# Ammonia as an Alternative Fuel for Large Passenger Ships: Benefits and Challenges

Filippo SCAMARDELLA[a,1], Giorgio ZAMBONI[b], Edward CANEPA[b], Paola GUALENI[a] and Angelo MACOCCO[c]
[a] *DITEN - UNIGE*
[b] *DIME - UNIGE*
[c] *Fincantieri*

**Abstract.** The shipping industry is under increasing pressure to comply with new demanding requirements for exhaust gas emissions. Alternative fuels as well as new technologies need to be developed to meet these goals and reduce Green-House Gases (GHG). This paper investigates ammonia as an alternative fuel for the cruise ship market. A focus is given on the regulatory framework (e.g. EU, IMO and Classification Societies) that at present defines requirements for gaseous emissions and design principles of the fuel containment as well as supply systems. Ammonia allows for effective reduction of $CO_2$ but is potentially toxic for human life and the environment. Due to the innovative nature of ammonia as a fuel, the regulatory approach is based mainly on alternative design instead of prescriptive rules. A case – study, with Internal Combustion Engine ICE (Dual-Fuel) and Propulsion Electric Motors (PEM) as selected standard propulsion system, has been carried out to investigate the impacts of ammonia as fuel on a large passenger ship. The purpose is to evaluate the variation of navigation autonomy, arrangement and weights/stability, considering also specific storage and handling requirements.

**Keywords.** Alternative fuels, Ammonia, Decarbonization, Ship Design.

## 1. Introduction

Air pollution is a central topic of discussions on an international level. To prevent waterborne air pollution due to maritime transportation many solutions are currently under investigation. Alternative fuels (such as ammonia, hydrogen, etc.) are among the most attractive solutions in the perspective of a complete decarbonization. Nonetheless, these fuels still pose several challenges to be faced concerning their handling and storage onboard and their impact on the ship range. To completely replace traditional fuels and meet the decarbonization goals, the supply chain of alternative fuels, as well as international regulations, need to adapt to the demands of the sector as soon as possible.

Ammonia is one of the possible options for decarbonization since it is a relevant hydrogen carrier, and it can be a fuel suitable for the use in Internal Combustion Engines (ICEs) and in fuel cells to produce electricity.

This paper will discuss the chemical and physical characteristics of ammonia, with particular attention to their impact on ICEs, on the ship's range and onboard arrangements.

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[1] Corresponding Author, University of Genova - DITEN, Via Montallegro 1, 16145 Genova, Italy; E-mail: filippo.scamardella@unige.it.

## 2. Regulatory Framework

The growing attention on climate change has pushed the IMO (International Maritime Organization) and the EU (European Union) to develop appropriate and innovative regulations to limit air pollution due to waterborne transportation with the aim of fully decarbonize worldwide fleet. [1-3]

Alternative fuels are the most promising solution and zero-carbon fuels, such as ammonia, are currently being studied as well as the necessary relevant regulations.

Since decades, in the rulemaking environment ammonia is dealt with in the IGC Code but only as a commodity [4]. On the other hand, alternative gaseous and low-flashpoint fuels are regulated by the IGF Code since 2015. This Code, at present, provides prescriptive rules only as far as LNG is concerned. For other gases or low-flashpoint fuels a goal-based approach is requested. This performance-based approach provides greater freedom in design and therefore in the development of innovative solutions. So, being ammonia a gas, from a statutory point of view, an alternative design approach is needed providing that this meets the intent of the goals and the functional requirements reported in the IGF Code. The equivalence, in terms of safety, of the alternative design shall be demonstrated as specified in SOLAS regulation II-1/55. [5]

Classification societies are supporting the shipping industry developing several class notations and regulations able to pave the route toward the safe and efficient exploitation of alternative fuels [6-9]. These regulations are mainly based on the IGF Code, introducing some further rules as the case of ammonia which is harmful to human beings and the environment.

## 3. Ammonia as Alternative Fuel

### *3.1. Chemical and physical properties of ammonia*

Ammonia is a chemical compound of Nitrogen and Hydrogen whose formula is $NH_3$. Ammonia is a colorless gas in standard condition, and is characterized by a particularly pungent smell. Table 1 shows (for gaseous and liquid states) ammonia physical, chemical, and fuel-air mixture properties compared to Methane/LNG and MDO. [10][11] Properties that differ from those of conventional fuels have been commented on and discussed in relation with their impact on storage or use in ICEs.

**Table 1.** Ammonia physical, chemical, and fuel-air mixture properties compared to Methane/LNG and MDO

| | **MDO** | **Methane/LNG** | **Ammonia** |
|---|---|---|---|
| Density (STP)[2] [kg/m$^3$] | 840 | 0.72/470 | 0.73/603[3] |
| Boiling point at 1 bar [°C] | 175-350 | -161.5 | -33 |
| Heat of vaporization ($\lambda_{ev}$) [kJ/kg] | 270-300 | 510 | 1370 |
| Kinematic viscosity at 40°C [mm$^2$/s] | <11 | N/A | 0.08-0.1 |
| Lower Heating Value (LHV) [MJ/kg] | 42.5/42 | 50/49 | 18.7 |
| Volumetric energy density [MJ/m$^3$] | 35700 | 32.50/21100 | 13.7/11300 |
| $CO_2$ Specific emission [g/MJ] | 72.8 | 54.87 | 0 |

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[2] Standard Temperature and Pressure (except ammonia, data for liquid state at 10 bar, t = 25 °C; LNG, data for liquid state at 1 bar, t = -162 °C).

[3] In [12] the density of ammonia at -33 °C (and 10 bar pressure) is 682 kg/m$^3$.

| | | | |
|---|---|---|---|
| Self-ignition temperature [K] | 500 | 813-859 | 930 |
| Adiabatic flame temperature [K] | 2300 | 2225 | 1850 |
| Minimum ignition energy in air [mJ] | N/A | 0.28 | 8 |
| Octane Number (RON) | 12-25 | 120 | >130 |

Table 1 shows that ammonia is characterized by:

- higher heat of vaporization value than other fuels. In the case of ammonia fueled Diesel engines with direct injection this might imply a longer time to complete the fuel vaporization and the combustion process, with reduction of combustion efficiency and formation of unburnt materials. Meanwhile, the high heat of vaporization, in the case of injection into the intake duct, could cause a strong reduction of temperatures with difficulty in completing the phase passage and possible implication of condensation risk;
- low viscosity that influences the capability to lubricate engine components;
- no carbon atoms in the formula so the $CO_2$ specific emission is equal to zero;
- low adiabatic flame temperature that is crucial to lower nitrogen oxides formation (thermal $NO_X$). Nevertheless, the contribution of the fuel to $NO_X$ formation (fuel $NO_X$) should be further investigated given the presence of Nitrogen in the molecule;
- low LHV which contributes to a low volumetric energy density resulting in a need of greater storage volumes compared to traditional fuels to guarantee the same energy storage;
- very high minimum ignition energy. The higher this value, the more difficult it will be to trigger combustion;
- high Octane Number, indicating a high resistance to detonation, which makes ammonia suitable for use in spark-ignition engines.

### *3.2. Internal Combustion Engine characteristics*

Ammonia, as an energy carrier, could be used in certain types of fuel cells or in ICEs utilizing already existing technologies.

As mentioned, the high Octane Number is a positive feature for use in spark-ignition engines but it brings delays in the ignition of the fuel in the case of compression ignition (Diesel) engines. To trigger the combustion process in a Diesel engine it is, therefore, necessary to use a second fuel, as already developed for LNG and methanol.

Possible approaches for the use of ammonia in Diesel engines are:

- Injection of ammonia into the intake duct. Here ammonia evaporates and mixes with the air. The charge is then drawn into the cylinder, where it is ignited by a pilot injection of conventional fuel (HFO or MDO);
- Direct injection of ammonia into the combustion chamber near the TDC. Pilot injection of conventional fuel is also required to ignite the charge. [13]

It is necessary to highlight how the first approach is technically simpler, requiring minor engine modifications for the development of an experimental prototype that can allow the necessary investigations. Several studies were therefore conducted using an injection in the intake duct highlighting limits on the maximum substitution rate of Diesel fuel achievable, and on the combustion efficiency. For this reason, it is hypothesized that the use of direct ammonia injection may represent a more adequate solution considering different objectives: high substitution rate of Diesel fuel, efficiency, reduction of $CO_2$ emissions and reduction of pollutant emissions ($SO_X$, PM). [13-15]

### *3.3. Storage options*

Liquified ammonia is characterized by a temperature of -33°C at atmospheric pressure or by a vapor pressure of 18 bar at a temperature of 45° C (which is the reference temperature in the engine room prescribed by the rules).

The storage of liquified gas is possible by using Type A, Type B, Type C or membrane tanks [5]. The two most promising solutions for cruise ships are:

- Type C tanks: independent tanks, generally, of cylindrical or bilobed shape. These tanks are designed to withstand high pressures that can allow the gas to be stored in liquid form at higher temperatures. This is the sole solution that allows for the storage of ammonia at a temperature of 45° C (fully pressurized tanks). These are the most commonly used tanks for the storage of LNG allowing its storage at -163° C with an adequate insulation layer;
- Membranes: integrated tanks realized by covering the structure of the ship with thin membranes. These membranes are supported by the ship structures they cover and require a complete secondary barrier. Membrane tanks are provided with thermal insulation and the Maximum Allowable Relief Valve Setting (MARVS) is set to 0.25 barg; higher MARVS can be reached with structural enhancement but never above 0.7 barg. [5]

Regarding the secondary barrier, the IGC Code allows for the use of ship structures as a secondary barrier if the storage temperature of the liquefied gas is not below -55°C as it is in the case of ammonia, stored at atmospheric pressure.[4]

Moreover, if ammonia is stored at -33 °C (e.g. in membrane tanks), despite the thermal insulation surrounding the fuel tank, an inevitable heat flow comes from the outside to the inside. The vapor that generates in the tank is called Boil-Off Gas (BOG), while the vaporized mass flow over a certain time is the Boil-Off Gas Rate (BOR).

$$BOR = Q/\lambda_{ev} \qquad \text{Eq. (1)}$$

Where Q is the thermal flow and $\lambda_{ev}$ is the heat of vaporization.

If tanks were hermetically closed, this effect would lead to an increase in internal pressure which could exceed the MARVS. Therefore, it may be necessary to remove part of the vapor generated and manage it with a BOG treatment system which increases the fuel supply system complexity. The most common BOG treatment systems are: reliquefaction of vapors, thermal oxidation of vapors, pressure accumulation and liquefied gas fuel cooling. At the same time, when ammonia is stored in fully pressurized type C tanks, the BOG treatment system is no more necessary as the tank is considered capable to withstand the maximum pressure achievable.

## 4. Application Case

This chapter describes the ship selected as Case Study for ammonia power generation. This ship will act as a benchmark to evaluate in a comparative perspective the use of different alternative fuels.

### 4.1. *The model ship and the operational profile*

For this study, an LNG fueled cruise ship, powered by LNG Dual-Fuel ICE, has been selected. The main characteristics of the ship are shown in Table 2.

**Table 2.** Case Study ship main data

| | |
|---|---|
| Ship type | Cruise Ship |
| Length Overall | Abt 330 m |
| Moulded Breadth | 24.1 m |
| Gross Tonnage | Abt 161000 GRT |
| Power Available Onboard | Abt 60 MW |
| Passengers | 4932 |
| Crew | 1568 |

The power system is composed of five ICEs and two PEMs (Propulsion Electric Motors). The ICEs are distributed on two adjacent Engine Rooms. In both compartments boilers are installed to produce steam from LNG combustion. For this study, boilers will be assumed to be fueled by MDO and not by ammonia.

LNG bilobed type C tanks are positioned in the forward half of the ship and extend from deck A to deck 2 as shown in Figure 1.

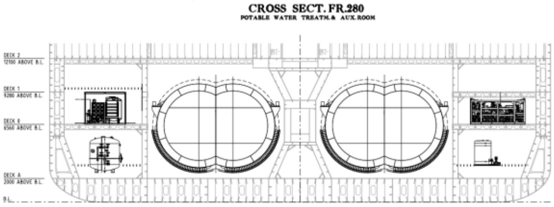

**Figure 1.** Case Study LNG tanks

Regarding the cruise profiles, four main geographical areas of interest have been identified and named Cruise A, B, C and D. Cruise A, B and D last for 7 days while Cruise D lasts for 14 days.

### 4.2. *Evaluation of ship range*

The ship's range was calculated for the four assumed cruise profiles.

Not having, at the time of writing this article, any experimental feedback yet regarding ammonia fueled Dual-Fuel ICEs, the following assumptions were made:

- reduction in efficiency of 0.04 along the entire engine efficiency curve, as shown in Figure 2, where η* is the efficiency of the LNG DF ICEs installed on the Case Study ship. This reduction is assumed considering the less favorable ammonia characteristics and the value applied in [16] for deep sea ships;

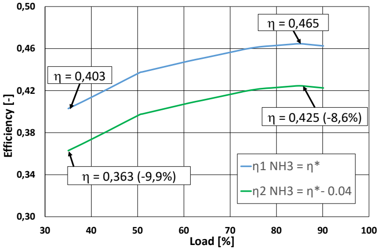

**Figure 2.** Ammonia ICE efficiency reduction compared to LNG DF ICE

- Variability of the MDO substitution rate in a range between 60% and 95%.

In the following, the substitution rate should be understood as the share of energy provided by ammonia in respect of the total energy provided and it is, therefore, defined as:

$$Substitution\ Rate\ (SR) = \frac{m_{NH3} * LHV_{NH3}}{m_{MDO} * LHV_{MDO} + m_{NH3} * LHV_{NH3}} \qquad \text{Eq. (2)}$$

The results obtained in terms of the volume of consumed fuel for a single cruise are reported in Figure 3 and Figure 4.

In Figure 3 (left i.e. Cruise A) the consumption amount of alternative fuel is reported on the vertical axis, normalized with reference to the LNG consumption in the specific case of Cruise A. The black horizontal dashed line represents the amount of LNG necessary for Cruise A (NV $_{LNG-A}$) that in the diagram becomes the reference value equal to 1. The dashed red line represents the available storage volume (in the fuel tanks) expressed as a ratio with reference to NV $_{LNG-A}$. Lastly, results for ammonia as a fuel are also reported as a ratio with reference to NV$_{LNG-A}$ and for two different engine efficiencies (η* and η*-0.04). It is interesting to note that for higher substitution rates (SR) the available storage tank volume onboard can still provide the necessary capacity.

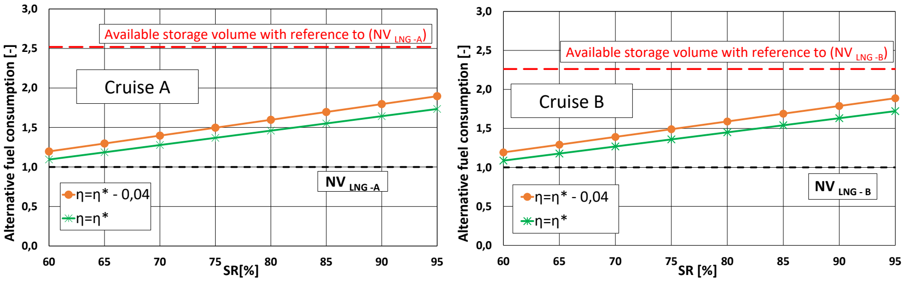

**Figure 3.** Cruise A (left), Cruise B (right) – Ammonia consumption

In Figure 3 (right i.e. Cruise B) and Figure 4, information is presented with the same principle, that is, curves referred to ammonia consumption are normalized with the LNG necessary volume. However, minor difference can be spotted due to the use of boilers that in the case of ammonia solution are fed by MDO and not by the alternative fuel as it is on the Case Study ship. The general outcome shows that the Cruise B, as well as Cruise D, are perfectly compatible with the available storage tank volume. This is not the case for Cruise C, as put in evidence in Figure 4 (left).

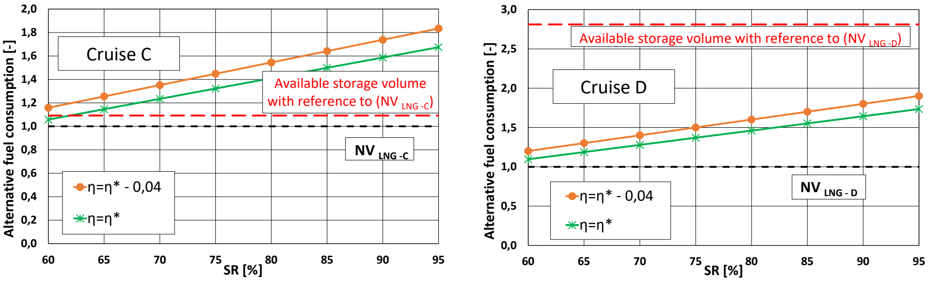

**Figure 4.** Cruise C (left), Cruise D (right) – Ammonia consumption

To recover the lost range due to the lower energy density, it is possible to vary the size of the tanks by changing the type (e.g. membrane instead of Type C) or it is possible to reduce the ship speed, as far as practicable, as shown in Figure 5.

An investigation about the influence of ship speed (horizontal axis) on the ship range (vertical axis) have been carried out when ammonia is assumed as alternative fuel. For this calculation a 75% SR has been used and an engine efficiency equal to $\eta_{2\ NH3}$ as presented in Figure 2.

Ship range is normalized with reference to the value in nautical miles provided by LNG as a fuel at design speed. For the design speed value, the ammonia fuelled ship range is nearly 35 % less than LNG one.

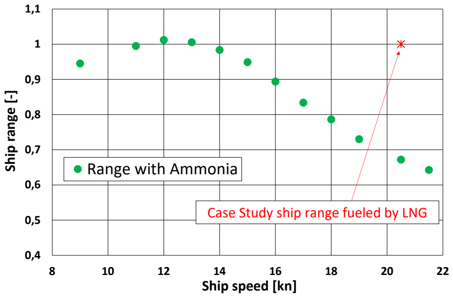

**Figure 5.** Ship's range varying the cruising speed

### *4.3. Integration onboard and stability*

The integration on-board of a gaseous and toxic fuel as ammonia poses many significant challenges, for example in terms of necessary volumes (as shown in Figure 3), implied weights, and safety issues.

As far as weights are concerned, the comparison with an LNG fuelled solution is expected to be nearly comparable considering, nevertheless, that ammonia has a specific gravity 1.45 times higher than LNG. It seems reasonable to believe that the storage of a fuel with a higher specific gravity than LNG, in the lower part of the ship, can provide an overall reduction of the center of gravity vertical coordinate, with positive effects on the ship stability.

Safety, instead, is an outstandingly important issue that implies appropriate solutions such as: double-walled piping, Boil-Off Gas treatment systems, segregation of the plant (e.g minimum distances with bottom and side shell; separate bilge systems), increased ventilation and installation of sophisticated ammonia detection systems.

Most of the items listed above are necessary also for a LNG solution nevertheless specific attention is needed when dealing with increase ventilation and detection systems due to the harmful characteristic of ammonia.

## 5. Conclusions

In this study, ammonia as a fuel was examined from a regulatory, chemical, and physical standpoint by comparing it with MDO and LNG. The analysis showed that ammonia has probably worse performance as a fuel when used in ICEs when compared to other fuels, implying a lower engine efficiency and a substitution rate that cannot reach the levels obtained in LNG DF engines. In particular, the substitution rate is related to the reduction of $CO_2$ emissions, but, at the same time, to the reduction of the ship's range i.e. maximizing the reduction of emissions (increasing the share of ammonia burned) results in a reduction of ship range. These aspects have been highlighted by selecting as a Case Study a large LNG-fuelled cruise ship and analyzing four cruise profiles. Among these four profiles, only 3 are still viable (within the range of the ship) maintaining the same storage volume, while one, the longest, is not viable even for very low substitution rate values.

An investigation was also carried out to point out how a speed reduction would affect the range reduction.

In addition, the available solutions for the carriage of liquified gas onboard and the possible thermodynamic conditions of ammonia storage have been discussed together with the possible impact of their integration onboard, with specific reference to ship safety. Nevertheless, regarding these latter aspects, further studies need to be carried out as safety is a key aspect especially when dealing with cruise ships and human lives.

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