ESCUELA TÉCNICA SUPERIOR DE NÁUTICA

UNIVERSIDAD DE CANTABRIA

Trabajo Fin de Máster

WATER INJECTION IN THE CYLINDER AS AN ENERGY EFFICIENCY MEASURE

INYECCIÓN DE AGUA EN EL CILINDRO COMO MEDIDA DE EFICIENCIA ENERGÉTICA

Para acceder al Título de Máster Universitario en

INGENIERÍA MARINA

Autor: Andreu Josep Prats van der Ham

Director: Manuel Alfredo Girón Portilla

Septiembre – 2021

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Acknowledgements

To my family, specially to my mother and father who always help me and advise me, to my sisters as the light to follow in my academic life , to my partner who is always by my side loving me, helping me and supporting me, to the friends I've made along these voyage, giving advice and support and to the teachers who have helped me.

Key words

Cylinder

Combustion

Injection

Water

Energy efficiency

Overview

The merchant marine nowadays is a very regulated sector, with a lot of organisations that rule and control all the ships and its activity.

Everyday there are thousands of vessels that are sailing from all abroad to bring us goods improving our social well-being, things that improve the global market but that day after day are increasing the levels of pollution.

This pollution is not only caused by the thousands of vessels sailing the seas, but it is a fact that it is one of the causes, so it's to us, following the different international organisations to help to slow down this increasing levels of pollution by improving the fuels that we consume and improving the systems, making them more efficient and greener.

This project is composed of three chapters: an analysis about the regulations that rule the vessels in matters of pollution, a brief study of the engines that are used in the maritime industry and for ending the particularities of the injection of water inside the cylinder.

First chapter is going to analyze the different regulations from the different organizations like the IMO and the EMSA, its rules and their purposes.

In the second chapter I'm going to explain the different propulsion systems that are currently in the marine industry with their respective thermodynamic cycles and the fuels that are used for running those engines.

Third chapter examines the study of several techniques for using distilled water to enhance the reduction of NO_x particles, and enhance the efficiency of the engine.

Palabras clave

Cilindro

Combustión

Inyección

Agua

Eficiencia energética

Resumen

La marina mercante hoy en día es un sector muy regulado, con muchos organismos que rigen y controlan todos los barcos y su actividad.

Cada día hay miles de buques que navegan desde todo el mundo para traernos bienes que mejoran nuestro bienestar social, cosas que mejoran el mercado global pero que día a día van aumentando los niveles de contaminación.

Esta contaminación no sólo es causada por los miles de buques que navegan por los mares, sino que es un hecho que es una de las causas, por lo que nos corresponde a nosotros, siguiendo a las diferentes organizaciones internacionales ayudar a frenar este aumento de los niveles de contaminación mejorando los combustibles que consumimos y mejorando los sistemas, haciéndolos más eficientes y ecológicos.

Este proyecto se compone de tres capítulos: un análisis sobre la normativa que rige a los buques en materia de contaminación, un breve estudio de los motores que se utilizan en la industria marítima y para finalizar las particularidades de la inyección de agua dentro del cilindro.

En el primer capítulo se van a analizar las diferentes normativas de los diferentes organismos como la OMI y la EMSA.

En el segundo capítulo se van a explicar los diferentes sistemas de propulsión que hay actualmente en la industria naval con sus respectivos ciclos termodinámicos y los combustibles que se utilizan para el funcionamiento de dichos motores.

El tercer capítulo examina el estudio de varias técnicas para utilizar el agua con el fin de mejorar la reducción de las partículas de NO_x, y mejorar la eficiencia del propio motor.

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BSFC: Brake-specific fuel consumption.

ECA: Emission Control Areas.

EEDI: Energy Efficiency Design Index.

IMO: International Maritime Organization.

ISO: International Standard Organization.

MARPOL: Maritime Pollution.

MCR: Maximum continuous rating.

MDO: Marine Diesel Oil.

ME: Main engine.

OEM: Original equipment manufacturer.

PM: Preventive maintenance.

RPM: Revolutions per Minute.

SFOC: Specific Fuel Oil Consumption.

Introduction

The merchant marine is always under the eye of the administrations because of their activity, the amount of ships sailing around the world has made the IMO and the EMSA, in Europe, one of the most important legislators in terms of the international shipping industry.

The maritime industry is always trying to reduce the fuel consumption, by several reasons:

- Maritime regulations in terms of maritime pollution, MARPOL Annexes.
- Fuel prices increasing in the main bunkering ports.
- New technologies introduced by different marine engine manufacturers.

In the first chapter, we introduce the two main documents that are used on the ships nowadays. The EEDI an the SEEMP are the two documents that regulate and control the ship in matters of energy efficiency, the first one in the design phase and the second during the operation of the ship itself.

In the second chapter we take a view on different topics, different marine systems for the propulsion of the ships in the actual marine industry, a brief overview of the fuel characteristics and some theory of the different thermodynamical cycles that exist and are used in the industry.

For ending, in the third chapter we take a look at the technology of water injection in the cylinder of a thermal engine. This technology although it is a not very new technology it is seen as the one for permitting the continuity of the use of the diesel engines for all kind of applications in the industry. This technology is in experimental phase but there is a lot of inversion from the side of the engine manufacturers for permitting it to reach the market as soon as possible, permitting enhance the efficiency of the system itself, reducing de NO_x emissions and enhancing the refrigeration of the cylinder in which the water is injected.

CHAPTER I. LEGAL REGULATIONS FROM THE IMO AN THE EMSA IN MATTERS OF AIR POLLUTION

The IMO is a worldwide organization created by the United Nations, Its purpose is to regulate the maritime industry with the support of all the countries that form the UN. In Europe the agency that rules with the IMO is the EMSA.

In this chapter we will get an overview about the different regulations from the different organizations like the IMO and the EMSA, its purpose and its use for the ships all around the world.

We are going to overview two main plans, the Energy Efficiency Design Index (EEDI) and the Ship Energy Efficiency Management Plan (SEEMP).

1.1 INTERNATIONAL REGULATIONS

1.1.1 Energy Efficiency Design Index (EEDI)

The EEDI addresses the former type of measure by requiring a minimum energy efficiency level for new ships, by stimulating continued technical development of all the components influencing the fuel efficiency of a ship; and by separating the technical and design-based measures from the operational and commercial ones. It is already being used to enable a comparison to be made of the energy efficiency of individual ships with similar ships of the same size that could have undertaken the same transport work (i.e. moved the same cargo).

Discussions at IMO have resulted in the development of an Energy Efficiency Design Index (EEDI)[1] that has the broad and emphatic support of Governments, industry associations and organizations representing civil society interests.

All are united in the same purpose: to ensure that the EEDI delivers environmental effectiveness by generating, through enhanced energy efficiency measures, significant reductions in GHG emissions from ships.

The coverage of the EEDI includes:

- Applicability
- Safe Speed

[1] ("EEDI - rational,safe, effective," n.d.)

- Installed Power
- Effectiveness of EEDI in reducing CO_2 emissions
- Conclusion

Applicability

The EEDI formula – as presently drafted – is not supposed to be applicable to all ships. Indeed, it is explicitly recognized that it is not suitable for all ship types (particularly those not designed to transport cargo) or for all types of propulsion systems (e.g., ships with diesel-electric, turbine or hybrid propulsion systems will need additional correction factors).

For ship types not covered by the current formula, suitable formulae will be developed in due course to address the largest emitters first. IMO's Marine Environment Protection Committee (MEPC) is poised to consider the matter in detail at future sessions, with a view to adopting further iterations of the EEDI.

Safe Speed

The need for a minimum speed to be incorporated into the EEDI formula has been duly acknowledged by the MEPC[2] and, to that end, a draft EEDI regulation (22.4) states that "For each ship to which this regulation applies, the installed propulsion power shall not be less than the propulsion power needed to maintain the maneuverability of the ship under adverse conditions, as defined in the guidelines to be developed by the Organization."

[2] ("EEDI - rational,safe, effective," n.d.)

Installed Power

Although the easiest way to improve a vessel's fuel efficiency is, indeed, to reduce speed – hence the move to slow steaming by a significant number of ships – there is a practical minimum at which fuel efficiency will decrease as a vessel is slowed down further. There are other ways to improve fuel efficiency, such as waste heat generators, which do not impact on speed (they impact on auxiliary engines). Indeed, improvements in road transport efficiency have been made through advances in technology that have, however, not led to a sacrifice in speed; rather, quite the opposite.

It has been (wrongly) argued that the EEDI limits installed power and so induces owners to use small-bore high-rpm engines, thereby increasing fuel consumption. However, a reduction of installed power does not require a reduction in engine bore and increasing rpm.

The easiest way to reduce power would be to "de-rate" the exact same engine by limiting the "maximum" rpm (remember, horsepower = torque multiplied by rpm). This would have the impact of increasing propeller efficiency (if the exact same propeller is installed), as propeller efficiency will generally improve as rpm decreases. Another practical way to reduce installed horsepower is to install an engine with one cylinder less. This would have no impact on specific fuel consumption or rpm. Such engines can be identified by reference to the catalogues of major engine manufacturers.

Of course, there are "economies of scale" in ships' fuel efficiency. The larger the ship (at a given speed), the lower the fuel consumption per unit of cargo. However, such economies of scale are limited by trade considerations, physical port limitations (generally, draft) or cargo logistics issues. Therefore, ships tend to be designed to be as large as practical for a given trade.

Effectiveness of EEDI in reducing CO_2 emissions

It has also been suggested that the EEDI will result in little or no reduction in CO_2 emissions in those sectors where slow-steaming is already practiced.

Consider the following simplified EEDI formula:

$$EEDI = \frac{CO_2\ emission}{transport\ work}$$

The EEDI, in establishing a minimum energy efficiency requirement for new ships depending on ship type and size, provides a robust mechanism that may be used to increase the energy efficiency of ships, stepwise, to keep pace with technical developments for many decades to come. It is a non-prescriptive mechanism that leaves the choice of which technologies to use in a ship design to the stakeholders, as long as the required energy-efficiency level is attained, enabling the most cost-efficient solutions to be used. Such technologies have been comprehensively considered in the 2009 IMO GHG Study.

Conclusion

Following adoption in 2011 and entry into force in 2013, the introduction of the EEDI for all new ships will mean that between 45 and 50 million tons of CO_2 will be removed from the atmosphere annually by 2020, compared with "business as usual" and depending on the growth in world trade. For 2030, the reduction will be between 180 and 240 million tons annually from the introduction of the EEDI.

There is, therefore, every confidence, among the vast majority of the international maritime community, that the EEDI will result in more energy efficient ships, in reduced emissions of GHGs, in environmental effectiveness and in a significant contribution by a global industry to the global efforts to stem climate change.

1.1.2 Ship Energy Efficiency Management Plan (SEEMP)

IMO requirements, industry initiatives, fuel prices and corporate responsibility are driving owners/ operators to implement a Ship Energy Efficiency Management Plan (SEEMP). In July 2011, IMO adopted an amendment to MARPOL Annex VI[3] that makes a SEEMP mandatory for all new and existing ships as of 1 January 2013. (For existing vessels, the SEEMP is to be on board at the first intermediate survey or engine certificate renewal date after 1 January 2013, whichever comes first.)

The scope and detail of the SEEMP can vary and there are several guidelines already published for owners and operators to reference. It is also understood "that the best package of measures for a ship to improve efficiency differs to a great extent depending upon ship type, cargoes, routes and other factors," (MEPC.1/683). So, no one-size-fits-all SEEMP exists, even if the overall framework and process are the same.

[3] ("Air Pollution," n.d.)

Figure 1 displays the four main steps for SEEMP implementation:

- Planning
- Implementation
- Monitoring
- Self-evaluation and improvement

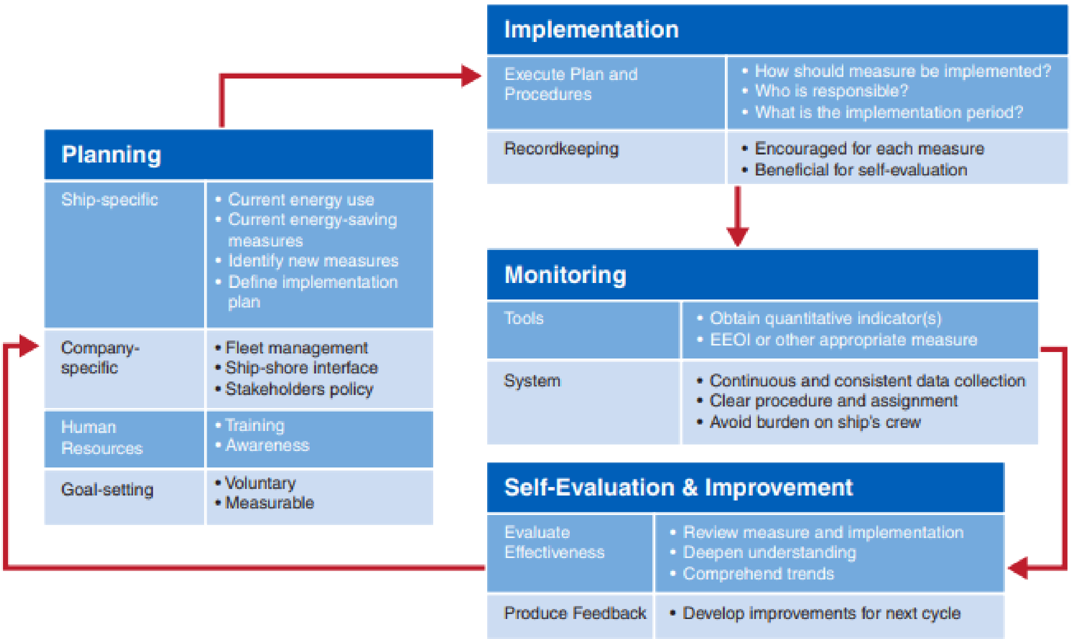

Figure 1: Four-step continuous improvement process. Figure by ''eagle.org''.

Planning

The core functions of the planning phase (and most time consuming) are the assessment of current vessel and fleet energy efficiency and the evaluation/selection of new measures to implement[4]. These can be done to varying levels of detail depending on the goals of the owner.

[4] ("MARPOL Annex VI and the Act To Prevent Pollution From Ships (APPS) | Enforcement | US EPA," n.d.)

The goal setting and drafting of the plan document are less time intensive. Specific planning tasks include:

- A fleet and ship energy use assessment.
- Setting of ship, fleet and corporate energy efficiency goals.
- Evaluation and selection of energy-saving measures.
- Planning the changes to processes and equipment necessary for ships and fleet.
- Identifying and developing tools for monitoring and measuring performance.
- Drafting the full SEEMP.

Implementation

This phase requires concrete plans for making the necessary changes to the vessels, their operations and management. Included are the assignment of responsibilities for each element of the SEEMP, engineering design development and training.

Implementing the SEEMP should include the following elements:

- Publish the SEEMP.
- Make changes to processes and systems.
- Assign responsibilities.
- Provide training to the crew and shoreside staff.

A key part of the implementation and training is to increase energy efficiency awareness throughout the organization. Personnel at all levels should be aware of the efficiency goals and participate in the process of continual improvement. This is especially critical for the shipboard crew responsible for day-to-day operation of the ship and its machinery.

Monitoring

Monitoring means continuous collection of pertinent data. The plan for monitoring is established in the planning phase. The monitoring phase covers efforts during operations and for the life of the vessel. It should be a combination of automated data recording and manual documentation that minimizes time for shipboard personnel.

The company should implement a monitoring system and process with well-documented procedures that include reporting and data analysis.

Self-evaluation and Improvement

As specified in the SEEMP this evaluation should occur on a regular basis[5] within a clear framework. It should include the following actions:

- An analysis of vessel and fleetwide monitoring data and a review of performance against established metrics and the plan.
- Identification of the cause and effect for observed performance and recommendations for changes and improvements for better performance.
- A review of the effectiveness of the SEEMP and recommendations for improvements to the SEEMP based on the review.
- Implement changes and continue monitoring.

[5] (“MARPOL Annex VI and the Act To Prevent Pollution From Ships (APPS) | Enforcement | US EPA,” n.d.)

CHAPTER II. MARINE INDUSTRY MAIN PROPULSION SOLUTIONS AND THE FUELS USED NOWADAYS

The marine industry uses a lot of different types of marine propulsion, normally these different systems come in relation with the cargo, ships particularities or activity.

We present a brief resume of the different types of marine powerplants and marine propulsion systems. With these systems we also include a brief study of the fuels used and their characteristics, particularities and examples.

2.1 MAIN PROPULSION SYSTEMS

2.1.1 The thermodynamical cycle of Carnot

French Engineer Sadi Carnot showed that the ratio of Q_{Heat} to Q_{Cold} must be the same as the ratio of temperatures of high temperature heat and the rejected low temperature heat. So, this equation, also called Carnot Efficiency[6].

A general expression for the efficiency of a heat engine can be written as:

$$\text{Efficiency} = \frac{\text{Work}}{\text{Heat Energy}_{\text{Hot}}}$$

We know that all the energy that is put into the engine has to come out either as work or waste heat. So work is equal to Heat at High temperature minus Heat rejected at Low temperature. Therefore, this expression becomes:

$$\text{Efficiency} = \frac{Q_{\text{Hot}} - Q_{\text{Cold}}}{Q_{\text{Hot}}}$$

Where, Q_{Hot} = Heat input at high temperature and Q_{Cold} = Heat rejected at low temperature. The symbol is often (Greek letter eta) used for efficiency this expression can be rewritten as:

$$\eta'(\%) = 1 - \frac{Q_{\text{Cold}}}{Q_{\text{Hot}}} \times 100$$

The above equation is multiplied by 100 to express the efficiency as percent.

[6] (“The Carnot Efficiency | EGEE 102: Energy Conservation and Environmental Protection,” n.d.)

$$\eta'(\%) = 1 - \frac{Q_{Cold}}{Q_{Hot}} \times 100\%$$

Note: Unlike the earlier equations, the positions of T_{cold} and T_{hot} are reversed.

The Carnot Efficiency is the theoretical maximum efficiency one can get when the heat engine is operating between two temperatures:

- The temperature at which the high temperature reservoir operates (T_{Hot}).
- The temperature at which the low temperature reservoir operates (T_{Cold}).

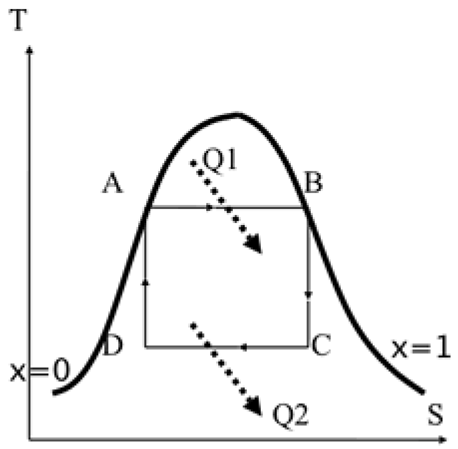

Figure 2: Representation of the Carnot cycle, note that Q1 is QHot and Q2 is QCold. Figure by ‘’ textoscientificos.com/fisica/termodinamica/maquinas-vapor’’.

2.1.2 Systems that follow the Diesel thermodynamical principle

When we refer to systems that follow the Diesel thermodynamical principle, we refer to all those propulsion systems that use an engine that uses this cycle for the propulsion of the ship, they can be categorized in two main groups, 4 stroke engines and 2 stroke engines.

Theoretical explanation of the 4 stroke Diesel cycle

In the Diesel thermodynamical principle[7], the heat is introduced at constant pressure.

The equation is presented in the following form:

$$dQ = dU + dW \rightarrow Q = \int_1 dU + \int_1 dW = (U_2 - U_1) + (P_2V_2 - P_1V_1)$$

$$= (U_2 + P_2V_2) - (U_1 + P_1V_1) = (H_2 - H_1) = C_P (T_2 - T_1)$$

We know the value of the heat extracted from the cycle or the heat introduced, through the concept of enthalpy or constant pressure Cp:

Heat inserted - $Q_1 = C_P (T_3 - T_2)$

Heat subtracted - $Q_2 = C_V (T_4 - T_1)$

The extraction phase is performed following the next mathematical expression:

[7] (Remacha 2018)

$$\eta_{\varepsilon} = \frac{C_P(T_3 - T_2) - C_V(T_4 - T_1)}{C_P(T_3 - T_2)} = 1 - \left(\frac{C_V}{C_P}\right) \cdot \frac{T_4 - T_1}{T_3 - T_2} = 1 - \frac{1}{K} \cdot \frac{T_1 \cdot \left(\frac{T_4}{T_1} - 1\right)}{T_2 \cdot \left(\frac{T_3}{T_2} - 1\right)}$$

We verify the following:

a)

$$\frac{T_1}{T_2} = \left(\frac{V_2}{V_1}\right)^{K-1}$$

b)

$$\frac{T_4}{T_3} = \left(\frac{V_3}{V_4}\right)^{K-1}$$

Stating the following:

$$\frac{T_4}{T_1} = \frac{T_3}{T_2} \cdot \frac{\left(\frac{V_3}{V_4}\right)^{K-1}}{\left(\frac{V_2}{V_1}\right)^{K-1}}$$

c)

$$V_1 = V_4$$

d)

In the transformation 2-3 with constant pressure:

$$\frac{V_3}{V_2} = \frac{T_3}{T_2}$$

Moreover:

$$\frac{T_4}{T_1} = \frac{V_3}{V_2} \cdot \left(\frac{V_3}{V_2}\right)^{K-1} = \left(\frac{V_3}{V_2}\right)^{K}$$

Adding the performance η_ε:

$$\eta_\varepsilon = 1 - \frac{1}{K} \cdot \frac{T_1 \cdot \left(\frac{T_4}{T_1} - 1\right)}{T_2 \cdot \left(\frac{T_3}{T_2} - 1\right)}$$

We replace values in the equation:

$$\eta_\varepsilon = 1 - \frac{1}{K} \cdot \left(\frac{V_2}{V_1}\right)^{K-1} \frac{\left[\left(\frac{V_3}{V_2}\right)^{K} - 1\right]}{\left(\frac{V_3}{V_2} - 1\right)}$$

Keeping in mind that:

$$\rho = {}^{V_1}/_{V_2}$$

It is the volumetric ratio of compression and called:

$$t' = {}^{V_3}/_{V_2}$$

Volume of end and start of the combustion phase at constant pressure, we will have:

$$\eta_\varepsilon = 1 - \frac{1}{\rho^{K-1}} \cdot \left[\frac{t'^{K} - 1}{k \cdot (t' - 1)}\right]$$

4 Stroke Diesel Engines

This type of engine is widely used in the marine industry, they offer a lot of different options in terms of power, torque and they are relatively small. They are mounted generally in ships with a lower design engine room, making a longer engine room with a lower ceiling, permitting the upper deck to allow more space for cargo in a longitudinal direction or for allowing a working deck on the engine room.

This type of engine is categorized in two main groups, the medium speed engines[8] (400 rpm to 1200 rpm) or high-speed engines[9] (1400 rpm and above).

Figure 3: 4-Stroke marine engine, general overview. Figure by "marineinsight.com".

Manufacturers of this type of engine try to make every set of engines better that the set before so they put a lot of effort in the evolution and reliability of their engines, energy efficiency, low fuel consumption and low air pollution are

[8] («Diesel engine» [sin fecha])

[9] («Diesel engine» [sin fecha])

their main goal to keep this engine one of the most widely used in the marine industry. They can be used as a main engine for propulsion or as an auxiliary engine for the generation of electric energy.

The most famous brands with this type of engine can be the following:

- **Wärtsilä**

Established in 1834 in Finland[10] it is one of the most famous marine engine builders, they are famous because of their strength and robustness and their well performing ratio. In figure 4 we show one of their classical engines, the Wärtsilä 20[11], that can be used as a propulsion unit in small ferries, tug boats or cargo vessels.

Figure 4: Wärtsilä 20, 4-stroke marine engine. Figure by "wartsila.com".

[10] («History» [sin fecha])

[11] («Wärtsilä 20 - Diesel engine» [sin fecha])

Wärtsilä is also one of the first brands in introduce an entire set of engines capable of working with dual fuel (LNG and MDO). The Wärtsilä 20DF[12] is one of these examples based on the well proven and reliable Wärtsilä 20 diesel engine, fuel flexibility means the engine can be optimized for constant speed generating sets, as well as variable speed mechanical drives, for main engine applications.

- **MAN**

Established in 1895 in Augsburg[13], Germany, it's one of the biggest engineering firms in the world, their marine implications are far well known with reliable and energy efficient engines[14], they offer a multiple sort of marine engines, both in 2-stroke or in 4-stroke.

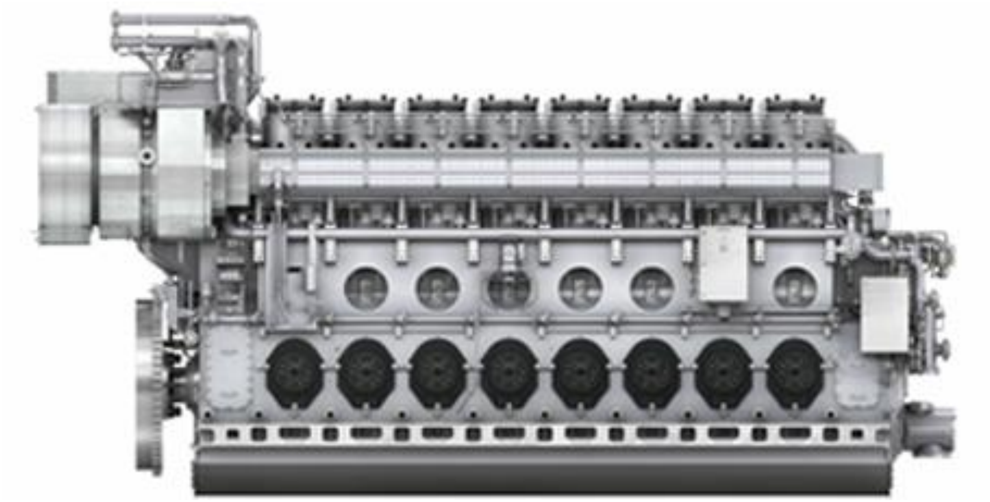

Figure 5: MAN L+V48/60CR 4-stroke marine diesel engine. Figure by "man.com/marine".

[12] («Wärtsilä 20DF - fuel flexibility in a small unit» [sin fecha])

[13] («MAN Diesel | History of MAN Marine Engines | RDI Group» [sin fecha])

[14] («Propulsion | MAN Energy Solutions» [sin fecha])

They also offer multiple engines with a dual fuel layout, this permit them to explore more options in the market and to offer more solutions for ships navigating in specific areas, such as the ECA zone that are located around the world.

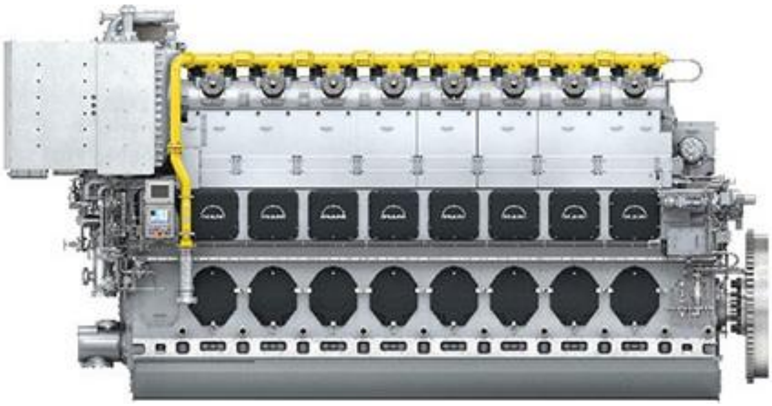

Figure 6: MAN L+V51/60DF dual fuel marine engine. Figure by "man.com/marine".

- **Caterpillar**

Established in the USA in Peoria (Illinois) and Stockton (California) in 1905[15]. Their first appearance was in the form of an improved tracks for a Holton tractor. After a successful test and improvement of the current machinery their goal was to provide different industries with reliable and energy efficient engines and propulsion solutions. Nowadays they are one of the most successful marine engine manufacturers for the fishing industry[16], although they offer multiple solutions for multiple vessels such as tug boats, ferries and cargo vessels.

[15] («Caterpillar | The Story of the Caterpillar Name» [sin fecha])

[16] («C280-16 Commercial Propulsion Engines | Cat | Caterpillar» [sin fecha])

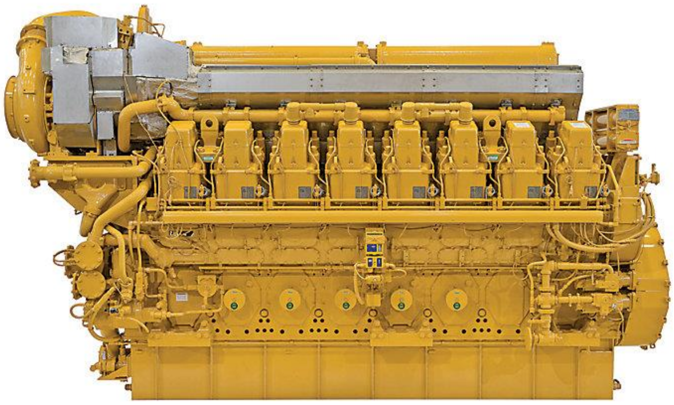

Figure 7: CAT C280-16 marine diesel engine. Figure by "cat.com/marine/power-systems".

2 Stroke Diesel Engines

This type of engine is widely used in the marine industry, they offer a lot of different options in terms of power, torque and they can be medium-sized, or big. They are mounted generally in ships with a higher design engine room, making a shorter engine room with a higher ceiling, permitting more cargo space to the bow of the engine room.

This type of engine is categorized in the low speed engine group they work up to 400 rpm[17], permitting a much longer bore of the piston and a much longer stroke.

[17] («Diesel engine» [sin fecha])

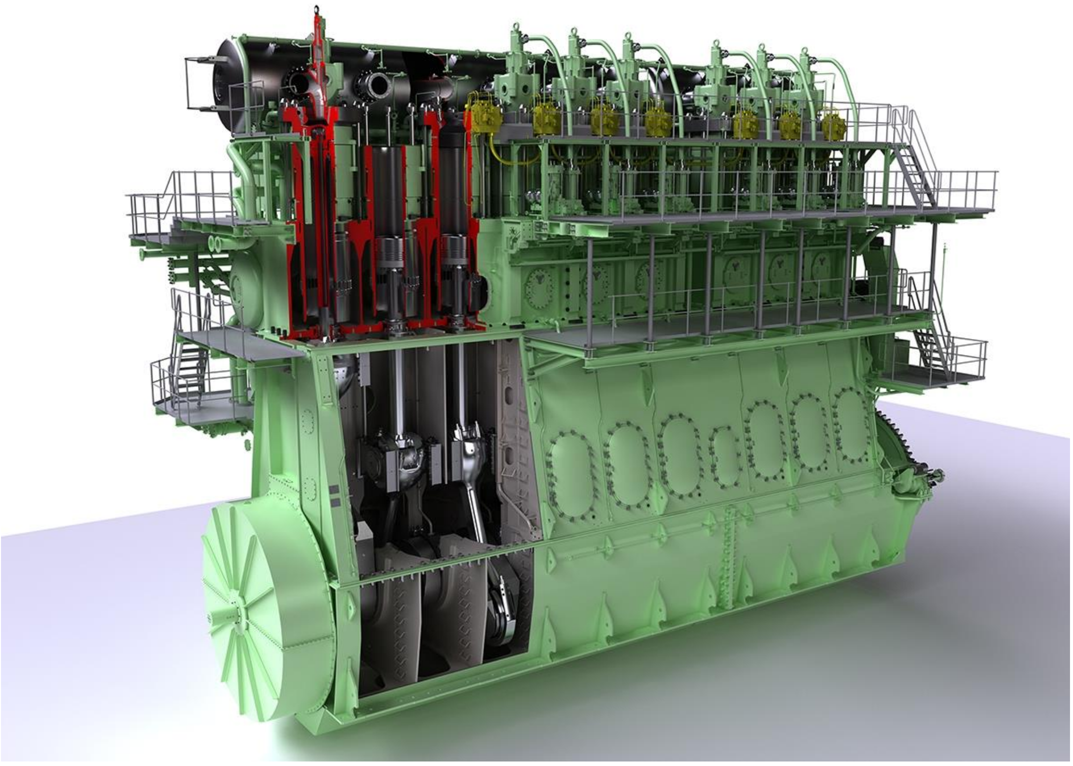

Figure 8: 2-Stroke marine Diesel engine, general layout. Figure by "themotorship.com".

These engines are fitted generally in the cargo ships, therefore they are present in the majority of ships of the merchant marine, they are quite simple and with less parts than a 4-stroke engine. A lot of the auxiliary systems that are associated to the operation of this type of engine are external to it, making it a very configurable engine with multiple options for the work to be carried out by the engine.

- **Wärtsilä**

Established in 1834 in Finland[18] it is one of the most famous marine engine builders, they are famous because of their strength and robustness and their well performing ratio. In figure 9 we show one of their slow action two

[18] («History» [sin fecha])

stroke engine, the Wärtsilä x92[19], that can be used as a propulsion unit in container ships, bulk carriers or other type of big vessels.

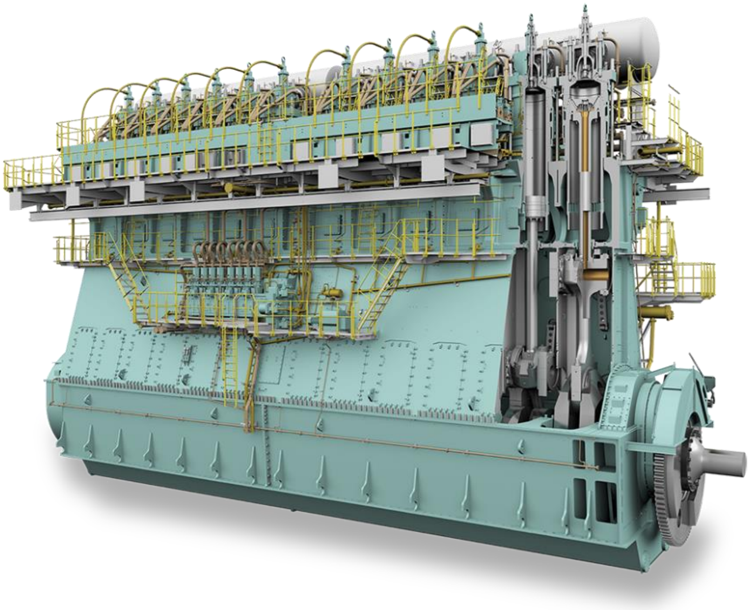

Figure 9: Wärtsilä two-stroke x92 engine in a virtual cross-section. Figure by "windgd.com".

- **MAN**

Established in 1895 in Augsburg[20], Germany, it's one of the biggest engineering firms in the world, their marine implications are far well known with reliable and energy efficient engines[21].

19 (Wärtsilä 2014)

20 («MAN Diesel | History of MAN Marine Engines | RDI Group» [sin fecha])

21 («Propulsion | MAN Energy Solutions» [sin fecha])

They also offer multiple engines with a dual fuel layout, this permit them to explore more options in the market and to offer more solutions for ships navigating in specific areas, such as the ECA[22] zone that are located around the world.

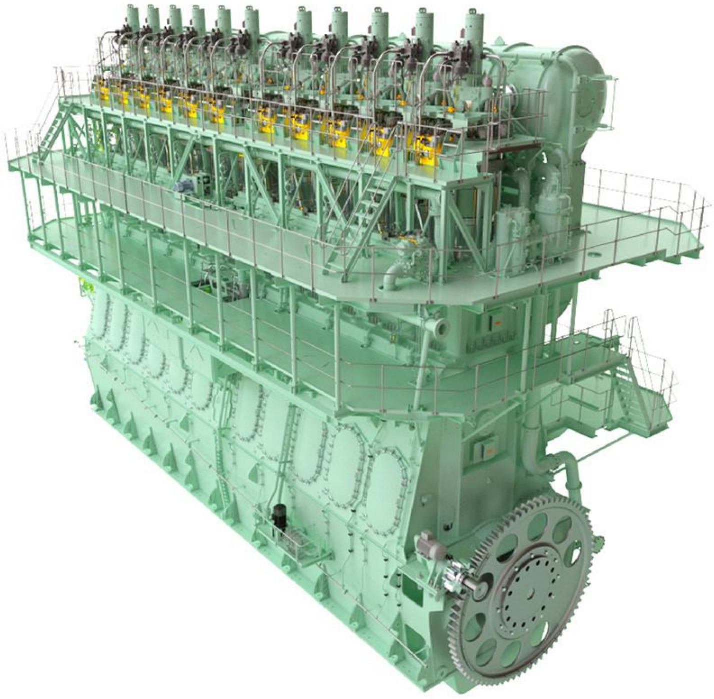

Figure 10: MAN two-stroke ME-GI Mk.2. Figure by "man-es.com/marine".

[22] (Wärtsilä 2014)

2.1.3 Systems that follow the Rankine thermodynamical principle

This thermodynamical principle is used for steam systems in the industry on shore and in the vessels that mount this steam power plants. The Rankine thermodynamical principle is the one used for the calculus and operation of the steam turbines.

Theoretical explanation of the Rankine cycle

This cycle permits to bring the Carnot cycle to an industrial use. The Rankine cycle[23] gives solutions to the main theoretical problem of the Carnot cycle.

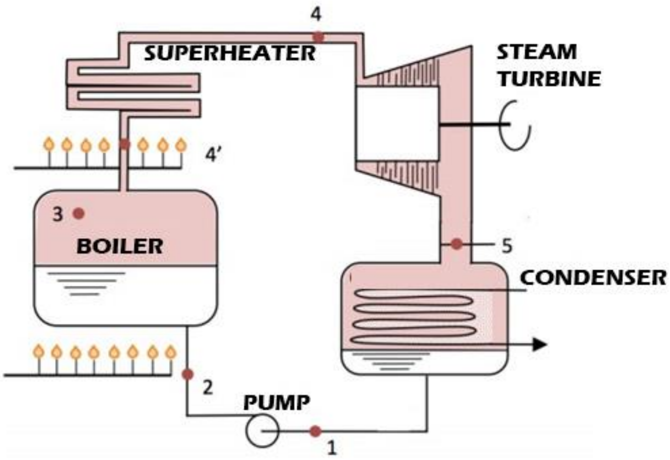

Figure 11: Rankine cycle layout. Figure by "es.slideshare.net''.

We can retrieve three main phases of this cycle:

[23] (Remacha 2018)

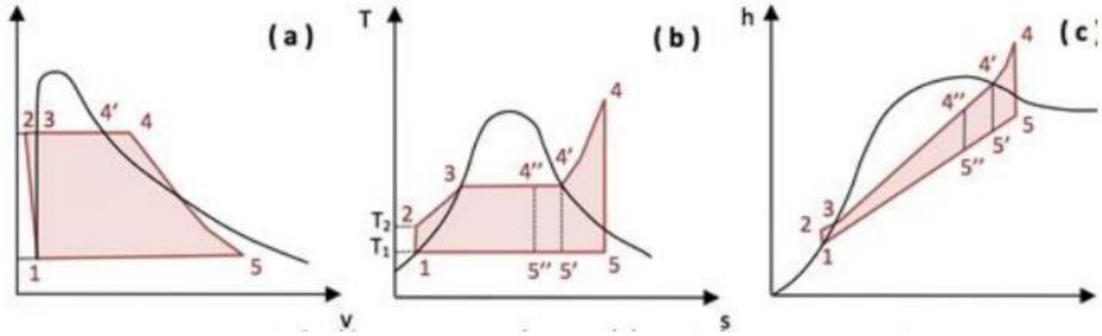

Figure 12: Theoretical cycle of Rankine with steam in position Pv (a); in position Ts (b); in position hs (c). Figure by “es.slideshare.net”.”.

a) Process of isentropic expansion of steam in the turbine, originating at point 4-5 of the diagram. Being this reversible - isentropic process is also adiabatic, therefore, Q=0, and applying the first principle:

$$Q = \Delta h + \Delta zg + \Delta\left(\frac{c^2}{2}\right) + W$$

We retrieve:

$$W_{45} = \text{Turbine work} = -\Delta h - \Delta\left(\frac{c^2}{2}\right) = -\Delta h_{tot} = -(h_{tot\,5} - h_{tot\,4}) > 0$$

Where:

The subscript "tot" is the total magnitude. In case the kinematic energies of the steam before and after do not vary much.

$$\Delta\left(\frac{c^2}{2}\right) \simeq 0$$

And:

$$W_{45} = h_4 - h_5$$

b) Isobaric condensation process, originating at point 5-1 of the diagram. In this process, unlike other cycles such as the Carnot cycle, it is carried out up to the saturated liquid state. In this process the heat is given up only by the vapor. If the increase in kinetic energy is not negligible, we should use total enthalpy. The heat given up will be:

$$-Q_{15} = (h_5 - h_1)$$

c) Adiabatic - isentropic compression process, originating at point 1-2 of the diagram. Unlike some cycles, such as the Carnot cycle, it is carried out in the liquid phase. This is as follows:

$$W_{12} = \text{ Pump work } = -(h_{tot\,2} - h_{tot\,1}) < 0$$

Or also in the case that $\Delta\left(\frac{c^2}{2}\right) \simeq 0$ between pump inlet and pump outlet would be:

$$W_{12} = -(h_2 - h_1)$$

d) Isobaric heat addition process in the boiler and in the superheater, if any, originating at points 2-3-4 in the diagram. These represent the heating and evaporation of water from 2-3 and reheating from 3-4. In more detail it is expressed as follows.

- The 2-3 process must be reversible, which would give rise to an infinite number of heat sources at increasing temperatures. In actual practice this process is irreversible, since the boiler water at temperature T3 mixes with the water driven by the pump at temperature T2.

- The process 3-4' is only isothermal. The heat transferred to the fluid will be:

$$Q_{24} = h_4 - h_2$$

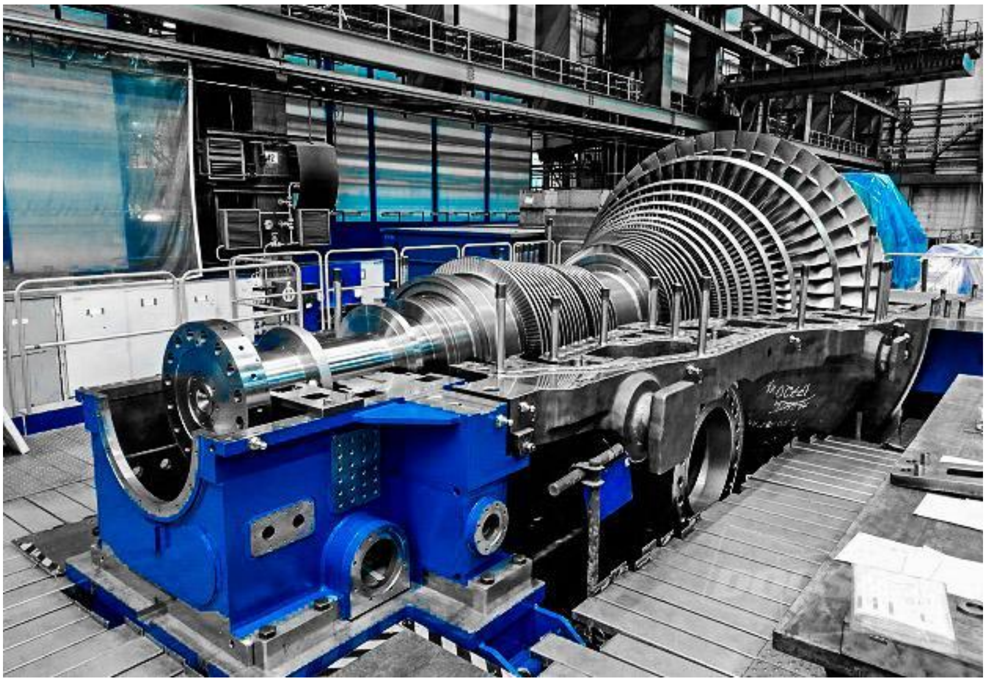

Figure 13: Steam turbine open for maintenance. Figure by "renewableenergyworld.com".

2.2 Fuels used in the marine industry

Fuel is a very general term for describing the powder that make an engine run, there are a lot of different synonyms and definitions[24], in this thesis we are going to define it as the matter that combined with oxygen (that is present in the air) and the combustion of these two elements releases an amount of energy.

By using this definition, we can encompass many substances, but not all of them are suitable for propulsion.

Fuels are characterized by being made up of combinations of a few elements, where the greatest proportion of weight is made up of the truly combustible elements such as carbon, hydrogen and, in most cases, sulfur. The rest of the compounds, which are usually quantitatively smaller, are made up of ash, moisture, nitrogen and oxygen.

Fuels used in the marine industry

- **Natural gas (NG)**

It is a gas that is usually found underground, although it is also found in other places that are not necessarily subway. In its usual composition there is a large amount of methane, together with heavier hydrocarbons, among which ethane, propane, normal butane and isobutene stand out. However, in their raw form they contain a considerable proportion of other non-hydrocarbon gases, such as hydrogen sulphide, nitrogen and carbon dioxide.

[24] (Remacha 2018)

All these characteristics indicate the presence of a number of trace compounds such as carbonyl sulphide, helium and various n-captans. In addition, the raw natural gas is saturated with water[25].

	Molar % (above ground plant)	**Molar % (in-line plant)**
Nitrogen	0.30	0.35
Methane	91.63	98.60
Ethane	5.72	1.05
Propane	1.63	
Isobutane	0.29	
n-butane	0,31	
Isopentane	0,12	

Table 1: List the typical composition of natural gas as a fuel in industry. Figure by ''sciencedirect.com/topics/engineering/molar-percentage''.

Natural gas has a high calorific value, its composition is uniform and it is free of undesirable impurities. This makes it a valuable gaseous fuel.

This gas is an excellent fuel for internal combustion engines[26]. Because of its high anti-explosive value, high compression ratios are possible, resulting in increased efficiency.

Both natural gas and methane are satisfactory fuels for gas turbines.

The calorific value of this gas is much higher than that of most of the gaseous fuels used. However, in order to burn this gas efficiently, special apparatus must be used, such as burners in case of the gas turbines and specific injections systems for the use in engines.

[25] («Máquinas marinas, Combustibles utilizadosRemacha»- 2018)

[26] («Máquinas marinas, Combustibles utilizadosRemacha»- 2018)

- **Distilled products from the petroleum**

If we make a classification based on their use, we can differentiate two types:

- Light oils or essences
- Heavy oils

Light Oils or Aromatics:

Used for the internal combustion engines and in jet engines[27]. The liquid fuels that are in this category comprise:

- Those more volatile and lighter fractions obtained by distillation or cracking of natural crude oils, shale oils and natural deposits.
- Light fractions obtained by hydrogenation of coal, heavy oil residues and coal tar.
- Light fractions obtained from the synthesis of hydrocarbons by the Fischer-Tropsch process.
- In alcohols, mainly methyl and ethyl alcohols, which are obtained by synthesis or by fermentation processes.
- Benzol, obtained by the distillation of coal tar or by the extraction of coal gas.

Heavy oils

These are heavy petroleum products, synthetic or natural, for which no more valuable use can be found[28]. They are mainly used for combustion in furnaces.

[27] («Máquinas marinas, Combustibles utilizadosRemacha»- 2018)

[28] («Marine Heavy Fuel Oil (HFO) For Ships - Properties, Challenges and Treatment Methods» [sin fecha])

They comprise the heavier fractions of natural or cracked oils, from which the more valuable fractions of lubricating and motor oil fuels, such as bitumen, have been separated by distillation, followed by other heavier and less valuable products of coal distillation, or synthetic oils.

Crude oil

Most of the crude oil is made up of hydrocarbons, 5% derived with oxygen, sulfur or nitrogen heteroatoms, traces of metallic constituents such as Ni, Fe, V, Cu, Pb, Zn, emulsified and saturated water with Na and Mg chlorides and Ca and Mg sulfates. For this reason, it is said that the composition of these compounds is very complex.

The most important elemental compounds of crude oils are listed below:

- Hydrocarbons
  - Paraffinic
  - Cycloparaffins
  - Aromatics
  - Ophynic
- Sulfur compounds

Hydrocarbons

According to the types of hydrocarbons that predominate in them we can make four main groups:

- Paraffinic

These are saturated hydrocarbons[29], where carbon atoms are found in the form of chains, generally branched, where their empirical formula is C_nH_{2n+2}.

[29] (Wang et al. 2014)

Those with linear chains are called normal kerosenes and those with branched chains are called isoparaffins.

Normal kerosenes are gaseous, the first four at room temperature, liquid those with a number of carbon atoms between 4 and 16 and those with more than 16 are solid.

- Cycloparaffins

Saturated hydrocarbons with an empirical formula such as C_nH_{2n} where their carbon atoms are joined to form rings. Those with a low boiling point are usually derived from cyclopentane and cyclohexane; and those with a high boiling point are molecules formed by the union of several naphthenic rings (cycloparaffinic)[30].

- Aromatics

Unsaturated hydrocarbons with a cyclic structure.

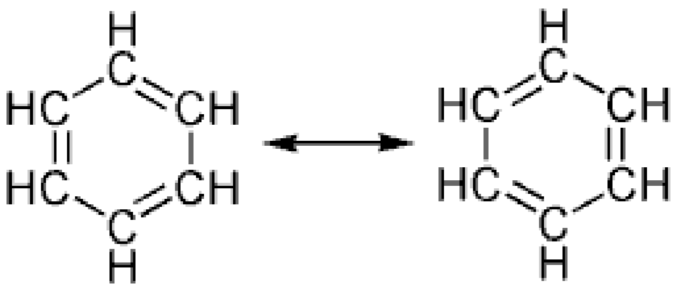

Figure 14: Example of the structure of an aromatic hydrocarbon. Figure by “Los combustibles y su tecnología”.

30 (Adebiyi y Akhigbe 2015)

- Ophinic

These hydrocarbons are unsaturated hydrocarbons with open, branched or straight chain. As a general rule, these compounds are found in the treatment process and not in the crude oil itself.

	Carbon %	Hydrogen %	Sulfur %	Density at 15.6 ºC	P C kcal/kg	Viscosity cSt at 37.8 ºC
Paraffinic *(Pennsylvania)*	84,0	13,8	1,0	0,820	10780	49,1
Aromatics *(Borneo)*	86,7	10,7	2,1	0,960	10500	5,75
Cycloparaffinic *(Texas)*	86,3	12,2	1,3	0,860	10670	44,1

Table 2: Comparison between different crude oil compounds.

Sulfur compounds

In crude oil itself, in any state, there is a level of sulfur, which ranges between 0 and 8%. The higher the amount of sulfur, the higher the operating cost for refining[31].

We can find in a combined form:

- Cyclic compounds.
- Oxygenated compounds.
- Acid compounds, such as hydrogen sulfide SH2, and mercaptans, of formula R - SH.
- Sulfides, of formula such as R - S - - -R; disulfides with formula R - S - S - R and polysulfides.

[31] («Máquinas marinas, Combustibles utilizadosRemacha»- 2018)

Fuel oils

These petroleum-derived compounds comprise a number of products obtained by reforming and distillation processes. These can be direct distillation products if they are obtained by atmospheric and vacuum distillation, or blends of these with residual oil fractions obtained by reforming processes[32].

The main factor that determines the atomization equipment used for the combustion of these oils is viscosity. Low viscosity is an inherent property of light fractions, where gas-oils and kerosene are examples. The high viscosity of waste oils can be reduced by blending with less viscous products or by Visbreaking.

Visbreaking is a mild thermal cracking process for reducing the viscosity of heavy waste oils.

We can classify fuel oils, according to their demand, as follows:

- Fuel oil number 2: located for large consuming industries such as thermal power plants and cement plants.
- Fuel oil number 1: the rest of the industry.

These compounds are heterogeneous[33]. In them we can find:

- Impurities foreign to hydrocarbons.
- Hydrocarbons in solid or gaseous form emulsified in liquid phase.
- Emulsions with air bubbles of small size and with different water droplets, normally they are carriers of soluble metallic salts where when combustion takes place, they can create corrosive compounds.

The importance of the order of magnitude of the measures that will be offered below are related to the processes of decanting, centrifugation, filtering,

[32] («Marine Heavy Fuel Oil (HFO) For Ships - Properties, Challenges and Treatment Methods» [sin fecha])

[33] (Adebiyi y Akhigbe 2015)

abrasion of fixed and mobile elements of the installations, cleaning of tanks and ducts and the analysis of the thermal powers in which fuel oils can be used.

- Decanting of particles heavier than silica for sizes larger than 0.3 - 0.5 mm.
- Decanting of water droplets when it reaches about 1 mm.

Gas oil

They belong to a category of liquid fuels derived from petroleum called pure distillates, which are composed of a range of hydrocarbons whose number of carbon atoms is between C_{14} and C_{20}, resulting in a boiling range between 220 ºC and 390 ºC.

This fuel is a homogeneous mixture, which maintains its composition and regular characteristics during storage and use[34]. It is difficult to find foreign particles, since they are easily separated by the difference in densities relative to the fuel and by the little friction that this one opposes to its fall or ascent. The water and sediments that it contains are normally in solution.

Decanting for particles heavier than silica occurs for sizes greater than 0.01 mm and in the case of water, when the droplets have a diameter of 0.1 mm.

Properties of the fuels:

This section will detail the most important parameters of the fuels, not only for their correct operation, but also the most relevant aspects to be taken into account in the fuels for the use and care of the installations.

[34] (Remacha 2018)

- **Viscosity**

It is the physical measure of the resistance of a liquid to flow when an external force is applied to it[35]. It is one of the most important properties of liquid fuels in terms of their storage, use and transfer.

We can explain this phenomenon with two parallel plates filled with fluid in their intermediate space, sufficiently large to be able to neglect edge effects, and arranged at a small distance, which we will call d, with respect to each other. We assume that the lower plate is fixed and the upper one is the one that is made to move in parallel with a velocity, V0, given to the application of a force, F, in correspondence with a certain surface, A, of the moving plate.

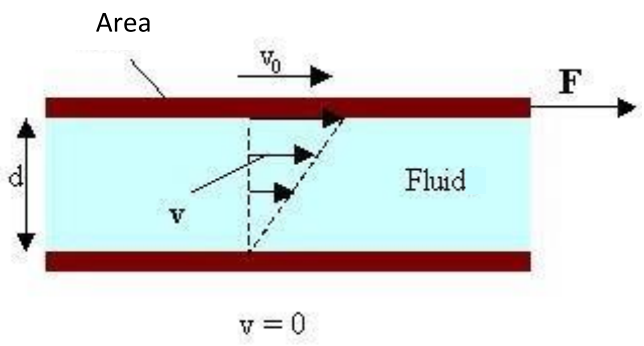

Figure 15: Effect that appears on a plate by the effect of the viscosity. Figure by "espaciociencia.com".

When this happens, the fluid particles that are in contact with each of the plates adhere to them, if the velocity and distance are not very large, the velocity gradient is a straight line. The representation of the fluid would be that of a series of parallel thin plates, each of which slips with respect to the adjacent ones.

[35] (Wärtsilä 2014)

Experience shows that:

$$F = K\frac{AV}{Y}$$

From the viscosity law formulated by Newton, fuels in the liquid state satisfy a wide range of temperature variation. However, from more or less low temperatures they already show deviations from Newton's law. Depending on their constitution and characteristics, they behave as non-Newtonian fluids. All this is mainly due to the crystallization of some of their components, such as kerosene and asphaltenes, which flocculate in the liquid matrix.

Any liquid fuel can be conducted as a Newtonian fluid, a suspension or a plastic material (boundary between liquid and solid states), depending on the temperature at which it is found. For economic reasons it is advisable to handle liquid fuels in the Newtonian fluid range.

In the international system, the unit of viscosity is the Kg - s x m^{-2}. In the absolute MKS system, the unit is the $Kg - m^{-1}$ x s^{-1}.

The quotient of absolute viscosity and density, both measured at the same temperature, is called kinematic viscosity. Its dimensions in the CGS system are:

$$v = \frac{dina\ s\ x\ cm^{-2}}{dina\ s^2\ x\ cm^{-4}} = cm^2\ x\ s^{-1}$$

This unit is called Stoke. In the international system kinematic viscosity is measured in $m2$ x s-1, although we will normally find the measurements in centistoke (cSt).

Kinematic viscosity is finished by measuring the time in seconds, required for a fixed volume of liquid to flow by gravity, through the capillary of a viscometer, calibrated under a reproducible liquid column and at a precisely controlled temperature. The kinematic viscosity is the product of time measured by the calibration constant of the viscometer.

The viscosities of a liquid fuel vary markedly with temperature and is little sensitive to pressure oscillations, such effects will be practically negligible.

In contrast to gases, the viscosity of liquids decreases with increasing temperature.

Importance of viscosity in fuel oils:

Viscosity varies according to the batch and is almost always indicated for two temperatures in order to describe the behavior of the fuel during preheating. This property is usually found in the name:

The viscosity of RMG 380 marine fuel, for example, is approx. 380 cSt at a temperature of 50 °C. As the temperature increases, the viscosity decreases, reaching a value of approx. 25 cSt at 100 °C in this type of fuel oil.

In this case, the viscosity depends both on the composition of the residual oil (base material) and on the amount of diluent in the final blend. The diluent generally has a low viscosity and a low boiling point. If the ratio is not carefully chosen, a very heavy fuel oil can decompose in the preheater, even if the viscosity is correct, because the highly volatile components will boil off.

In principle, it is possible to pump fuel oil only when its viscosity is 350 cSt maximum. This means that HFO must always be heated before it can be pumped. In addition, atomization principles have different viscosity requirements. Steam-assisted atomizing burners always need a less viscous fuel oil than is required by rotary cup atomizing burners. The latter can also perfectly atomize heavier fuels with a viscosity of up to 45 cSt.

- **Density**

Density is a function of pressure and temperature[36]. In liquids, because their compressibility coefficient is small, the pressure components can be neglected in practice. This is not the case with temperature, where it is mandatory to express the value of this parameter when indicating the density of the liquid.

Thus, we can define the density under calculation as the empty weight of the product, as shown in the above equation:

$$D = \frac{M}{V};\ D = \left(\frac{M}{L^3}\right)\ ;\ \frac{kg}{dm^3}$$

However, as mentioned above, this is not the case in practice, since the weight of the unit volume is expressed in the following equation:

$$Pe = \frac{P}{V} = \frac{M}{V} \cdot g = Dg$$

$$\mathrm{g = gravity\ acceleration}$$

It is important to note that the terms density and specific gravity are not synonymous in calculations as they do not apply the corresponding unit.

The relative density or specific gravity is the ratio between the density of the fluid or specific gravity and the density of water or specific gravity of water, in the case of liquids. This result has no unit and is expressed by the following equation:

$$Relative\ density\ (d) = \frac{Dliquid}{Dwater} = \frac{Pe_{liquid}}{Pe_{liquid}}$$

In Europe, water at a temperature of 4ºC is taken as a reference temperature, since the expansion curve of water as a function of temperature produces a minimum for this value.

36 («FUEL PROPERTIES» [sin fecha])

The Americans use the A.P.I. (American Petroleum Institute) degree as the hyperbolic function of the specific gravity for density measurement[37].

$$^{o}API = \frac{141{,}5}{sp \cdot gr \cdot {}^{60}/_{60} \cdot {}^{o}F} - 131{,}5$$

The A.P.I. degrees are the terminology most commonly used in the oil world, the conversion between these degrees and the density at 15.6 ºC (density in Spain, where it is defined as the mass of liquid per unit volume, expressed in kg/1 at 15ºC) can be made by means of the above equation.

- **Calorific value**

This parameter of liquid fuels indicates the amount of heat released by them when they are subjected to a combustion process to obtain products in their final oxidation state[38]. In other words, it can be said to reflect the thermal energy potentially available.

This is a very important characteristic to know about fuels, since it will determine the performance of the thermal installations.

The way to express it is in kcal/kg.

As a general rule it is advisable to have a record of the value of the calorific value of the fuel at the point where it is going to be burned.

[37] («FUEL PROPERTIES REFERRED TO API» [sin fecha])

[38] (Remacha 2018)

Higher calorific value:

It is the total amount of heat given off in the complete combustion of 1 kg of fuel when the water vapor originated in the combustion condenses and the heat given off in the phase change is therefore accounted for.

Lower calorific value:

According to the regulations that refer to it, as mentioned above. We can say that it is the heat released by the combustion of the unit mass of fuel, at a constant pressure of 1 atmosphere, with the water remaining in a gaseous state. Another way to define it would be to say, it is the same as the superior one, only changes that the combustion water is in vapor state.

This one differs from the previous one in 50.68 kcal for each percentage by weight of hydrogen in the fuel. We can represent it as:

$$PCI = PCS - 50.68 \pm \% JC \ kcal/kgg$$

In cases where this percentage is known for certain its value can be represented as:

$$PCI = PPCS - 600 \ kcal/kkg$$

- **Flash point**

Flash points of liquid fuels indicate the temperature at which the fuel emits sufficient vapors to be ignited by the action of a pilot flame[39]. These vapors are caused by heating.

This parameter gives an idea of the existence of volatile products in the fuel.

- **Ramsbottom carbonaceous residue**

It is a measure to quantify the carbonaceous material[40] (mainly coke) that remains after having subjected a liquid fuel cylinder to a process of evaporation and pyrolysis.

This applies as a general rule to those petroleum products which are relatively non-volatile and which are partially decomposed in a distillation at atmospheric pressure.

Those fuels that contain a high amount of ash will give an erroneously high content of carbonaceous residue, so it is necessary to determine their ash content by subtracting the value of the Ramsbottom residue found.

The Ramsbottom index provides important data for the correct operation of the machines, since a tendency of a fuel to form unburned fuel would cause failures in the injectors. Consequently, this index gives us an important value on the frequency of cleaning of the machines.

High values of this residue give important indications of the tendency of certain liquid fuels, such as fuel oil, to coke during preheating prior to combustion.

[39] («Flash points - Liquids» [sin fecha])

[40] («Carbon Residue - an overview | ScienceDirect Topics» [sin fecha])

- **Distillation**

Distillation is carried out in order to characterize fuels[41], i.e., to verify that the temperatures at which certain distillate percentages have been taken correspond to the specifications for the fuel in question.

- **Sulfur**

Sulfur is found in crude oil in the form of thiophenes, disulfides, mercaptans and elemental sulfur, all depending on the quantity and distribution of these agents according to the geographic location of the field and the geological age of their formation[42].

The heavy fuel oil obtained from a given crude oil has a sulfur content approximately double that of the crude oil used for its manufacture. In the refinery, the administrative specifications of the market must be respected when obtaining a crude oil for its commercialization.

The presence of sulfur in fuel has significant effects, as defined below:

- It causes environmental pollution problems.

- It has to be treated with extreme delicacy in those processes in which the combustion gases come into direct contact with the product being treated.

- The calorific value of the fuel is affected, since the sulfur in the fuel reduces its combustion heat.

[41] (Remacha 2018)

[42] («The supply and use of 0.50%-sulphur marine fuel» 2019)

- It causes corrosion problems in fuel consuming equipment or auxiliary equipment. There are two types of corrosion, high temperature corrosion and low temperature corrosion.

High temperature corrosion:

This type of corrosion is usually found mainly in boilers with a high degree of overheating, the most affected being the superheaters and reheaters, and in gas turbines the worst affected are the blades.

The main responsible for this corrosion is the formation of sodium sulfate (SO_4Na_2).

The easiest way to deal with this problem is to perform combustion with very low excess air. Another way to act is by modifying the structural composition of the deposits or by adding compounds with high melting points. In this way we can see a series of compounds that have given results against this problem: with additives of the dolomite type good results have been achieved against vanadium, with alumina improvements have been noted against sodium and with some silica compounds in powder or in soluble solutions in fuel oil it has been possible to obtain harmless alkaline silicates instead of alkaline sulfates.

Corrosions at low temperature:

Combustion in a liquid fuel gives rise to various components, the most important of which are water vapor and sulfur dioxide (SO_2). If combustion is carried out with a higher amount of oxygen than is strictly necessary for burning the fuel, part of the SO_2 may change to SO_3, in turn reacting with H_2O according to:

$$SO_3 + H_2O \rightarrow SO_4H_2.$$

Between 200 ºC and 500 ºC is the equilibrium of this reaction. If we are below 200 ºC we only have SO_4H_2 vapor in the presence of excess water. On the other hand, if we are above 500 ºC, SO_4H_2 is unstable.

At the acid dew point SO_4H_2 starts to condense and is completely deposited at the water vapor dew point in the gases.

The most prominent way to avoid this corrosion phenomenon is to perform the combustion stoichiometrically or with a very low air level[43]. However, there are other systems, such as: maintaining a permanent flue gas temperature above that corresponding to the dew point, the use of neutralizing agents or the use of additives that paralyze SO_2 oxidation.

- **Cloud Point**

This is the temperature at which the first kerosene crystals begin to appear in the diesel oil when it cools under specific conditions. This temperature is expressed on a unit scale of degrees Celsius.

Depending on the geographical location, its treatments and its constituent components, each diesel oil will have a different cloud point.

A major problem caused by this characteristic is the clogging of filters and atomizers and the pumping system itself due to the first kerosene crystals.

This symptom appears at temperatures higher than the cold filter clogging point.

[43] («The supply and use of 0.50%-sulphur marine fuel» 2019)

- **<u>Cold filter plugging point</u>**

This is an indication of the lowest temperature at which a fuel can flow through a given mesh filter under certain cooling conditions[44].

The CFPP (Cold Filter Plugging Point) is severely affected by the composition of the fuel, where the most important part is the kerosene compound in the fuel. However, there are many factors at sea that alter these characteristics, one of them, and it could be the most important, is the change of temperatures that the installations suffer due to the seaworthiness zones. These problems can be eliminated by heating the pipes and other equipment that may suffer from these symptoms.

- **<u>Water and sediments</u>**

Water contributes in many ways to the subsequent separation and agglomeration of the sediments contained in the fuel[45]. Water can be found in suspension in all liquid fuels, particularly in those that are residual.

The way to decant the water from the remains of the components found in the fuel is by centrifugation of the fuel.

The most important parameter in this aspect of fuels is to know the chemical and granulometric composition.

The aspect detailed in the previous paragraph is of vital importance, since the sediments can accumulate in the storage tank, which would require an expensive and prolonged maintenance or, simply, the obstruction of filters, or in more extreme cases, cause obstructions in the atomizers of the burners or abrasion in metallic parts.

[44] («The supply and use of 0.50%-sulphur marine fuel» 2019)

[45] (Remacha 2018)

In the case that the foreign particles, are in great quantity of compounds such as silica or iron oxide, when circulating in the fuel, through atomizers or displacement pumps originates an abrasion in these elements, which can be translated as breakdowns and high costs in the installations. However, if on the other hand, the sediments are composed of soft particles, their action will not be harmful, as long as it is not for a long period of time.

- **Water**

It is inevitable, however little, that the water in the crude oil is not incorporated in the fuel.

The problems caused by water in the fuel depend on its physical state. If the diameters of the droplets in the fuel itself are of such diameters that their settling is rapid at temperatures reached by the fuel during preheating before combustion, the appearance of these droplets at percentages of 1% can cause a malfunction of the burner and poor flame stability.

In the opposite case, if the diameters of the water droplets are so small that they are susceptible to settling, higher percentages of water can be admitted without affecting the burner operation in an essential way, although it should not be forgotten that high water contents would considerably reduce the calorific value of the fuel, not only due to the loss of heat of the fuel for the vaporization of the water, but also due to the reduction of fuel matter per kilogram of product injected.

Other important characteristics of fuels

- **Ashes**

These compounds are the non-combustible inorganic residues[46] that originate when complete combustion has taken place.

They are mainly composed of:

- Impurities that are in the water associated with the crude oil, such as salts and clays.

- Silicates and silica coming from the oil strata.

- Iron oxides in colloidal state that derive from the transport and storage of fuel.

- Organometallic compounds that are emulsified or in solution in fuels, based on calcium, vanadium, potassium and sodium.

Pumps or atomizers are some of the clear examples of the elements that will suffer the problems of these compounds.

In addition to the problems of mechanical origin that these compounds can present, we find that sodium and vanadium, present in the said fuels, cause corrosion at high temperatures.

On the other hand, it is confirmed that vanadium compounds act as a catalyst in the formation of SO_3, which helps in the creation of sulfuric corrosion at low temperature.

The ash content of a fuel oil is currently very low[47], approaching an average value of 0.05%).

46 («Carbon Residue - an overview | ScienceDirect Topics» [sin fecha])

47 («The supply and use of 0.50%-sulphur marine fuel» 2019)

The percentage of vanadium depends on the type of crude oil. At present it is between the following values; 15 and 200 ppm.

The Na percentage is affected by the percentage of water in the fuel. Values such as 6 - 40 ppm of Na when the crude has little water, even in waters with very high saline content, reaching values in the order of 200 ppm.

CHAPTER III. WATER INJECTION IN THE CYLINDER AS AN ENERGY EFFICIENCY MEASURE

Third chapter examines the study of one of a kind technique, the use of distilled water to enhance the efficiency of the engine itself by using less fuel and making more power out of the process of changing the state of the water that is injected in the cylinder.

Although it is a totally new technology, several engine manufacturers have decided to invest in these systems for enhancing the efficiency of their engines.

3.1 WATER INJECTION IN THE CYLINDER

3.1.1 Introduction

Water injection to the combustion chamber of a diesel engine starts in the early years of the XX century[48][49]. Later when the pollution regulations became more and more stringent, researchers started using water injection for the purpose of reducing emissions[50]. They have used water injection during suction, compression and combustion processes. Theoretical calculations were well matched with the experimental values, reporting up to 90% reduction in NO_x.

There are several ways found to introduce water into the combustion chamber of an engine:

- Fumigation is where liquid water is injected into the inlet manifold during suction stroke of the engine.
- Fuel and water are blended using surfactants to form an emulsion which can be used as an alternative fuel.
- Direct water injection system carries a dual feed injection nozzle with corresponding water supply system.

All the water introduction methods have shown noticeable reduction in NO_x and PM emissions from diesel engine and in several cases, they have improved the reaction of the engine, increasing its thermal efficiency.

[48] (F. O. 1948)

[49] (W. B., L. Y. y F. H. 2002)

[50] (Nicholls y I. A. 1969)

3.2.1 Different types of introduction of the water in the cylinder

After the introduction to this topic and have a brief overview of what we are going to explain in this chapter we can divide the way to introduce water inside the cylinder in three different methods, fumigation, emulsion and direct injection.

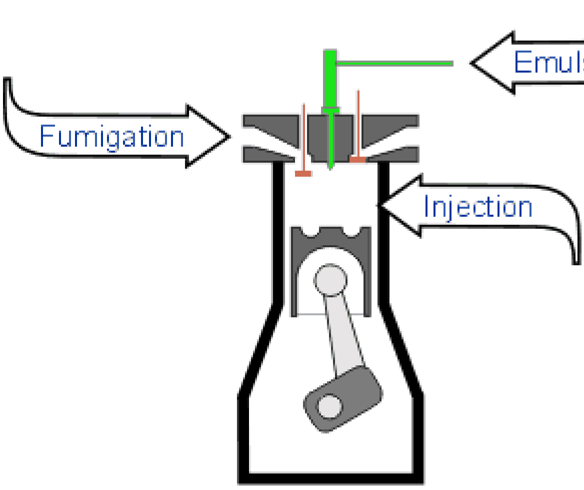

Figure 16: Overview of water addition in the cylinder. Figure by "dieselnet.com".

Fumigation: (Inlet Manifold Water Injection Method)

At present this method can be widely used in large marine diesel engines. This method may be the easier way to supply water to the combustion chamber of diesel engine without major modifications. The main advantage of this system is its simplicity and ease with which it can be integrated within the existing engines. Also advantages like uniform on-line variation of water quantity, increase of volumetric efficiency due to cooling effect, nearly or homogeneous water distribution in combustion chamber, no alter in fuel property etc. make fumigation system more interesting system to study in reducing tail pipe emissions from diesel engines.

Many researchers have used different methods to inject water into the inlet air: multipoint water injection in the intake pipes close to the inlet valves and single point water injection upstream the compressor or downstream the compressor[51].

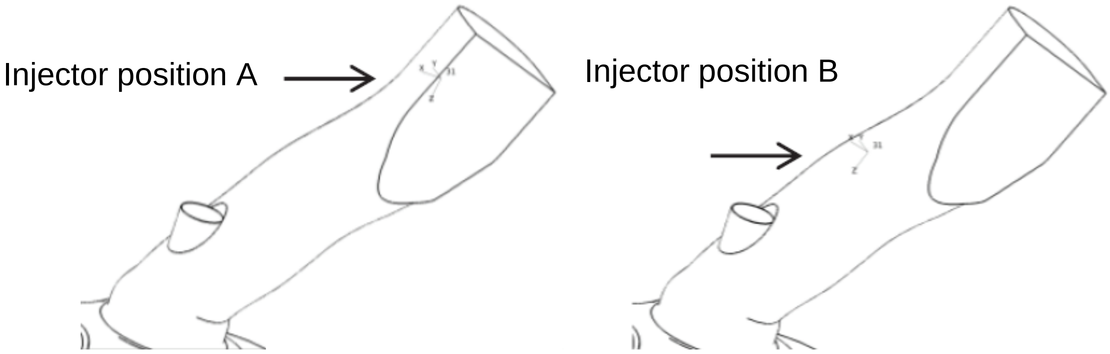

Figure 17: Possible positions for the water injector in the fumigation system. Figure by ''energyprocedia.com''.

The main weakness of fumigation is that the quantity of water required to reduce a significant NO_x is very large when compared to water in diesel emulsion system. A water mass of about 60-65% of the fuel is needed for achieving 50% NO reduction[52][53].

Investigators compared water in diesel emulsion with timed water injection to intake manifold to a 1500 rpm running diesel engine. Their investigation was fixed to Water-to-diesel fuel ratio for emulsion and water injection methods as 0.4:1 (by mass). They concluded that both methods were capable of reducing NO emission drastically. However, CO and HC levels were higher for water emulsion than for water injection.

[51] (Sahin, Tuti y Durgun 2014)

[52] (B., R. y F. 2012)

[53] (X, A y Shah 2010)

Peak pressure, ignition delay and maximum rate of pressure rise were lesser for water injection compared to emulsion method[54].

They have concluded that water injection to intake air does not show any significant change in cylinder pressure and indicated power.

If instead of water, steam is injected into the intake air very close to the inlet valve. We can appreciate improvements in torque, effective power, efficiency and SFC with steam injection and decrease in NO emissions significantly[55].

Steam injection yields positive effect on performance and NO emissions at all speeds. They mentioned that steam injection does not affect CO and HC emissions considerably.

Other investigations studied the effect of inlet water injection in a biodiesel engine. Also, this study showed that the water injection in the intake manifold under different operating conditions had little effect on the in-cylinder pressure and heat release rate of the diesel engine.

Use of fumigation system to reduce emission has given positive results. An intensive work on theoretical model will give more input to the different parameter of fumigation like location of injector, pressure, quantity, temperature of water to be injected to get better results in performance and emission.

One of the problems that can appear during the use of this system is when the fumigated water does not completely evaporate in the intake air, it will impinge on the cylinder walls causing disintegration of the lube oil film and engine damage. A safer approach is to fumigate water vapor rather than liquid as explained above. Water vapor may be generated using waste heat from the engine, such as from the exhaust gas and/or from the compressed charge air.

[54] (B., R. y F. 2012)

[55] (Sahin, Tuti y Durgun 2014)

Another possibility is to use steam, which may be available in certain stationary engine applications.

Emulsion

An emulsion is a mixture of two or more liquids immiscible in nature, one present as droplet, or distributed throughout the other, in dispersed/continuous phase[56]. It is generated by means of a mechanical agitation in the presence of surface-active agents, called emulsifiers or surfactants, for stability.
The fact that emulsion is used as a fuel in diesel engine, it is recommended that it should be stable and this can be realized with the help of suitable surfactants. Surfactants should easily burn with no soot and free of sulfur and nitrogen[57].

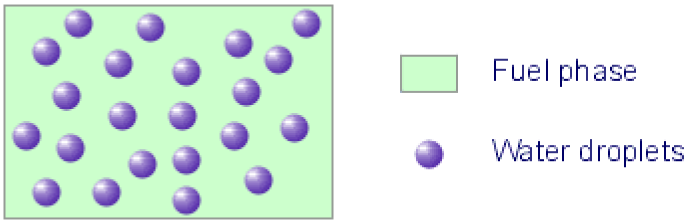

Figure 18: Water-in-fuel theoretical layout in an emulsion. Figure by ''dieselnet.com''.

There has been a limited literature about the effect of surfactant on the characteristics of water-in-diesel emulsion as far as combustion and emissions are concerned[58]. Investigators have studied water-in-diesel emulsion with conventional (sorbitan-mono-oleate) and gemini surfactants.

[56] («Effect of Introduction of Water into Combustion Chamber of Diesel Engines – A Review» [sin fecha])

[57] (Y y C-F 2006)

[58] (A. y K. 2006)

They have studied the emissions by fueling it in a four stroke and four-cylinder engine test bed and concluded that for 15% water content[59], there is 71% reduction in PM emission with gemini surfactant water in diesel emulsion fuel.

- **Theoretical Advances**

Theoretically the combustion process of water in diesel emulsion has been explained by many researchers. Water gets entrenched into the diesel fuel with the help of surfactants. When the emulsified fuel gets into the combustion chamber, heat transfer takes place to different fluids of supplied emulsion at different stages. Since the boiling point of water is less than the diesel, the water molecules reach their superheated stage faster than the diesel producing a vapor expansions breakup[60]. This is the stage where the two phenomena, micro-explosion and puffing, prevail:

- Micro-explosion is that the whole droplet breaks up into small droplets quickly.
- Puffing, water leaves the droplet in a very fine mist (a part of the droplet breakup).

These micro-explosions help in faster fuel breakdown, allowing them for secondary atomization, resulting in better mixing of air and fuel[61].

Micro-explosion is an important phenomenon in the secondary atomization process of water-in-diesel emulsion fuels. Generally, this phenomenon is depending on the diameter of the dispersed liquid, location of the dispersed liquid and ambient conditions like pressure and temperature[62].

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59 (C, C. y K. 2006)

60 (Tarlet, Bellettre y Tazerout 2009)

61 (Hiroshi, Mitsuhiro y Toshikazu 1993)

62 (Jeong, Lee y Kim 2008)

Although many studies have been conducted both experimentally and numerically to understand the phenomenon of micro-explosion, yet the study of its effects inside the combustion chamber are quite few. It is believed that fuel injection and the passage of emulsified fuel through the narrow exit of the injection nozzle affect the dispersed liquid behavior of the fuel. It is therefore very important to study the micro-explosion phenomenon inside a combustion chamber and its effect on the combustion process like the secondary atomization, spray penetration, evaporation, and mixture ignition.

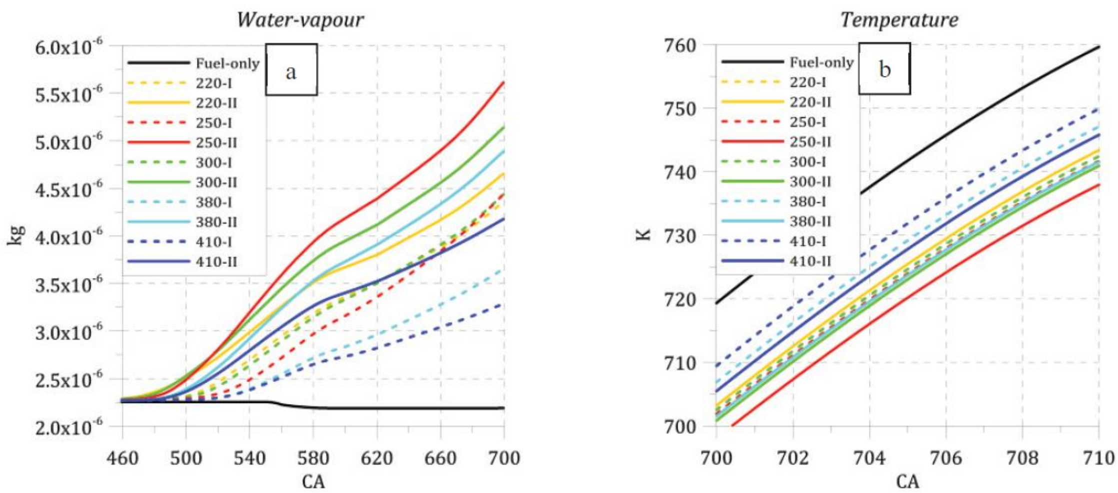

Table 3: Simulations with the emulsion type water injection. Figure by ''energyprocedia.com''.

- **<u>Experimental Advances</u>**

Experimental studies show that reduction in emission parameters specially on NO_x and PM using emulsified fuel meet the emission regulations. Researchers has studied torque, power, BSFC and brake thermal efficiency by increasing the percentage of water by volume from 0 to 20 with 5% resolution. They report that at 20% water in emulsion brake thermal efficiency[63] increased by 3.5%.

[63] (Khan y Z. A. 2014)

We conclude that the engine power increases with an increase in the percentage of water.

The percentage of water in this case is known but other particularities like the size of the engine and the rpm that where used in this particular scenario did not transcend during the test of the 20% water in emulsion scenario.

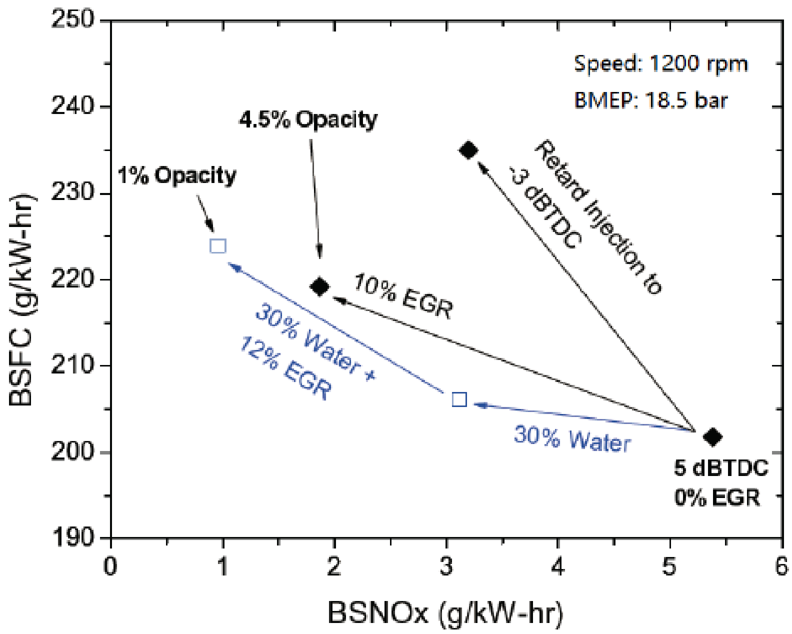

Table 4: Comparison and combination of EGR and water addition to reduce NOx. Figure by "A review of water injection applied on the internal combustion engine".

The situation reveals the need of further investigations of the combustion processes of water in diesel emulsion. The application of new methods of observing, such as laser diagnostics techniques, may help to better understand in-cylinder processes of water in diesel emulsion combustion, which could lead to establishment of more precise models of emission formation.

Direct injection

The in-cylinder direct water injection method is also attracting attention from the use of water-diesel emulsion and fumigation[64], for the purpose of reducing NO_x and PM.

One of the disadvantages of the water-diesel emulsion technique is that the water percentage cannot be changed under transient engine conditions (e.g. at cold start or changing load) compared to fumigation and direct water injection system. Similarly, the disadvantage of the fumigation technique over direct injection system is that the water cannot be injected at the end of compression stroke along the fuel. So direct water injection system will have more degree of freedom compared to both emulsion and fumigation systems[65].

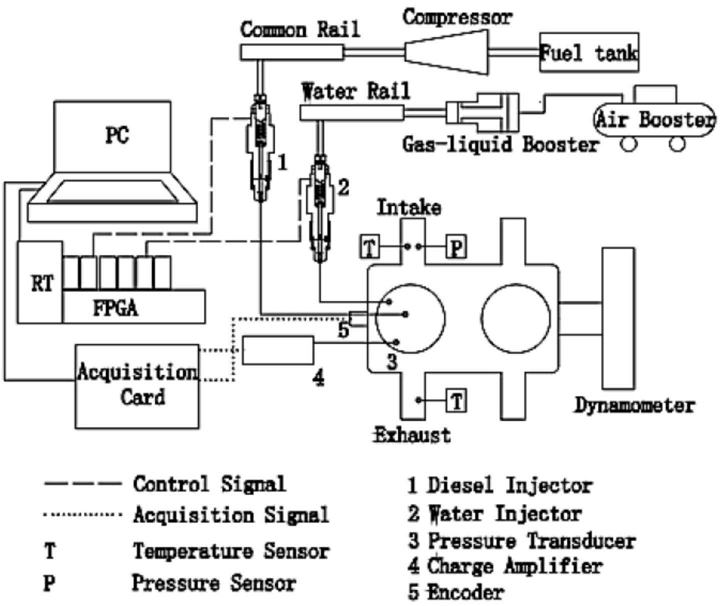

Figure 19: Schematic of system control and layout. Figure by "www.elsevier.com/locate/procedia".

Addition cost on modification of the injector make this system less popular compared to other two systems. The key to the direct water injection system is the dual feed injection nozzle with the corresponding water supply system.

[64] (Psota, Easley y Fort 1997)
[65] (Fingas y Fieldhouse 2001)

Here the water supply system does not support high pressure like the fuel injection system[66]. The water and diesel mixed in the injector tip such that initial portion of the injected diesel contained mostly diesel. However, having water towards the front of the injection may cause ignition delay.

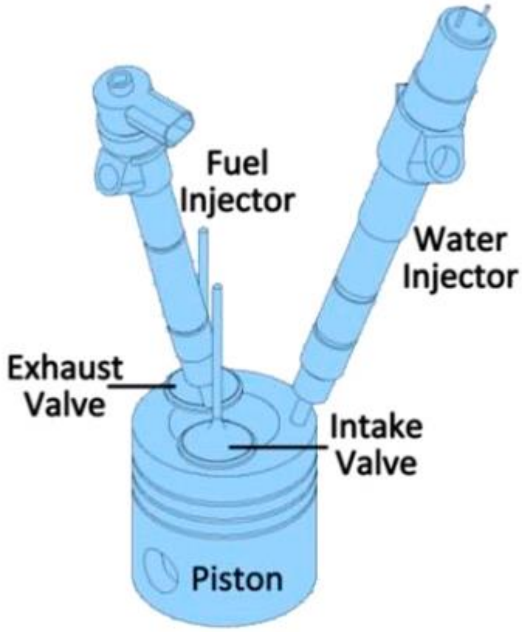

Figure 20: Schematic of combustion chamber layout. Figure by "www.elsevier.com/locate/procedia".

In-cylinder injection of water requires a separate, fully independent injection system, preferably under electronic control[67]. This method offers the capability to inject very large quantities of water without the need to derate the engine. This system also allows to switch the water injection on and off, as may be needed, without affecting engine reliability. Direct water injection needs to be carefully optimized with respect to injection timing, water consumption, emissions, and other parameters.

[66] (Psota, Easley y Fort 1997)

[67] (Christopher y Chandwell 2008)

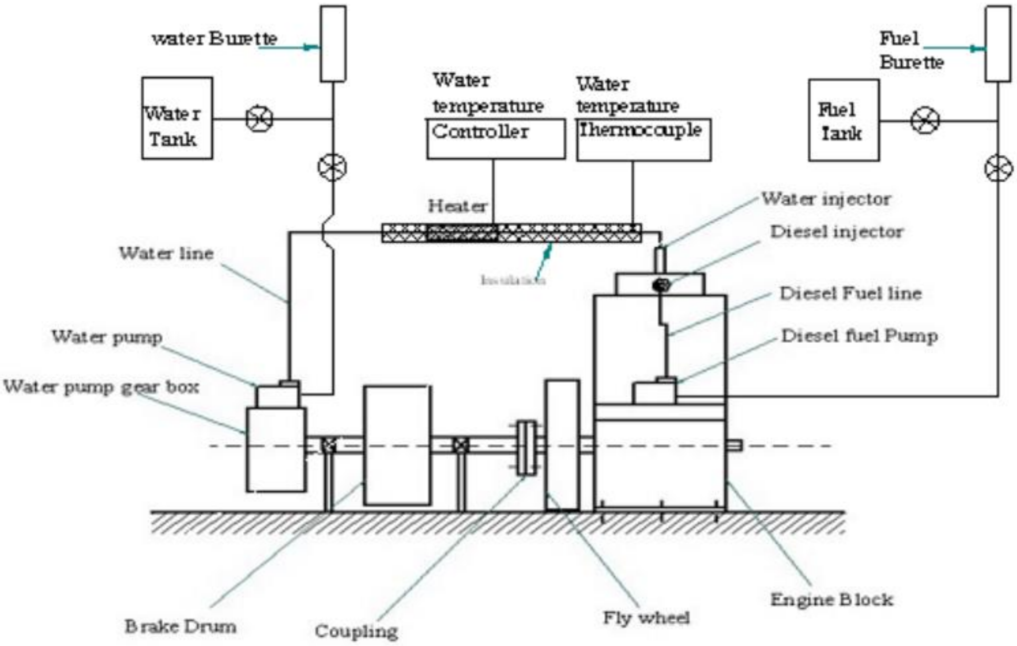

Figure 21: Experimental setup for the water direct injection test facility. Figure by ''materialsandscienceengineering.com''.

This flexibility in optimizing parameters allows to achieve NO_x reductions similar to those seen in emulsion systems, despite the fact that water is not introduced directly into the diesel flame area as an integral part of the spray[68]. However, PM emission reductions, if any, do not match those with emulsified fuels. The complex development work required for water injection systems in different engine types makes this approach suited for OEM rather than for retrofit applications.

[68] («Effect of Introduction of Water into Combustion Chamber of Diesel Engines – A Review» [sin fecha])

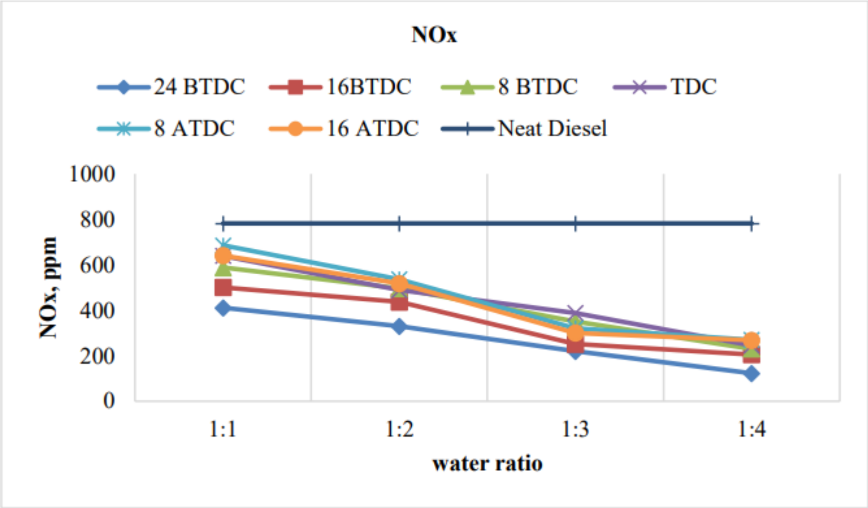

Table 5: Variation of NOx emission with water injection quantity and water injection timing. Figure by ''materialsandscienceengineering.com''.

They reported that water injection at a rate of 3 kg/h resulted in the reduction of NO_x emission by about 50% without causing any significant change in the BSFC.

Researchers also reviewed effectiveness of different methods introducing water into combustion chamber of Marine diesel engines[69]. In the direct injection method employed, a specially designed nozzle containing two needles were used, one for fuel and other for water respectively. Also, cylinder head and pistons were made with stainless steel alloy material to provide sufficient strength and high resistance to corrosion. Fuel to water ratio was kept below 1:1 and water was injected before diesel injection so that it does not affect the combustion process. Experimental result showed 40-60 % reduction in NOx.

[69] («Effect of Introduction of Water into Combustion Chamber of Diesel Engines – A Review» [sin fecha])

But due to operational problems, this method could not be implemented successfully at the time but it is not clear if it will be implemented during these next years as a result of the implementation of more measures for reducing the NO_x particles resulting from the combustion of the marine fuels.

- **Water injection measurement**

Diesel to water ratio is a parameter used to measure quantity of water injected which is defined as follows.

$$\text{Diesel: Water} = \frac{Volume\ flow\ rate\ of\ diesel\ at\ full\ load}{Volume\ flow\ rate\ of\ water}$$

Flow rate of water is controlled using the push rod of the water pump and measured with the help of a burette and stop watch arrangement:

- At full load, diesel flow rate was found to be 20 cc/min.
- At 1:1 diesel water ratio, volume flow rate of water is same as that of diesel
- At 1:3, volume flow rate of water is regulated to three times that of diesel flow rate.

Since rate of water injection is independent of diesel injection, greater flexibility is available for controlling the flow rate of water which is limited in the case in emulsion and fumigation techniques[70]. Since water injection is done after the start of combustion process, a large scope of work is also available to study in detail the effect of injecting larger quantity of water into the combustion chamber at different crank angles across prior and post combustion process in a diesel engine which are not yet studied by anyone and we have not yet more information for reviewing if it is suitable for becoming an active system for the engines to come or not.

[70] (Series y Science 2018)

Conclusions

This thesis has been a voyage through a lot of different kind of data, the first chapter makes a review of the two main regulations that are involved in the efficiency of the ship, from the design of the ship with the EEDI and the operation of the ship itself with the SEEMP.

After the first chapter, we move from the international regulations and we proceed to overview what kind of technology is mainly used in the ships nowadays, with the three main ways of propulsion systems. We also include a study of the fuels used and their principal characteristics.

Finally, in the third chapter, we introduce the water injection technology for the reduction of NO_x emissions, temperature in the cylinder and in some cases the enhance of the power of the engine in which the water is injected. From this third chapter we can extract the following conclusions:

1. This technology is still not advanced enough for become relevant in the marine industry in the years to come.
2. Although it is not yet clear if this technology is going to be implemented in the marine engines, it is very useful for the reduction of the NO_x particles resulting from the combustion phase.
3. The injection of water in the compression phase can help enhance the power of the engine.
4. The injection of water could reduce the fuel consumption.
5. The injection of water in the cylinder can lead up to an increase of the thermal efficiency until its peak, after which it goes down.
6. Early injection timing is beneficial for small water injection duration, while late injection timing is beneficial for relatively larger water injection duration.
7. The stoichiometric mixture produces higher engine power compared to other mixtures due to complete combustion.

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