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DISTRIBUTION & MANAGEMENT OF VESSEL FUELS & THE USE OF 3D PRINTING IN SPARE PARTS PRODUCTION

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Summary

This thesis primarily focuses on the distribution and management of vessel fuels and the use of 3-dimensional printing for the production of marine fuels management and treatment machinery consumable spare parts. The following two chapters will cover various aspects, starting from the extraction of raw materials required for fuel production, followed by the refining process that transforms these materials into the final product used for propulsion of vessels. More specifically, for each fuel there will be a thorough research consisting of, the chemical composition, the different properties that each one has and the treatment process to reach the required properties, in order to make the different types of fuels, for appropriate use in engines. Moreover, the thesis will analyze the path of each product from its extraction till its use in a vessel, especially from bunkering to the systems that have to do with storage, filtering, refining, and consumption. In addition, every vessel has its crew in order to carry out specific tasks, so they can have a safe and efficient voyage. With this in mind, depending on the position each person has, they are responsible with monitoring, maintaining, and supervising all of the departments that the fuels go through. This thesis will also examine methodically and in details this part, in order to fully understand the whole process and the crew responsibilities aboard a vessel about this significant task of the distribution and management of vessel fuels. The newbuilding vessels, can use a variety of fuels in order to fulfil their purposes, ranging from the conventional petroleum-based fuels such as Heavy Fuel Oil, Marine Gas Oil, Intermediate Fuel Oil, to more sophisticated, alternative and safer for the environment fuels such as Ammonia and Natural Gas. Each company, depending on its targets and equipment will choose accordingly which one to operate on. In the concluding chapter, the thesis will address the potential implementation of 3-dimensional printing technology aboard a vessel for the production of consumable parts.

The viability and potential benefits of utilizing this technology within the company will be thoroughly examined and discussed.

Περίληψη

Η συγκεκριμένη πτυχιακή εργασία εστιάζει στην κατανομή και την διαχείριση το ναυτιλιακών καυσίμων καθώς και την χρήση της τρισδιάστατης εκτύπωσης για την παραγωγή αναλώσιμων ανταλλακτικών των μηχανήματων διαχείρισης και καθαρισμού ναυτιλιακών καυσίμων. Τα επόμενα δυο κεφάλαια θα καλύψουν αρκετές πτυχές, ξεκινώντας από την εξόρυξη των πρώτων υλών οπού χρειάζονται για την παραγωγή των καυσίμων και στην συνέχεια την διύλιση τους που τα μετατρέπει στο τελικό προϊόν που χρησιμοποιείται για την πρόωση των πλοίων. Πιο συγκεκριμένα για κάθε καύσιμο θα υπάρχει μια αναλυτική έρευνα που θα συμπεριλαμβάνει την χημική σύσταση, τις διαφορετικές ιδιότητες που έχει το καθένα καθώς και την διαχείριση που δέχονται για να αποκτήσουν τις κατάλληλες ιδιότητες που χρειάζονται, έτσι ώστε να δημιουργούνται διάφορα είδη καυσίμων, κατάλληλα για τις μηχανές. Επιπρόσθετα η εργασία θα αναλύσει την επεξεργασία του κάθε καυσίμου πάνω στο πλοίο από την πετρέλευση, την αποθήκευση, την φίλτρανση, τον καθαρισμό και την χρήση. Κάθε πλοίο έχει το πλήρωμα του για να εκτελεί τα καθήκοντα του έτσι ώστε να έχουν ένα ασφαλές και αποδοτικό ταξίδι. Με αυτό κατά νου, ανάλογα με τη θέση που έχει κάθε άτομο, είναι υπεύθυνοι για την παρακολούθηση, τη συντήρηση και την εποπτεία όλων των τμημάτων που περνούν τα καύσιμα. Η παρούσα διπλωματική εργασία θα εξετάσει επίσης μεθοδικά και λεπτομερώς αυτό το μέρος, προκειμένου να κατανοήσει πλήρως την όλη διαδικασία και τις ευθύνες του πληρώματος επί ενός πλοίου σχετικά με αυτό το σημαντικό έργο της διανομής και διαχείρισης των καυσίμων των πλοίων. Τα νεότευκτα πλοία, μπορούν να χρησιμοποιήσουν μια ποικιλία καυσίμων για να εκπληρώσουν τους σκοπούς τους, που κυμαίνονται από τα συμβατικά καύσιμα με βάση το πετρέλαιο όπως το βαρύ μαζούτ, το πετρέλαιο εσωτερικής καύσης πλοίων, το ενδιάμεσο μαζούτ, έως πιο εξελιγμένα, εναλλακτικά και ασφαλέστερα για το περιβάλλον καύσιμα όπως η αμμωνία και το φυσικό αέριο. Κάθε εταιρεία, ανάλογα με τους στόχους και τον εξοπλισμό της, θα επιλέξει

ανάλογα σε ποια θα λειτουργήσει. Στο καταληκτικό κεφάλαιο, η διατριβή θα εξετάσει την πιθανή εφαρμογή της τεχνολογίας 3-διάστατης εκτύπωσης σε ένα πλοίο για την παραγωγή αναλώσιμων εξαρτημάτων. Η βιωσιμότητα και τα πιθανά οφέλη από τη χρήση αυτής της τεχνολογίας εντός της εταιρείας θα εξεταστούν διεξοδικά και θα συζητηθούν.

Introduction

In 1903, a significant milestone was reached in the maritime realm, as the Russian Vandal, a river tanker, became the first ship to be powered by a diesel engine. Navigating the canals of the Russian North, this pioneering vessel marked a crucial turning point in the maritime industry. The introduction of diesel propulsion sparked a renewed focus on enhancing ship efficiency and optimizing their capabilities, an imperative driven by the growing global population's increasing demand for goods. The event propelled the exploration and adoption of diesel engines as a means to meet these expanding needs. As the years progressed, ships got larger, faster and had to carry new goods, to greater distances. Those challenges, led to the creation of new fuels, thus also new fuel handling technologies and systems, that were more complex and difficult to maintain, increasing the dangers and costs for a vessel. This meant that, more personnel with more experience and knowledge had to be hired, in order to carry out, the new tasks that emerged from the evolution of technology. As maritime traffic increased exponentially, this lead to an increase in accidents and pollution of the atmosphere and the sea. These events caused the creation of organizations and companies, that aimed to deal with those serious problems, by enforcing laws and regulations to shipping companies all around the world. The main problem with pollution and accidents came from the type of fuel used by a vessel. Before 1997, there weren't any serious laws set for the atmospheric pollution caused from ships, which meant fuel didn't have to be cleaned and prepared before use either in the refinement process or aboard the systems of a vessel. Nowadays, all of the companies that are involved in the maritime world are obliged to follow these laws and regulations, and to turn to more environmentally friendly methods of propulsion, due to the world efforts to reverse the damage caused by the mistakes of the past. With all these in mind, lets to delve into the process of the creation, preparation, and journey, of the most commonly used fuels, either the conventional ones that are being use in the last century or the more environmentally friendly ones that have been introduced more recently to the maritime world.

Conventional Fuels

The use of diesel oil to propel vessels in the early 20th century, effected the world in many ways, either with great advancements in technologies of refining and handling fuels to many ecological disasters that effect the world still today. Up until 2019, more than 90% of merchant ships use diesel oil as fuel, which means the production and refining of diesel oil must be at an all-time high in order to catch up with the needs of the maritime world.

It all starts with the extraction of crude oil from certain points of the earth's underground deposits, called reservoirs. Crude oil is a fossil fuel mostly comprised of hydrocarbons such as alkanes, cycloalkanes, and aromatics, plus compounds of nitrogen, sulfur, and oxygen. Moreover, there is a plenty amount of metals, and saltwater. It originates from the accumulation of significant amounts of deceased organisms, primarily zooplankton and algae. These organic remains get buried beneath layers of sedimentary rock and undergo an extended period of heat and pressure over time. After it has been extracted from the reservoirs it has to go through a thorough process of pretreatment, in order to not cause any fouling or corrosion in any stages of the operation either it is the distillation, the reforming or any secondary processes.

The crude oil refining process begins with field separation which occurs in the vessel that it transported in, because due to gravity a separation occurs, that separates water, dirt, and other impurities from the oil. After the transportation is complete the oil gets transported to the desalting unit, where the crude requires desalting to minimize fouling and corrosion caused by salts like sodium and calcium chlorides. The crude oil is firstly heated close to 150◦C in order to achieve maximum efficiency in the operation of the desalination. After the heating is complete, the oil is blended with hot water creating a mixture that dissolves and removes impurities from the oil. In the final stage, water needs to be removed from the mixture, so it can procced to next phase of refining. This can happen with the introduction of chemicals or high potential electric current.

After desalting, the crude oil is preheated close to 400◦C and it is sent to the flash zone of the atmospheric fractionator, were due to the lower pressure and increased temperature it becomes a vapor. The vapor enters the tower and as it rises it is cooled, condensed and it is separated with the use of multiple sieve trays that hold the different products that have occurred, depending on their boiling points and weight. The refining column consists of plenty of sections, depending on the boiling point of the product, and it is separated in the overhead section, heavy naphtha section, kerosene section, light gas oil section, heavy gas oil section and reduced crude section. Depending on the section, the products of the atmospheric column are Liquid Petroleum Gas, naphtha, kerosene, gas oil and residuum. In order to avoid thermal cracking of the crude oil, a vacuum is used in order to achieve fractionation at a lower temperature. The temperature of the reduced crude oil is close to 360◦C, as it enters the flash zone of the vacuum column, and it is separated in multiple streams. From the vacuum column the products that occur, are gas oil, lube distillates, and residuum.

After the separation that occurred in those columns, the products that have been created go through some processes of chemical conversion in order to make them more suitable for their purpose, and depending on the product, a different method is used, to achieve this alteration. For heavier hydrocarbons there coking and two types of cracking, the Fluid Catalytic Cracking and Catalytic Hydrocracking. With the first method, a finely divided catalyst, is introduced to the crude oil. The catalyst helps facilitate the cracking reactions and allows the process to occur at lower temperatures. FCC is particularly effective for converting heavy gas oils into lighter and more valuable products. As for the second method, it similar to the first one but there is the introduction of hydrogen that helps create lighter products. Coking is a type of thermal cracking were coke and lighter products are created. In this method, the vacuum residue is heated and sent to drums were the products are separated with distillation.

For lighter hydrocarbons there are multiple methods such as the catalytic reforming in which, a catalyst transforms the naphtha fractions into aromatics and into naphtha with higher octanes. There is also the polymerization, which refers to the process by which smaller hydrocarbon molecules in the feedstock combine or polymerize to form larger molecules. Moreover, there is isomerization, where the low octane hydrocarbons are transformed into products with the same amount of carbon molecules but with higher amount of octanes.

Finally, those products have to go under purification in order to remove even more impurities and to get the desired characteristics. This purification is achieved with hydrotreating in which hydrogen is used to clean the fractions from sulfur, nitrogen, waxes, and metals that can cause environmental and operational issues.

Traditionally, the types of fuel used in the maritime world, were categorized by their kinematic viscosity. As of today, almost every type of fuel is based on previous parts of the distillation process, because viscosity by itself, does not provide enough details for the quality of the fuel. Mainly, there are two types of fuels, the residuals, and the distillates, and that depends on, from where the fuel occurred during the distillation process. From 1987, the required standards that fuels must fulfil are determined by the ISO 8217:2017, which specifies the requirements for fuels for use in marine diesel engines and boilers, prior to conventional onboard treatment. In addition, there is the ISO 8216, that determines the name of each fuel. In the beginning of the name, there is the ISO written, after that the letter F (Fuel) and in the end there is a combination of three letters, that determine the specific characteristics of each fuel. The first letter show the origin of the fuel and it can be either a D (Distillate) or a R (Residual). The second letter that is the M (Marine), shows the area of use. And the final letter (K,A,B,C…X) implies the specifications each type has. There is also a number in the end that shows the kinematic viscosity (mm^2/s) at a temperature of 50°C, where numbers like 800 mm^2/s shows a quite viscous residual type of fuel. These types of fuel are used in slow rotating vessel engines of medium and large size, if they are not restricted by emission-controlled areas. Meanwhile, fuels with lower viscosity tend to be used by vessels with fast rotating engines, and or in emission-controlled areas due to its capability to produce fewer dangerous emissions. As it is mentioned before, there are plenty of characteristics that vessel fuels have and are determined by certain indexes. In the following part there will be a listing of the most crucial characteristics these fuels contain.

- Ash: Ash is the inorganic residue that can occur during and after the combustion of the fuel. These compounds contain harmful particles that can cause damage to the fuel injection system and or the piston area of the engine.
- Kinematic viscosity: It is a measure of the internal resistance of flow. According to the International System of Units(SI), the viscosity of a liquid is measured in centistokes(cSt) and is inversely proportional with the temperature of the liquid. It is not a basic indicator of fuel quality, but it is crucial to know the value of it, in order to adjust the temperature of the fuel, so it can flow ably into the fuel systems of the vessel and efficiently combust.
- Density: It is the absolute connection of mass and volume at a certain temperature, and it is measured in kg/m^3. Density is important, in order to determine the amount of fuel a vessel will receive during bunkering, and it can indicate the quality of the fuel by comparing the density of other components mixed with the fuel.
- Sulfur: Sulfur content in the fuel depends on the type of crude oil it originated from. Its presence creates deposits in the combustion chamber and damages the parts of the engine, due to the fact that it is converted to sulfuric acid that is highly corrosive. Moreover, the fuel must have a low sulfur content, in order to avoid environmental issues due to the creation of sulfur oxides(SOx).

- Flash point: It is the lowest temperature were the vapors of the oil can be ignited with the assistance of an external flame. Flash point is determined in order to minimize the chance of a fire, during storing and handling of the fuel.
- Pouring point: When the temperature of a liquid drops below a certain point, certain components will begin to solidify thus increasing its viscosity. This will affect the handling of the fuel, due to the fact that the systems of a vessel require from the fuel to be at a certain temperature and viscosity.
- Vanadium and Sodium: They are both metals found in crude oil and in the residuum and their quantities depend on the place of origin of the oil. Even though both metals are catalysts and assist with the combustion, in high quantities they are corrosive and could cause damages in the engine.
- Energy content: It is a major property of a fuel, and it measures the amount of energy released during the combustion, which is crucial for the calculation of the energy efficiency of a fuel.

Heavy Fuel Oil

Heavy Fuel Oil (HFO) is the most common type of fuel used in vessels nowadays throughout all around the world, due to its low cost of both production and price, when in comparison to other lighter and cleaner fuels or more environmentally friendly ones. It primarily consists of residue that come from the distillation and or cracking units from a refinery, thus making it more pollutant due to its high concentration in dangerous components sulfur, sodium, and carbon dioxide. The quality of it depends mostly on the quality of the crude oil, and by the quantity of distillate fuels it was blended with, thus gaining specific characteristics such as viscosity, density, and sulfur. From the MARPOL convention of 1973, heavy fuel oil is determined by a viscosity greater than 380mm^2/s at 50°C or a density of 900kg/m^3 at 15°C. Another way to determine heavy fuel oils is from their content of sulfur oxide, that must not exceed the limit of 3.5% and not be less than 1%. Some very well-known grades of heavy fuel oils are RMK 500, RMK 700, RMG 500 and RMG 700.

Intermediate Fuel Oil

Intermediate Fuel Oil is the blend of a large proportion of residual fuel oil and smaller quantity of distillate fuel oil. This type of fuel in comparison to the heavy fuel oil is cleaner, less pollutant and needs less treatment when onboard, due to its blend with a distillate fuel but because of the latter it makes it more expensive. Similarly, to heavy fuel oil, the quality of it depends on the quality of the products that were used, in order to gain the characteristics needed. The fuel is defined by its certain limits of viscosity being between 180-380cSt at 50°C, making it less viscous than heavy fuel oil, because of the blending with distillate fuel oil. The RME 180, RMG 180 and RMG 380 grades are mostly used as intermediate fuel oils in vessels.

Marine Diesel Oil

Marine Diesel Oil is also a blend of fuels, but it has a higher concentration of distillate fuel than intermediate fuel oil and less of residual fuel. It needs little to no treatment when it is used in a vessel, apart from some filtration, because of its low viscosity and purity. Marine Diesel Oil can be used either to power the main engine of the ship, in sulfur emission-controlled areas if it has the acceptable content of sulfur, or to power the electric generators of the ship. Most blends of Marine Diesel Oil have a viscosity lower than the Intermediate Fuel Oil, which means at 50°C it will have lower than 180cSt. DMB is the most common grade of Marine Diesel Oil.

Marine Gas Oil

Marine Gas Oil is a pure distillate fuel. It is the most expensive out of all the other types of fuel because of its characteristics. Being a pure distillate, it requires none preheating or cleaning, it has a very low viscosity, and it has the lowest content of sulfur. It is used in the vessel's auxiliary medium to high speeds units. Similarly, to Marine Diesel Oil, it is also used in sulfur emission-controlled areas as it has a very low content of sulfur, where the limit is less than 0.1%. DMX, DMA and DMZ are the grades of marine gas oil from the ISO 8217:2017.

Bunkering and Treatment

Bunkering is the action were a vessel fills up its fuel tanks with different types of fuel. It is a difficult task that in the past was the reason for multiple environmental incidents due to the lack of safety parameters. The International Maritime Organization with its VI annex for prevention of pollution from ships, has set plenty of strict parameters that vessels must oblige to, in order to safely operate throughout the world. Bunkering requires plenty of attention and alertness from the crew of a vessel, in order to avoid any type of accident that can harm the crew, the environment and or the cargo. There are two ways a vessel can bunker fuel oil, the first one is from ship to ship, and the second one from shore to ship. A vessel can choose which method to fill up with fuel depending on many factors like the location, the cost of the port, the vessel's characteristics, how much time it has left for its journey, if there is a queue at the desired port, and if the company has agreed upon either way. The first method is ship to ship transfer bunkering procedure, and it involves two ships where one is the terminal and the other one is the receiving ship. The vessels get close side by side and with the assistance of a crane, the fuel lines are transferred from one ship to the other, connections are made, and the fuel gets transferred. Ship to ship refueling is more versatile, it is done easier and faster, and it is less costly because there won't be any port charges. On the other hand, it may be difficult to refuel at sea in excessive weather conditions that could lead to more accidents/pollution, during an emergency there can't be immediate assistance from the shore, and it is a method that isn't available at all ports. The second method involves the ship berthing at a designated port, making connections to shore and the fuel gets bunkered this way. As for the shore to ship refueling it is more common than the aforementioned method, it is safer because it done inside of a port, that is less susceptible to bad weather conditions, there are facilities that can act immediately in case of an emergency, and the rate of fuel can be greater due to larger onshore pumping machinery. Using this method can be costly due to port fees, the vessel will have to change its course, spend time in a queue and for berthing.

Bunkering is a high-risk procedure, due to the probability of a tank being overfilled with fuel oil, or the rupture of damaged fuel line, or any amount of leakage from a defective manifold connection. These types of incidents can cause a serious amount of pollution that can damage the sea environment and biodiversity if proper actions are not taken immediately. Furthermore, an oil spill can cause multiple hazards such as creating flammable fumes that could harm the crew and or vessel. Apart from the aforementioned repercussions, the vessel will have to stay at port so the oil spill can be cleaned up which can a costly procedure, thus delaying the vessel's journey, leading to financial claims and ''damage'' to the reputation of the company. In order to prevent a spill an emergency plan needs to be created, minimizing the risk of pollution and damage. This plan is called SOPEP, ship oil prevention emergency plan, as per the MARPOL 73/78 requirement under Annex I, all ships with 400 GT and above must carry an oil prevention plan as per the norms and guidelines laid down by International Maritime Organization under Marine Environmental Protection Committee act. The captain of the ship is the one in charge of the plan, along with the other members that assist him, with the implementation of it. SOPEP contains the duties of each member at the time of the spill, steps for the containment of the oil, the oil spill kit that contains absorbent pads, sawdust bags, booms, waste bags and protective gear for the crew.

Before the initiation of bunkering the supervisor, which is the chief engineer, has to check which tanks will be filled with fuel and how much of will it receive in general. In order to avoid any mixing of old fuel with the new, certain tanks will have to be emptied and have their fuel transferred to other ones, thus eliminating the chance of creating incompatible mixes. After these procedures a meeting is held place in order to inform the rest of the crew about the procedures that will happen during bunkering, such which tanks will be filled up, how much fuel which one will get, important safety procedures during an oil spill or any other accident and have the officers informed about their responsibilities. The crew will always have to communicate via VHF radios and hand signals in order to maintain a smooth bunkering operation and in case of an emergency it needs to halt the operation. Furthermore, the sender side of the bunkering needs to also be informed about the bunkering plan after the meeting has ended and have its specification paperwork checked by the chief officer before beginning. There must also be a thorough inspection of both sides' manifolds, fuel lines, flanges, pipelines condition and deck scuppers, to ensure no leakage will occur during bunkering. When the fuel lines have been connected to vessel's manifold the chief engineer makes one last inspection that the correct valves are open and lead to the correct tanks. When every required task has been completed, the valves open but there is a slow rate in order to ensure no leaks occur, and after confirming with sounding that the fuel is going the right tank, the flow is increased. Sounding is the task of measuring how much fuel there is inside of it, by using either a sounding tape and or different remote sounding measuring systems. A sounding tape is a measuring tape graduated in mm, that has a weight attached at the end of it, to allow it to descend in the tank. There is also the sounding table which is a chart that describes the construction and the volumetric capacity of each tank, at different trims and every vessel has a unique bunkering table, that depend on its size, construction, and type. When bunkering is complete, the fuel lines are pressurized so no fuel stays inside, the sounding pipe covers of each tank are sealed, the chief engineer calculates the correct amount of fuel received after changes in temperature, heel and trim of the vessel and collects four samples of the fuel, one for the vessel, one for analysis, one for the port state and the final one for the supplier. If the received fuel quantity does not match the agreed quantity, the chief engineer will issue a note of protest to the supplier for compensation.

If the quantity is correct, the fuel lines are removed and finally the chief engineer creates an entry of the operation in the oil record book.

Below, figure 1.1 shows a flange and next to it in figure 1.2 is a gasket. A flange is a metal disc shaped object, that is fitted on the end of either a pipe, a pump, a valve, or any equipment that forms a piping system. A gasket is a seal that fits in between two connecting parts and prevents any liquids or gases, to leak from that connection. The gasket is made either from rubber or plastic to allow it to stretch. It is a common way of connecting machinery and or pipes together, and it can provide easy access to inspection and cleaning.

Figure 1.1 Figure 1.2

At shore, heavy fuel oil is preheated before entering the fuel lines, in order to achieve a certain viscosity to allow it to flow efficiently through the system and not cause any stagnation during the operation. Sounding must be done often when the flow is increased especially when the tanks are close to maximum allowable capacity, to ensure no overflow occurs. The bunker tanks of are regularly located at the double bottom and on the sides of the vessel, they are always at certain temperature using steam and their capacity must not exceed 95%. With the assistance of the fuel oil pumps, the oil is transferred to a settling tank, in which the fuel oil settles and gets cleaned by gravity, as the heavier liquids and solids sink to the bottom. When most of the fuel has settled, it gets pumped through a preheater and filters, which prepares the fuel for the centrifugal separator.

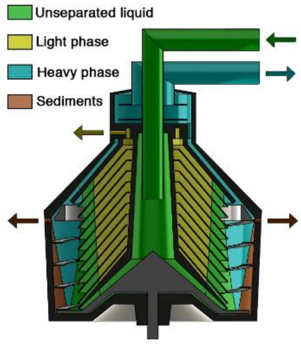

Figure 1.3 Figure 1.4

Figure 1.3 is the centrifugal separator consists of an electric motor, a vertical axle, and a container in which the fuel enters, and with centrifugal force the contaminants of the fuel get separated due to their specific weight. From the process three layers occur as it is seen in Figure 1.4, the outer one consists of solid waste and heavy sediments, the middle layer is mainly water, and the inner layer is clean fuel. The fuel then is supplied to the centrifugal purifier/clarifier for further cleaning, meanwhile the rest are sent to the sludge tank, which is a tank designed to hold and treat such waste until the ship reaches a port to discharge it. The centrifugal clarifier is used to clean an already water separated fuel, from finer waste and sediments that still remain in the fuel. The heavy fuel oil ends up in the fuel mixing tank along with other types of fuel such as the marine diesel oil.

Figure 1.5 shows the diagram of a pump that is pretty common among vessels. It is called a dynamic pump and it is a type of pump that use the velocity of a fluid in order to create momentum, thus pumping power. A pipe is connected to the side of the pump, in which the liquid is sucked by the spinning impeller and with the assistance of centrifugal force, the liquid has its velocity and pressure increased, and is sent to the outlet side. They are efficient both in cost and size, they have a low maintenance cost and are used to transfer less viscous fluids. As for the downsides of this type of pump the impeller and the seal rings wear off quickly, plus there can be alignment issues with the shaft.

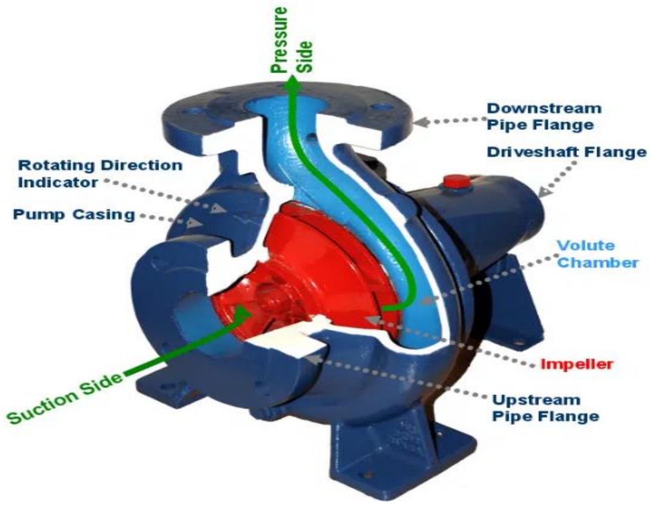

Figure 1.5

The procedure of bunkering the marine diesel oil is similar to the one of the heavy fuel oils, but in most cases the fuel requires little to no preheating and separation, due to being a distillate. Marine diesel oil is pumped directly to the marine diesel oil service tank and from there it is sent to fuel mixing tank. From the fuel mixing tank, the mixture of fuels is preheated, filtered, and pumped through the booster pumps of the vessel which increase the pressure and the flow of the fuel. From the pumps the fuel runs through the viscometer which is a device that is used to measure the viscosity of fuel oil at the fuel injection system of the engine. When the correct viscosity is achieved the fuel is injected into the main engine of the vessel, where it combusts and gives motion to the pistons of the engine. Parts of the fuel that was not injected into the main engine, is sent back to the mixing tank, in order to get rerouted to the main engine. Apart from the main engine, a vessel has generators that generate electricity for its systems and boilers that boil water to create steam for the preheating systems, and both type of machineries uses marine diesel oil as fuel. If the vessel is traveling to sulfur emission-controlled areas, it must bunker fuels oil that have a sulfur content less of 0.1%, due to recent changes in the MARPOL regulations in 2020. These types of fuel are Marine Gas Oil, and Very Low Sulfur Fuel Oil. They too get bunkered the same way as marine diesel oil does, due to their characteristics such as very low viscosity, and having very low contents of waste.

Alternative Fuels

These have been the conventional fuels used in the maritime industry, from the beginning of the 20th century. Even though they improved the efficiency of vessels, they have been the cause of numerous accidents and pollution incidents. Those causes led companies to invest in more safe and environmentally friendly types of fuel. In this part of the thesis there will be an analysis of these types of fuel, about how they are created, their characteristics, and treatment on a vessel. More specifically, Liquified Natural Gas, Ammonia and Nuclear will be the fuels that will be discussed thoroughly.

Liquified Natural Gas

Starting with Natural Gas, it is a fossil fuel mostly composed of microorganisms and organic matter, that were subjected to high temperature and pressure for a long period of time and can be found in underground formations just like crude oil. Natural Gas is a mix of gaseous hydrocarbons primarily methane and smaller proportions of other alkanes. When extracted from the formations, it has plenty of impurities such as water, sulfides and carbon dioxide that need to be removed in order to be compatible for use, without causing damage to the environment, the equipment, and the end users. The gas is transferred to a natural gas processing unit with the use of pipes in order to get treated. The raw natural gas in the beginning gets its oil condensate and water content removed, then it goes through a process called amine treating or gas sweetening in which, the natural gas gets its hydrogen sulfide and carbon dioxide content removed. Following the amine treating, water vapor and mercury also need to be extracted to increase its purity through complex processes. After the extractions are complete, it is crucial to recover valuable hydrocarbons that are fractions of the natural gas, that can be used for other industries. This is done in distillation columns by decreasing the temperature to approximately -100°C thus fractionating the products into single components. Finally, the distilled products are either sent through pipes to end users or are stored in order to be transferred.

From the process one product that occurs is Methane(CH_4) or Liquified Natural Gas, that has been condensed by cooling it down to -160°C and pressurized close to 1.2 atm. thus reducing its original volume by 600 times, in order to for it to be stored in very large quantities. It is an odorless, non-corrosive and colorless gas, that is composed mainly by methane, but it can have smaller traces of other gases like, ethane, butane, propane, and other hydrocarbons. Just like the fuel oil, this type of fuel has specific characteristics that need to be known, throughout all the procedures of transfer and usage.

- Chemical Composition: Liquified Natural Gas is a mixture of multiple hydrocarbons, and their content depends on the where the Natural Gas was extracted from. Different compositions will lead to different handling at the treatment unit thus increasing the purity and the efficiency of it.

- Boiling Point: An important property because it defines the temperature a liquid converts rapidly into a vapor at atmospheric pressure. Regularly, the boiling point of Liquid Natural Gas is about -160^{o}C. This is information is needed, so the gas stays in liquid form when transported and stored.

- Density: The density of Liquified Natural Gas can vary from 430-470 kg/m^3 depending on the composition of it. It can assist with the calculation of how much fuel the vessel will receive, and also determine the fuel quality.

- Flammability: Since the vaporization of the fuel happens right after coming into contact with the atmosphere, the crew needs to know when and for how long will the vapors be flammable.

Bunkering and Treatment

The procedures for ships other than LNG carriers, that use Liquified Natural Gas as fuel are similar in some parts of the procedure of conventional fuel oil bunkering, but due to the state of LNG different precautions and preparations need to be made. Since LNG is a cryogenic liquid, it must be transported through fuel lines and manifolds that are capable to withstand the sub-zero temperatures of the liquid. Apart from the integrity of the equipment used during bunkering, the crew must be prepared with personal protective equipment, such as cryogenic retardant clothing and goggles. Similarly, to the emergency plan of conventional fuels, the following types of fuel also need to have an emergency plan in case a problem occurs during their bunkering. Fuels that have a gaseous form in nature need to be pressurized and have their temperature lowered, in order to achieve a liquid state, for storing efficiency. If a fuel line or a manifold burst while fuel runs through it, it can cause a series of hazards for the vessel and the crew. First of all, the temperature of the fuel is many degrees below 0°C which means if it comes to contact with exposed skin, it can cause serious frostbite burns or if it comes to contact with the vessel, it can cause cryogenic damage to the steel making it brittle and weak. Especially with LNG it may not be a toxic gas, but it is heavier than air and can remove the present oxygen, causing asphyxiation to the members of the crew. Finally, apart from the flammable vapors that can be present during a leakage, if a tank is over-pressurized a phenomenon known as fireball might be created, due to the sudden release of the gas. Just like fuel oil, there are two ways to bunker LNG fuel, the 1st is from shore to ship, and the 2nd is from ship to ship, both ways follow similar procedures to fuel oil bunkering.

Before the vessel begins to bunker with LNG, it has to follow similar procedures like the fuel oil bunkering. The crew under the instructions of the chief engineer has to check the temperature, the pressure and capacity of each fuel tank, inspect the fuel lines, the manifolds, and other components for damage, prepare a bunkering plan that will be discussed in a meeting, and establish communication with the crew on both sides. When the vessel has moored the bunkering operation begins with the connection of the hoses, which are the cryogenic liquid transfer hose and the boil off gas return hose. Even though the connection is complete, the supplier cannot initiate the bunkering due to two reasons. The 1^{st} one is that the hoses are full of air and moisture, and with the introduction of LNG, a highly flammable mixture can form in the system. And the 2^{nd} one is that the hoses have an ambient temperature, thus a sudden drop of temperature may damage the integrity of the hoses and the connections. As for the 1^{st} reason, the supplier, releases inert gas into the system, which is usually Nitrogen(N_2), so that the air and moisture is vented out and there is not anymore danger of an explosion. Once the hoses and tanks are filled with N_2, it is time to slowly let LNG vapors into the hoses and tanks, so the temperature gradually decreases. This preparation can take up to 24 hours depending on the size of the tanks, but it is crucial, in order to avoid damage to the equipment. Once the specific temperature is achieved, the supplier can increase gradually the flow of the LNG. During bunkering, continuous capacity measurements of the tanks are taken and as the tanks are filling up, the flow rate is decreased. When the tanks receive the designated amount of fuel, bunkering is halted, and the hoses need to be cleaned of the vaporized LNG that is left inside of them. This is done by shutting the manifold valves of each side, which makes the vapor return to the respective tank. Finally, the receiving side, will have to purge the hoses with its N_2 system, so it is safe to disconnect the hoses from each manifold.

When LNG is supplied by the cargo tanks of the vessel it is Boil Off Gas(BOG). Boil Off Gas occurs due to temperature fluctuation of the cargo even though the tanks of the ship are insulated, they cannot always be at a certain temperature. The vapor that occurred must be removed from the tanks in order to maintain a stable internal pressure. In order for the vapors to be used in a vessel they need to go through some stages of preparation, so they are compatible with the main engine requirements. Firstly, the vapors go through the LNG spray pipe where they are sprayed through, thus their temperature reaches close to -105^{o}C, which the temperature that the compressor needs the vapors to be. Before the compressor, they go through the mist separator, in which, droplets and heavy elements, are removed, in order to avoid damage to the equipment they flow through. In the compressor, the vapors are compressed to approximately 5,5bar, so they can enter the main engine injectors efficiently. After compression, the vapors need to reach a certain temperature between 20-30ºC, in order to achieve efficient combustion in the main engine. Before the engine there is the thermal oxidizer, which is located above the deck of the vessel, and it burns vapors when the supply to the engine needs to be halted, and the Gas Valve Unit which regulates the vapor pressure before entering the main engine.

Ammonia

Ammonia(NH_3) is a compound of hydrogen and nitrogen and is being used in multiple sectors such as agriculture, pharmaceuticals, and chemical products. It is a colorless gas with an acrid smell that can naturally be found in organic matter. In 2022 the world production of ammonia is close to 150 million metric tons, with East Asia being the region with the highest production. Ammonia can be produced through different ways, using different processes and materials, that will be discussed further down the thesis. The first method is through the Haber-Bosch Synthesis, in which nitrogen and hydrogen are reacting together using a metal catalyst under extreme temperature and pressure. In this synthesis, nitrogen is extracted from atmospheric air and the hydrogen from electrolysis, solar hydrogen production and biomass. The second one uses non-thermal plasma, which is an alternative to the Haber-Bosch synthesis which uses biomass produced hydrogen and nitrogen from atmospheric air. Depending on the origin of ammonia, impurities like water, oxygen and argon can occur, and need to be removed in order to avoid the purity and efficiency of the product.

Ammonia similarly to LNG in order to maintain a liquid state, ammonia needs to have its temperature lowered to -33°C at 1bar or at a temperature of 20°C have its pressure increased to approximately 8bar. As a fuel its characteristics are unique comparing to fuel oils, thus new methods of handling and ignition need to be implemented, so it can be used efficiently in a vessel.

- Flammability limit: It is the range in which vapors of a substance will combust when mixed with air.
- Energy density: It is the total energy amount that is able to be stored in a system or substance.
- Octane number: It measures the fuel's ability to resist compression in an engine without igniting.

Currently there are no vessels that use ammonia but there are companies that are developing engines that can be fueled with ammonia, but there are companies that are developing engines that are dual fuel, similar to the LNG, which means that there is a pilot fuel that assists with the ignition of the main fuel, in this case ammonia.

Bunkering and Treatment

Since there are no ammonia-fueled engines in the market, ammonia has many similarities to LNG, thus its bunkering and treatment can be similar to theirs. This means that the fuel will have to be under pressure and or have a low temperature, in order to maintain its liquid form. Vaporizers and compressors might be needed in the system, so that the fuel has the correct state and characteristics throughout the whole process. MAN ES which is a company that produces engines for the maritime and railroad market, has a project dual fuel diesel engine that is fueled with diesel and ammonia, and its design and system layout, has many similarities with an LNG dual fuel engine.

Figure 1.6 is of a dynamic reciprocating piston air compressor. A rotating fan is pulling air from the atmosphere is sending it through the inlet, the moving piston creates a void inside the chamber and opens the inlet spring valve down. From the pressure of the surging air, the piston is driven down, the crankshaft rotates, filling the chamber with air, and as the piston returns to the highest position, the pressurized air pushes the outlet spring valve and exits through the outlet. It is one of the simplest forms of air compressors and can be found in most ships. Next to it in the figure 1.7 is a two-stage gas compressor, which can compress the boil off gas at a very low temperature close to 120 °C and with a pressure of 6 bar, in order to be used in the engine.

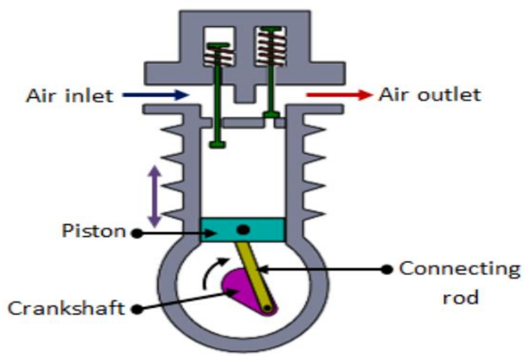

Figure 1.6

Figure 1.7

Three-dimensional printing used for spare parts

During bunkering and on-board treatment of any marine fuel, there are multiple systems that the fuel goes through in order to be prepared for consumption. These systems contain a plethora of consumable parts, that need to be replaced when they are worn out to a certain point, or they have to be replaced after a period of time. Since a vessel is constantly on the move, its units and machinery are working non-stop, thus it is important to keep a storage of multiple spare parts, in order to be able to fix any problem that might occur during voyage. Those spare parts in Figure 2.1 show a range from electric components, filters, flanges, flowmeters, gauges, indicators, motors, gears, cogs, seals, bearings, valves, and plenty more.

Figure 2.1

A company must keep its vessels spare parts inventories complete, so in case of an emergency, the crew will be able to fix any problem that occurs and keep the voyage going. Keeping track of the availability of spare parts onboard and offshore, is a difficult task, due to the enormous quantity of needed parts, combined with the fact that when a vessel has reached a port, the company must have already located a supplier that can provide those needed parts in less the amount of time the vessel will remain at port. If the spares are not provided on time, this can lead to equipment failure, thus forcing the ship to stay at port for a longer period of time for repair, which can cause complications with the charterers.

In order for a vessel to decrease the delays at a port, due to receive the spares parts, it can produce certain spare parts on board with the use of a three-dimensional printer. It is the process that produces objects layer by layer with the assistance of a computer. Three dimensional printers can create objects from a wide range of materials like plastic, powders, metals, and carbon fiber. It all starts with modeling the desired object with a designing software, so it can be understood by the computer and be as precise as it can be. After the modeling is complete, the printing software begins to scan the object layer by layer, so it can create a path to move the nozzle, in order to create the layers. Finally, the printing begins layer by layer, dispensing the selected material, letting each layer cooldown, until the object is complete. Back in 2020, one of the first applications of three-dimensional printing was established on a bulk carrier of Berge

Bulk, where they produced rubber scupper plugs for the ship's drainage holes. Depending on the material used to print, there are multiple ways to produce the aforementioned object, such as:

Plastics-Polymers

- Stereolithography: This technology uses a laser beam in order to achieve photopolymerization of the liquid resins. The resins are in liquid form, and they have the ability to harden once they are exposed to ultraviolet radiation.

- Selective laser sintering: Laser sintering uses a laser beam so it can melt the polyamide powder layer by layer, which usually is infused with fiber glass or aluminum.

- Fused deposition modelling: During this process, a roll of a thin plastic line is fed through a heated nozzle that is depositing the melted material and forming the object layer by layer.

Polymer three-dimensional printing can produce parts such gaskets, oil rings, cogs, deck scuppers, and seals, but it can also produce impellers, filters, and flanges for temporary use, until they are replaced by the correct ones. The Figure 2.2 shows the designing and development of a part in a specific software program of a company. Meanwhile the Figure 2.4 show the polymer printing process of a part, that is done by heating the polymer material and extracting it through a nozzle.

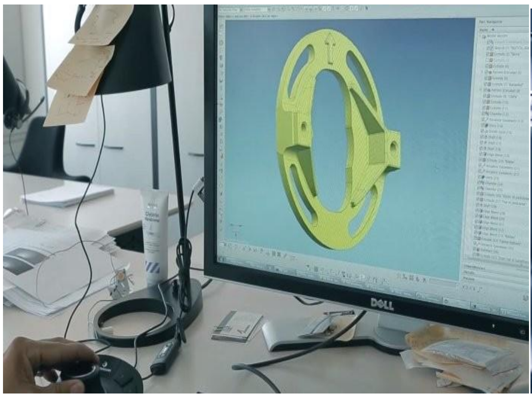

Figure 2.3

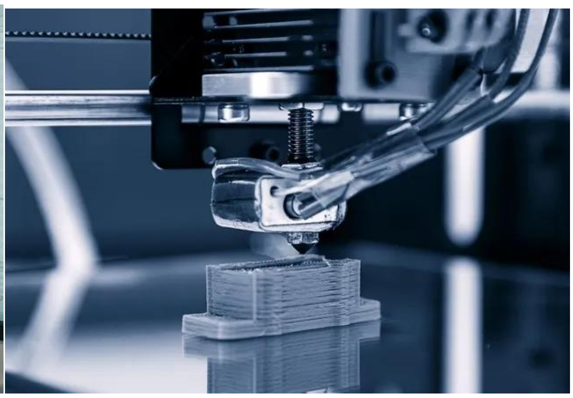

Figure 2.4

Metals

- Powder Bed System: In this process there is a platform on which, fine metal powder is settled, leveled, and heated repeatably in order for the powder to melt, and create a stable shape.

- Powder Feed System: This method is similar to the fused deposition modeling, in which the material is fed through a nozzle, and with the assistance of laser beams, the laid-out powder is melted into the desired shaped.

- Wire Feed System: This system uses an energy source and a wire of the specific material, that is fed out and melted onto the platform, one layer at a time.

As for the metal three-dimensional printing, from it there can be produced most consumable spare parts, from most sectors of the vessel such as, flanges, bolts, filters, impellers, flanges, piston parts, bearings, shafts, fans, valve components and more miscellaneous pieces.

Using this way to acquire spare parts can revolutionize the maritime supply chain, cutting down costs for the company, waiting time for the vessels and in general to minimize the time and expenses associated with storage, shipping, and customs procedures. Nowadays the need for a replacement occurs either from extensive damage of a unit or before a maintenance or if the predetermined stock for parts has decreased below the threshold. A ship is almost always on the move and is constantly changing locations, this means that the spare part will have to be delivered on time at the next port that the ship is reaching. There is a chance that the needed part might be out of stock from the supplier's inventory, so it will have to requested from a larger warehouse or be created from start, which can be quite costly and time consuming. If a company decides to install a three-dimensional printer on board it could save both time, money and it can assist with the protection of the environment. Basically, by having a digital warehouse, in which there are digitized models of the vessel's printable parts, where the vessel will always be connected and have access to it, it will be able to print any desired part without having to change its course to obtain one from a supplier, as mentioned before. This innovative idea has both its advantages and disadvantages, that are going to be listed below:

Advantages

- The benefits of this idea, compared to the traditional technology manner of manufacturing spare parts, is that it quite more energy efficient because will created only the spare parts needed and will not have to carry excess inventory on the ship.
- The spare parts created by conventional method will decline, and the emissions of the production lines will also decrease due to reduction of the demand for spare parts.
- By having every part in digitized printable form, the crew can increase the precision of spare creation, and produce parts more suitable for each machinery on the vessel.

- The ship will not have to modify the route of its voyages or any other delay in ports to obtain the spare parts.

Disadvantages

The disadvantages of three-dimensional printing on board, related to :

- The absence of enough evidence for the countering of forces and temperatures that are created, during the use of the machinery, because the three-dimensional technology has not tested enough on vessel machinery.
- The cost for the companies to digitization of the products, acquiring and installing the printers, and training the crew in order to be able to use the printers, is high.
- Copyright issues might occur from the companies that create the spare parts, making the digitization of their plans more difficult.
- The size of the parts that can be produced nowadays on the ship are limited, as well as the parts in order to be ready for use will need post preparation/cleaning.
- The process of production of such parts with the available technology is slow, and usually the printers to avoid the case of overheating or other malfunction need monitoring.
- This method due to the lower demand for workers in order to handle and transport of the parts, will increase the unemployment in those sectors.

Generally, this method by cutting down production time and costs for the maritime spare parts industry could be revolutionary. Furthermore, the vessels could reach their destination faster without having any interruptions on their voyages in order to receive new parts and enhance the reduction of pollutant emissions that are produced from the production of these parts. Actually, it is an innovative idea that has to face many challenges in order to prevail and become mainstream in the industry, and for these reasons, it is very attractive for the shipping industry since it could lead to new managing opportunities.

Conclusion

As it was thoroughly analyzed in this thesis, the whole process of handling all types of fuel, from the moment of extraction from the earth, the refining/purification processes, the bunkering, and treatment onboard a vessel, requires coordination, communication, and a lot of safety procedures. This will ensure that the fuel will be treated correctly, it will have the specifications the customer needs and no accidents/pollution will occur throughout the whole process. The crew of each vessel will have to be trained and prepared in order to face any type of emergency that might occur and prevent any further damage to the vessel and environment, during bunkering. Furthermore, the fuel handling equipment on board a vessel, must be inspected and serviced when needed by the crew, which include the fuel lines, the manifolds, the fuel tanks, the piping system, the filters, and the machinery that the fuel goes through. As for the systems and machinery of a vessel, they require service and most of them have consumable parts that need to be replaced after some time or after being damaged. Until recently the needed spare parts where acquired from a supplier but had to be either transported to the vessel either by sea or by air, or when the vessel reached a specific port. This traditional method could change in the following years, due to innovations in three-dimensional printing, which will allow vessels to create their own parts without relying on suppliers or causing delays to their journeys. This could lead to the reduction of cost for spare parts, the protection of the environment and the increase in the efficiency of the vessels. In general, the fuel sector in the maritime world is complicated, containing countless laws and precautions that the people involved must follow and adhere, thus protecting the environment, avoiding fines, and protecting their reputation.

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