Sub-Committee on Carriage of Cargoes and Containers

engine compartments should also be considered. Typical ventilation requirements include the necessary rate of air changes, stopping/activation of ventilation fans, closing/opening of vents, and the location of the air inlet and exhaust duct, respectively.

- Monitoring and sensorics: Bunker stations, ventilated ducts, and double-walled fuel piping systems should be equipped with gas/vapor detectors and leak detection suitable for the fuel. Infrared sensors for flame detection of non-visible flames, e.g., methanol and hydrogen, might be considered.
- Automatic isolation of potential leakages, such as fuel supply shut-off, should be installed. If applicable, water curtains and/or airlock access should be installed to ensure safe entry into and exit from the fuel preparation room in case of leakages.
- New fuels need new skills, so personnel need to be trained to handle the new fuels.
- Personal and fire protection equipment needs to be in place and carefully maintained.

Each alternative fuel has its unique characteristics in terms of a safety concept. A summary is provided below for each alternative fuel, although it is not exhaustive and the statements only provide a guideline for the safe use of alternative fuels.

4.1 Hydrogen

As a fuel, hydrogen is used either as a compressed gas at ambient temperature or as a cryogenic liquid at extremely low temperatures (20 K at 101.3 kPa). It is crucial to isolate other gases or compounds from liquefied or cryogenic hydrogen to prevent low-temperature embrittlement and the formation of condensate or ice. For liquefied hydrogen, the use of vacuum-insulated pipes is recommended. Certain metallic materials bear the risk of embrittlement when brought into direct in contact with pure hydrogen or high hydrogen concentration.

Hydrogen has a wide range of explosion limits and is easily ignited, especially under stoichiometric conditions. All hydrogen systems and outlets should be considered hazardous zones. All equipment handling hydrogen should be protected against electric charge buildup. Hydrogen gas systems should incorporate measures to protect against deflagration and detonation, such as pressure relief systems, rupture discs, pipe purging, and ventilation. The piping system should be purged of air, oxygen, or other oxidizers. For liquid hydrogen systems, helium should be used for purging, while for gaseous hydrogen (temperature > 80 K), nitrogen or a noble gas could be used.

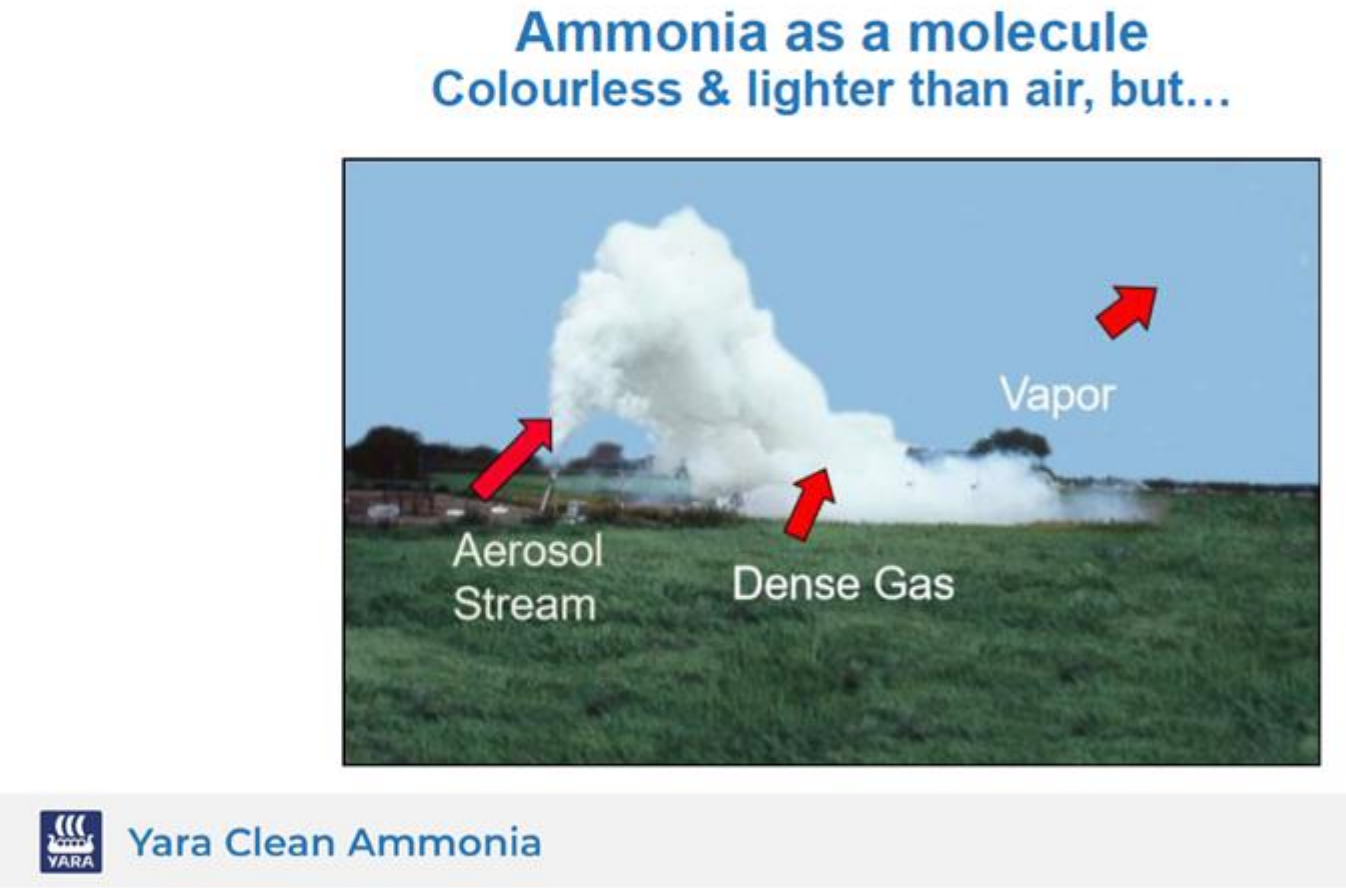
Leakages should be managed by ventilation systems. Double-walled pipes and valves are to be considered according to application-specific regulations and risk assessments. Evaporators are still under evaluation by class societies. Ventilation air from spaces where a leak might occur should be ventilated following similar criteria as for LNG. Vents from piping can likely be routed to the vent mast, although a larger/higher area of the hazardous zone at the vent outlet, compared to LNG, should be anticipated. As hydrogen is a light non-toxic gas that rises and disperses quickly in open air, it is recommended to keep systems in open air as far as reasonably practical.

4.2 Ammonia

As a fuel, ammonia, is generally stored as a liquefied gas, either compressed or refrigerated. Due to its low boiling point, ammonia has a significant cooling effect on its surroundings during evaporation. Consequently, materials used in its storage and handling should be resistant not only to corrosion but also to low temperatures. Ammonia can be stored in carbon steel tanks with applied controls to limit ammonia stress corrosion cracking.

Although ammonia is difficult to ignite and the likelihood of causing fires or explosive atmospheres in open spaces is relatively low, high concentrations of ammonia in closed and semi-closed spaces can be flammable. Ammonia is toxic to humans and mammals and poses a severe threat to aquatic life with long-lasting effects. Therefore, both hazardous and toxic areas must be carefully managed.

The density of ammonia must be taken into account when designing ventilation arrangements. Gaseous anhydrous ammonia is lighter than air, but released ammonia vapor could be heavier than air. Given the toxicity of ammonia, sufficient air change rates must be implemented to dilute the ammonia concentration to acceptable levels. In the event of an ammonia leakage, a higher air change rate should be installed. Areas where ammonia should not be present should be physically enclosed (in closed spaces) or separated by distance (in open spaces) to prevent toxic exposure.



Ammonia as a molecule
Colourless & lighter than air, but…

Figure 1: Ammonia release phases

Anhydrous ammonia is a hygroscopic compound, meaning it actively seeks water from the nearest source, including the human body. As such, the eyes, lungs, and skin, which have high moisture content, are at the greatest risk. Caustic burns occur when anhydrous ammonia dissolves into body tissues. With its low boiling point, anhydrous ammonia freezes upon contact with the skin at room temperature, causing burns that are similar to, but more severe than, those inflicted by dry ice. According to the Globally Harmonized System of Classification and Labelling of Chemicals [10], ammonia is classified as toxic to aquatic life, with long-lasting effects. The impact of various ammonia concentrations on the human body are summarized in Table 2.

Table 2: Karabeyoglu A. Brian E., 2012, DNV ammonia as a fuel safety handbook [11]

Effect	Ammonia concentration in air (by volume)
Readily detectable odor	20 – 50 ppm
No impairment of health for prolonged exposure	50 – 100 ppm
Severe irritation of eyes, ears, nose and throat. No lasting effect on short exposure.	400 – 700 ppm
Dangerous, less than ½ hours exposure may be fatal	2’000 – 3’000 ppm
Serious edema, strangulation, asphyxia, rapidly fatal	5’000 – 10’000 ppm

4.3 Methanol

Methanol is corrosive to certain materials, and its corrosive effect is amplified in the presence of specific metals such as aluminum and titanium alloys due to methanol’s conductivity. Therefore, the use of suitable materials, such as stainless steel, or special methanol-resistant coatings is required. Additionally, appropriate sealing materials like nylon, neoprene, or non-butyl rubber should be utilized.

Being a liquid at ambient conditions, methanol is easier to store and handle compared to ammonia or hydrogen. However, due to its relatively low flashpoint, care must be taken with the vapor phase that develops at ambient conditions. Methanol vapor is heavier than air and can be flammable at certain concentrations (flammability limit see Table 1). To prevent the formation of explosive atmospheres in the methanol tank vapor space, an inert gas, such as nitrogen, can be used. Moreover, the introduction of ignition sources or sparks to methanol conveying systems should be avoided. Due to methanol’s low viscosity compared to other liquid fuels, the risk of potential leakage (seal leaks) is increased. The detection of methanol leakages should ideally be redundant, covering both methanol vapor and liquid leakage.

The molecular weight of methanol vapor is slightly greater than that of air (32 versus 28 grams per mole). Consequently, depending on the circumstances of a release or spill, methanol liquid will pool, and vapor may migrate near the ground, collecting in confined spaces and low-lying areas. Methanol vapor, being near neutral buoyancy, will readily dissipate from ventilated locations but will not dissipate from non-ventilated locations such as sewers and enclosed spaces. If ignited, methanol vapor can flash back to its source.

Methanol is biodegradable and has less impact on aquatic life with non-long-lasting effects compared to conventional fuels. Due to its high solubility in water, methanol quickly dilutes if spilled in water, and only extremely high methanol concentrations are critical for the environment. However, the high toxicity of methanol to humans and mammals should be taken into account while handling methanol. A potentially lethal dose of methanol is approximately 30 to 240 mL or 1 gram per kilogram. Permanent visual damage may occur with minimum ingestion of 30 mL of methanol [12]. Methanol does not have to be swallowed to be dangerous since the liquid can be absorbed through the skin and other tissues, and the vapors through the lungs. Do not swallow methanol liquid, do not breathe methanol vapor, do not walk in pooled liquid, and do not allow vapor or liquid to contact skin. The inhalation risk is mitigated by a characteristic pungent odor. At concentrations greater than 2’000 ppm (0.2%), it is generally quite noticeable; however, lower concentrations may remain undetected while still being toxic over longer exposures and may still present a fire/explosion hazard. Toxicity alerts for methanol are normally set around 150-250 ppm, this is 0.015-0.025% in volume.

Methanol vapor may explode rather than burn on ignition. Methanol containers are subject to Boiling Liquid Expanding Vapor Explosion (short: BLEVE) when heated externally. Methanol is completely water miscible and retains its flammability even at very high concentrations of water. A solution of 75v% water and 25v% methanol should be considered a flammable liquid [13]. Methanol fires should be extinguished with dry chemical, carbon dioxide, water spray, or alcohol-resistant foam, as specified in Class Societies rules [13].

4.4 Ethanol

Ethanol shares many handling and safety characteristics with methanol and, where relevant, similar precautions apply. Like methanol, ethanol is corrosive to certain materials, though generally less aggressive; nonetheless, the use of compatible materials such as stainless steel and ethanol-resistant seals (e.g., fluoropolymers) is recommended. Ethanol is a liquid at ambient conditions and relatively straightforward to store and handle. However, due to its slightly higher flashpoint compared to methanol, ethanol still presents a vapor-phase flammability risk under ambient conditions. Its vapors are also heavier than air and can accumulate in low-lying or poorly ventilated areas, posing explosion hazards similar to methanol. While ethanol is less toxic to humans than methanol, it is still hazardous in high concentrations. Toxicity alerts for ethanol are typically set around 1’000 ppm (0.1% by volume), primarily to avoid effects such as dizziness, irritation, and long-term exposure risks. Ethanol can be absorbed via inhalation, ingestion, or skin contact, and prolonged exposure to high concentrations should be avoided. As with methanol, ethanol is fully miscible in water and retains flammability even in diluted form. Ignition sources must be strictly controlled around ethanol systems, and leak detection systems should monitor both vapor and liquid phases.

5 Multi-fuel capability

5.1 Single fuel operation

When an alternative fuel is used as single fuel, the full greenhouse gas reduction potential is possible. Additionally, avoiding the use of conventional fuels completely provides some additional benefits:

- The engine and mainly fuel supply design are simple, as there is only one fuel.
- Alternative fuels discussed in this paper do not form soot when burnt, therefore the soot emissions from such engines are very low and only related to the lube oil consumption.
- Depending on the chosen fuel and combustion concept (see §7), NOx emissions can be lower than with diesel combustion. See §8 for more information about emissions.

Using a single fuel also comes with downsides:

- There is no back up when the alternative fuel is not available, mainly an issue for ships or locomotives where there is no fixed trajectory.
- A single (alternative) fuel engine would require similar redundancy as a conventional fuel engine and for ships subject to the IGF Code, the “unacceptable loss of power” criteria should be considered for the arrangements.
- The most common combustion concepts used today will result in reduced dynamic response compared to diesel engines.

5.2 Fuel blend operation

Fuel blending or dual fuel combustion deals with these disadvantages. Methanol, ammonia or hydrogen cannot be blended as such with diesel. The dual fuel principle uses diesel fuel as pilot fuel to ignite the alternative fuel. The energy share of the alternative fuel can vary from about 60 % for simple systems and can go up to 95 % or higher with more complex systems.

By using this dual fuel principle, the engine can switch to full diesel operation instantly at any time, and thus providing full redundancy in case of emergency or simply when the alternative fuel is not available or not required. The same dynamic response as for diesel engines can be achieved.

Due to the required pilot fuel, the complexity of the fuel system increases, and the share of pilot fuel impacts the greenhouse gas reduction. This can be compensated by using biofuel or synthetic diesel as pilot fuel.

5.3 Retrofit

Since engines and their applications often have a lifespan of more than 20 years, retrofitting existing engines is the fastest way to defossilize.

Retrofitting existing engines is generally possible, suppliers have or are working on retrofit kits. Engine changes are different for different alternative fuels, but will include:

- Fuel system for the alternative fuel and optionally for the pilot fuel
- Charge air system
- Other hardware depending on the chosen approach, e.g., piston crown, camshaft
- Engine control system (electronic control of injectors, additional safety)

Apart from the engine itself, the aftertreatment might need a retrofit as well. See §8 for more details. In general, the impact on emissions is:

- Methanol reduces NO_X emissions. Methanol slip, formaldehyde and carbon monoxide can be present but can be reduced by a passive catalyst.
- For hydrogen, low NO_X can be achieved when extreme lean combustion is chosen.
- Ammonia combustion creates NO_X, but the emission level can be controlled by engine optimization and/or aftertreatment (SCR), unburnt NH_3 fuel must also be considered. N_2O emissions will be present and must be kept very low or have to be dealt with in aftertreatment as their global warming potential is 265 [IPCC AR 5] times that of CO_2
- None of these fuels form soot during combustion.

The fuel storage and supply retrofit often has the biggest impact. Some points of attention:

- Methanol can be stored liquid at atmospheric pressures, ammonia and hydrogen both can be stored pressurized or liquid when cooled. For hydrogen, cooling below 20 K is necessary.
- All alternative fuels have a lower volumetric density compared to diesel (cf. Table 1). For the same operating range more space is required. For methanol this is a factor 2.3 compared to diesel, for cooled ammonia this is a factor 3.4 and for cryogenic hydrogen a factor 7.7 [14].
- Fuel preparation complexity depends on the required pressure level, this depends on the injection strategy, see §6.

More information on examples of retrofits can be found in [15][16][17].

6 Fuel handling & admission concepts

Alternative fuels can be used with various fuel admission and combustion concepts. To provide a frame of reference for the options described in Chapter 6 (Fuel Admission) and Chapter 7 (Combustion), Table 3 illustrates where typical gas engines and compression ignition dual-fuel engines fall within these two categories.

Table 3: Overview of fuel admission for spark ignition gas engines and compression ignition dual-fuel engines

Fuel admission		
Single point fuel injection	Spark ignition gas engine	▨
Port fuel injection		Compression ignition dual-fuel engine
Low-pressure direct injection		
High-pressure direct injection	▨	

The following sections explain fuel injection for gaseous fuels in more detail. Liquid fuel injection pressures might deviate from the pressure ranges stated below.

6.1 Single point fuel injection

Single point fuel injection configurations include differential pressures from ~0.01 MPa up to ~1.0 MPa options with the difference being that lower pressure injection introduces the fuel before the turbocharger and the higher pressure concept introduces the fuel after the compressor of the turbocharger. Lower pressure is usually used in electric power applications where the supplied gas is often lower in pressure (like municipal distribution pressure) and higher pressure is used in some gas compression engine applications because the nearby gas pipeline has high pressure gas to feed the engine. These systems have the advantage that they are relatively simple, inexpensive, and the fuel/air is well mixed when they reach the engine cylinder. However, intake and exhaust valve timing must be optimized to minimize short-circuiting to the exhaust during overlap while not compromising volumetric efficiency or residual scavenging. Transient performance can also be a challenge because of the large premixed volume in the intake that must be consumed before changes in air-to-fuel ratio can influence engine output. Backfire is also a risk that must be managed due to the large premixed combustible volume in the intake manifold, especially with high flame speed/low ignition energy fuels like hydrogen.

6.2 Port fuel injection

Port fuel injection (PFI) uses injectors or valves at each intake port. While this reduces the volume of premixed fuel, it can impose mixture challenges because the physical space in which to accomplish mixing is much reduced. Some temporal control of the fuel admission is possible but is limited by valve timing. PFI enables several performance benefits when compared with single point fuel injection such as the ability to minimize fuel short circuiting with properly timed fuel injection even when longer valve overlap is used, the ability to adjust fuel quantity to each cylinder independently, and reduced fuel transport time from injection point to cylinder consumption. PFI requires one injector or fuel valve per cylinder and thus is a more complex fuel system compared with single point injection configurations. It is also mandatory that the fuel supply pressure is greater than the intake manifold pressure; typical systems operate at approximately 1 MPa fuel supply pressure.

6.3 Low-pressure direct injection

Low-pressure direct injection (LPDI) moves the fuel injection location one step closer to combustion both spatially and temporally compared with PFI. As the name implies, fuel is injected directly into each cylinder after the intake valve(s) closes. LPDI eliminates any premixed fuel in the intake manifold or port which can have several benefits. Fuels with low volumetric energy density and high ignitability, like hydrogen, benefit from improved volumetric efficiency and reduced risk of backfire. Liquid fuels have potential to be corrosive; moving the injection point into the cylinder eliminates intake component exposure to the corrosion/wear risk. Mixing can become a challenge for LPDI, though, as all air/fuel mixing must occur in-cylinder over a shorter time during compression. Charge motion strategies (swirl, squish, tumble) are often combined with injector characteristics to promote proper mixing. While there is no standardized fuel pressure limit for LPDI systems, most systems are typically designed to operate up to ~5 MPa fuel supply pressure.

6.4 High-pressure direct injection

High-pressure direct injection (HPDI) systems are similar to LPDI in that fuel is injected directly into each cylinder but is injected during combustion to produce a diffusive flame instead of premixed. HPDI systems often operate in the range of ~20- 50 MPa fuel supply pressures requiring complex fuel systems. When low cetane number fuels like hydrogen, methanol, or ammonia are used in HPDI systems it is common to require a more reactive pilot fuel like diesel to initiate combustion. The nature of diffusion flame has the potential to generate more NOx emissions compared with the premixed options already discussed due to the local air-to-fuel ratio at the flame zone.

6.5 Cracking of ammonia and methanol

Ammonia and/or methanol can be used as hydrogen carriers. The energy density of ammonia or methanol is 2 to 4 times higher than that of hydrogen, depending on hydrogen storage methods, making storage and transport more economical. In many cases green ammonia or methanol would be produced in regions with excess renewable energy and then transported via ship or pipeline to an unloading terminal where it would be cracked to hydrogen if a hydrogen distribution infrastructure exists; otherwise, the ammonia or methanol would be transported to a hub closer to the end use for cracking. Ammonia or methanol crackers may even be integrated within the fuel system of stationary engines that consume large amounts of fuel. Additionally, this hydrogen carrier scenario lends well to utilizing the ammonia or methanol as fuel for the cargo ships.

7 Combustion concepts

7.1 Spark ignition

Spark ignition engines utilize an electrical spark discharge to initiate combustion of an air/fuel mixture. A flame front propagates from the spark location across the combustion chamber consuming the mixture. Combustion in a spark ignition engine is very sensitive to the flame speed of the fuel. Air-to-fuel ratio and turbulence adjustments can be made to somewhat compensate for differences in flame speed.

7.2 Compression ignition

Compression ignition engines rely on fuel reactivity (autoignition temperature and ignition delay) to initiate combustion at in-cylinder pressure and temperature conditions near piston top dead center. Most compression ignition engines utilize liquid fuels and burn in a diffusive combustion process controlling combustion rate with injection rate. Alternative liquid fuels are often less reactive than diesel fuel and require ignition/cetane improver additives, or significantly increased compression ratio to drive in-cylinder conditions to higher pressures and temperatures for reliable and robust ignition of less reactive fuels.

In dual fuel engines utilizing alternative fuels as the main energy source a pilot diesel injection is used to initiate combustion that progresses via flame front propagation across the combustion chamber.

8 Exhaust gas aftertreatment

As above chapters already mentioned, alternative fuel options are different chemical compounds than more traditionally used energy carriers. Combustion of these alternative fuels can be achieved by the various mentioned combustion concepts explained in the previous section. In combination, the different composition and their different combustion concepts yield different emission spectra. Some of the observed compounds are already well-known pollutants, but in some combinations, they may come in very different concentration ranges than experienced so far. In addition, new exhaust species can be produced by combustion of alternative fuels, some of them acting as local pollutants, others as global greenhouse gas.

Exhaust gas aftertreatment technology can help to reduce the emissions from combustion of alternative fuels, not only for known pollutants but also for new emission compounds. The CIMAC Working Group 5: “Emission Control Technologies” has published a white paper on alternative fuels, providing an overview of the emissions which can be produced and what could be suitable technologies for their reduction. It is recommended to consult the referenced document for any further details regarding exhaust gas aftertreatment for alternative fuels.

9 Material compatibility

In this paragraph, major challenges of using alternative fuels in the current engine generations are discussed. Material compatibility regarding issues of using alternative fuels are known. Table 4 approaches the effect of alternative fuels and, for reference, methane on categories "corrosion", "wear", "ductility" and "dimensioning".

Alcohols react corrosively with most technical materials. The poor material compatibility of methanol due to the molecule polarity cause corrosion for both metallic components as well as elastomers used in fuel supply systems and engine seals. Methanol is the most aggressive alcohol towards copper, aluminum and magnesium, but steel and other ferrous metals are relatively less affected. In case of wear, the corrosion tendency in contact with alcohols probably leads to a tribocorrosive attack, which can be further aggravated by intermediate combustion products such as methanoic acid.

Ammonia is corrosive to brass, copper, nickel and elastomers as well as plastics. It is not critical for all other technical materials. However, there is a risk of nitric acid formation as a by-product of combustion. Therefore, not only the materials mentioned can be attacked by the ammonia combustion, but other materials and plastics can also be attacked by corrosion. Increased wear in direct contact with ammonia has not yet been observed. There is a risk, as with methanol, that wear may be increased by tribocorrosive mechanisms for the materials mentioned. In addition, corrosion can also occur if nitric acid is formed as a by-product of combustion.

Table 4: Effects of alternative fuels on materials relative to the reference (methane): → equal, ↓ worse, ↑ better

	Methanol	Ethanol	Hydrogen (H_2)	Ammonia (NH_3)
Corrosion	↓	↘	→	↘
Wear	↓	↘	→	→
Ductility	→	→	↓	→
Dimensioning	→	→	↓	→

Hydrogen cannot be assumed to have a direct corrosive or wear-promoting effect. Consideration can be given to the larger amount of water vapor produced during combustion (hydrogen: 268 g/kWh, natural gas: 162 g/kWh). A higher quantity of water vapor could increase the tendency to corrosion if it is not carefully purged from the combustion chamber. Hydrogen as a fuel does not contain carbon or any lubricating effect. Compared to all other fuels, hydrogen is the driest one and, therefore, an increased wear behavior in hydrogen atmosphere can be expected. Hydrogen is the only alternative fuel that is known to reduce the mechanical property ductility of technical materials, in particular high-strength materials. In order to minimize the hydrogen sensitivity and, therefore, hydrogen damage, components subjected to tensile and temperature loads should be carefully designed with an appropriated strength. This could be result in a change of component design under the same load.

Overall, the material compatibility issue of using alternative fuels requires a careful material selection in conjunction with a material-related design for manufacturing engine components. In case of non-dedicated engine for alternative fuels, consultation with the engine OEM is recommended to understand the extent of change required

10 Lubrication

As the development of engine hardware for alternative fuels is still ongoing at the time of publication, so too is the development of compatible lubricants. The current best practice is to align lubrication with the general principles of lubrication for zero sulfur fuels (e.g., gas or distillate). It is recommended to refer to current and evolving OEM guidelines and also consult with your lubricating oil supplier, as these guidelines may change dynamically. If not otherwise agreed, a fully approved lubricant suitable for the desired application should be selected, as these lubricants have undergone laboratory, engine, and field validation processes (OEM approval).

As always, lubricants will perform most effectively when used and maintained as part of a thorough engine maintenance plan. Such plan includes engine inspections and detailed used oil analysis to determine engine condition, oil lifetime and consumption.

11 Conclusions

Gas engines represent proven technology, having evolved successfully over decades to meet new regulatory and operational demands, including handling a broader range of fuel gases. The further broadening of this fuel (gas) range to include alternative fuels such as hydrogen, methanol, ethanol and ammonia for the purpose of minimizing the carbon footprint of gas engines represents a logical next step in engine technology development. And just like previous development steps, it requires careful consideration and/or mitigation of some key aspects which are summarized below.

- The use of gaseous and low-flashpoint fuels has a rule and regulatory framework originating from application of natural gas (methane) and which is being extended to cover other fuels of interest such as methanol, ethanol, ammonia and hydrogen. A comprehensive safety concept is required for the power generation machinery, such as internal combustion engines. From the marine side, the IGF Code requires that application of all gaseous and low-flashpoint fuels is considered by a detailed risk assessment covering all aspects of the ship installation covering fuel storage, fuel distribution and fuel consumers.

- Various fuel admission and combustion concepts – including spark ignition and compression ignition with diesel pilot fuel - can be implemented depending on the needs of the individual application. Single and dual fuel concepts are feasible and retrofit solutions are being developed.
- Exhaust gases may contain new exhaust species or different concentrations of well-known species, some of them acting as local pollutants or as global greenhouse gas, others are associated with safety considerations. Suitable technologies for their removal are being developed.
- Material compatibility needs to be ensured, particularly for all fuel-carrying components.
- Suitable lubricants should be selected according to OEM recommendations, and used in the engine along with proper maintenance and used oil analysis to support reliable engine operation.

The guidelines will be updated and supplemented as additional experience becomes available.

12 References

[1] Thermodynamik der Verbrennungskraftmaschine / Pischinger, Klell, Sams / ISBN 1617-8920
[2] https://www.swisseduc.ch/chemie/schwerpunkte/ethanol/docs/ethanol.pdf, accessed on November 3, 2024
[3] https://de.wikibrief.org/wiki/Adiabatic_flame_temperature, accessed on November 3, 2024
[4] AEGL (Acute Exposure Guideline Levels) https://www.epa.gov/aegl/ammonia-results-aegl-program, accessed on November 3, 2024
[5] https://impca.eu/resources/impca-reference-specifications/
[6] https://www.iso.org/standard/82340.html
[7] Interim guidelines for the safety of ships using methyl / ethyl alcohol as fuel, https://www.register-iri.com/wp-content/uploads/MSC.1-Circ.1621.pdf, accessed on November 3
[8] MSC.1/Circ.1687; 26 Feb 2025; INTERIM GUIDELINES FOR THE SAFETY OF SHIPS USING AMMONIA AS FUEL, msc1-circ1687-interim-guidelines-for-the-safety-of-ships-using-ammonia-as-fuel-secretariat.pdf
[9] UR M78 Rev1 - Safer and Cleaner Shipping - IACS, https://iacs.org.uk/resolutions/ur-m/ur-m78-rev1/ur-m78-rev1, accessed on December 2, 2024
[10] https://unece.org/about-ghs, accessed on November 3, 2024
[11] Karabeyoglu A., Brian E., 2012, DNV ammonia as a fuel safety handbook
[12] https://www.ncbi.nlm.nih.gov/books/NBK482121/, accessed on November 3, 2024
[13] Methanol Safe Handling Technical Bulletin – Atmospheric Above Ground Storage Of Methanol Available: https://www.methanol.org/wp-content/uploads/2020/04/Atmospheric-Above-Ground-Tank-Storage-Of-Methanol-Bulletin.pdf, accessed on November 3, 2024
[14] K. van Kranenburg, E-fuels: Towards a more sustainable future for truck transport, shipping and aviation, TNO VoltaChem Smartport, 2020. http://resolver.tudelft.nl/uuid:487a6a47-853d-4a1d-bc2e-dbe21d584cca
[15] Stojcevski, T., Jay, D.; Vicenzi, L.: Operation experience of world’s first methanol engine in a ferry installation, Paper No. 099, CIMAC Congress 2016, Helsinki.
[16] Christianen K., De Wilde E., Mattheeuws L.: “ABC´s DZ Dual Fuel Methanol engine”, Proceeding of 7th Large Engine Symposium 2022 The Future of large engine VII, Rostock.

[17] Ramne, B., Bomanson, B., Molander, P., Ellis, J., Errestad, E., Klintenberg, H.: GreenPilot – Pilot Boat with Minimal Environmental Impact, Green Pilot final report 2018, D8.3-Final-Report-ver20181128-with-appendices2.pdf

13 Additional CIMAC papers

CIMAC GHG Strategy Group | White Paper 3 and 4

CIMAC WG 17 | Impact of Gas Quality on Gas Engine Performance (May 2025)

CIMAC WG 17 | Information concerning the application of gas engines in the marine industry (December 2013)

CIMAC WG 17 | Transient response behavior of gas engines (April 2011)

CIMAC WG 17 | The influence of ambient conditions on the performance of gas engines (March 2009)

CIMAC WG 17 | Information about the influence of ammonia in the fuel gas on NOx emissions (April 2024)

CIMAC WG 17 | Information about the use of liquefied natural gas as an engine fuel (December 2008)

CIMAC WG 8 | Guideline on the Lubrication of Reciprocating Gas Engines (March 2021)

14 Abbreviations

AEGL	Acute Exposure Guideline Levels
DI	Direct injection
H2	Hydrogen
HFO	Heavy fuel oil
HPDI	High-pressure direct injection
LHV	Lower heating value
LPDI	Low-pressure direct injection
MN	Methane number
NG	Natural gas
NH3	Ammonia
OEM	Original equipment manufacturer
PFI	Port fuel injection
SNG	Synthetic natural gas
VLSFO	Very low sulfur fuel oil
WI	Wobbe index
%vol	Percent volume

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