Journal of Naval Sciences and Engineering
2025, Vol. 21, No. 1, pp. 97-121 *DOI: 10.56850/jnse.1649152*
Electrical-Electronics Engineering/Elektrik-Elektronik Mühendisliği

RESEARCH ARTICLE

**An ethical committee approval and/or legal/special permission has not been required within the scope of this study.*

Fuel Based Dynamic Ship Resistance Analysis of a Container Ship: An Alternative Approach to Marine Fuels

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Received: 28.02.2025 **Accepted: 06.05.2025**

ABSTRACT

In the literature, some properties of alternative fuels, such as low volumetric density (e.g. for hydrogen) and low heating value (e.g. for methanol, ammonia and etc.) have been mentioned as a "disadvantage". However, the precise impact of this disadvantage is not clear. To clarify this situation, in this study, 11 different alternative marine fuels have been analyzed according to fuel gravimetric energy density analysis, using fuel heating value and density value. Different scenarios have been created to see the dynamic behavior of ship resistance. According to results, alternative clean fuels can have "low ship sailing range" and "increased energy consumption per distance" disadvantages. Among the most popular fuels, range of hydrogen (H_2) and ammonia (NH_3) fueled ships can be 87% and 68% lower than HFO fueled ship, if fuel tank volume is not changed. Alternatively, equivalent energy can be stored in the ship to ensure same sailing range with more stored fuel mass. In this situation, consumed energy per distance is increasing for some fuels (e.g., 1% increase for ammonia).

Keywords: *Alternative marine fuels, ship resistance, fuel characteristics, decarbonization, ship energy efficiency.*

Konteyner Gemisinin Yakıt Bazlı Dinamik Gemi Direnci Analizi: Denizcilik Yakıtlarına Alternatif Bir Yaklaşım

ÖZ

Literatürde, alternatif yakıtların düşük hacimsel yoğunluk (örneğin hidrojen için) ve düşük ısıl değer (örneğin metanol, amonyak vb. için) gibi bazı özelliklerinden bir "dezavantaj" olarak bahsedilmektedir. Ancak, bu dezavantajın kesin etkisi açık değildir. Bu durumu açıklığa kavuşturmak için, bu çalışmada 11 farklı alternatif denizcilik yakıtı, yakıt ısıl değeri ve yoğunluk değeri kullanılarak yakıt gravimetrik enerji yoğunluğu analizine göre incelenmiştir. Gemi direncinin dinamik davranışını görmek için farklı senaryolar oluşturulmuştur. Sonuçlara göre, alternatif temiz yakıtlar "düşük gemi seyir menzili" ve "mesafe başına artan enerji tüketimi" dezavantajlarına sahip olabilir. En popüler yakıtlar arasında yer alan hidrojen (H_2) ve amonyak (NH_3) yakıtlı gemilerin menzili, yakıt tankı hacmi değiştirilmediği takdirde HFO kullanan gemi menzilinden %87 ve %68 daha düşük olabilir. Alternatif olarak, daha fazla depolanmış yakıt kütlesi ile aynı seyir menzilini sağlamak için gemide eşdeğer enerji depolanabilir. Bu durumda, mesafe başına tüketilen enerji bazı yakıtlar için artmaktadır (örneğin, amonyak için %1 artış).

Anahtar Kelimeler: *Alternatif denizcilik yakıtları, gemi direnci, yakıt karakteristikleri, dekarbonizasyon, gemi enerji verimliliği.*

1. INTRODUCTION

Reduction of airborne emissions is one of the primary objectives of authorities. International Maritime Organization (IMO) puts regulations and restrictions to ensure emission neutrality of shipping sector. Some of these regulations aim global warming gases, some of them aim pollutants (Yang vd., 2024)(Senecal & Leach, 2021). Adaptation of alternative fuels may be a sustainable way to achieve targets (Bilgili, 2021). Various solid (Kaya, 2024b), liquid and gas phase (Bekdaş vd., 2022)(Okumuş vd., 2024)(Sönmez vd., 2023)(Dağ vd., 2025)(Okumuş vd., 2023)(Kaya & Kökkülünk, 2020)(Sönmez vd., 2021)(Kaya vd., 2020)(Savaş vd., 2025)(Kaya, 2019)(Said vd., 2021) alternative fuels are considered to take place instead of conventional fuels.

Despite the all mentioned advantages of alternative fuels, replacement of conventional liquid hydrocarbon is not an easy task. Liquid hydrocarbons are safe, energy dense, cheap and can be transported easily (Kaya, 2024a). Moreover, alternative fuels may carry certain risks (Wang vd., 2023). All aspects should be evaluated for fuel transition, beside engine performance and emission aspects.

Fuels store a certain amount of energy. Stored energy capacity is important especially for mobile systems compared to stationary systems. Besides, energy storage capacity, low weights are desired for transportation vehicles such as airplanes, ships and road vehicles, which perform an action against gravity and friction. Energy storage systems are compared according to system gravimetric capacity (Demirci & Miele, 2011). System gravimetric capacity involves fuel weight and all equipment weights such as cables, sensors, tank, pump, filter etc. In the literature, dynamic analyses of energy storage systems are useful and are used to compare systems or fuels (Van Nievelt, 2019)(Lensing, 2020). Despite the accuracy of system based dynamic analysis, fuel based dynamic analysis can be used to reduce complexity in the evaluations and at the initial stage of analysis.

In this study, dynamic behavior of different alternative marine fuels in relation to ship resistance, power requirement, fuel and energy consumption, maximum sailing range, and released CO_2 emission amounts have been investigated. The idea that inspired the study is illustrated in Figure 1.

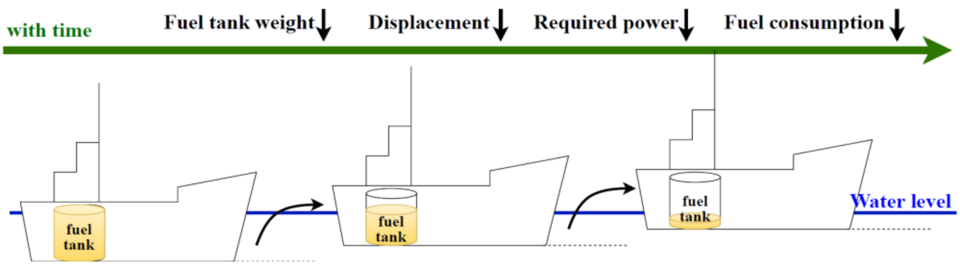

Figure 1. *Change in sailing ship fuel tank weight, ship displacement, required engine power and engine fuel consumption with time.*

Normally, sailing ship consumes a certain amount of fuel at each time period. Reduction in fuel weight decreases the ship displacement. Decreased displacement reduces ship resistance, power requirements and fuel consumption. By the end of the voyage, minimum fuel consumption per time can be observed compared to the initial stage of the voyage.

When the different marine fuels have been considered for the above scenario, we will encounter a different outcome. Different fuels have different calorific energy and density. Actually, some negative properties of these alternative fuels have been mentioned in the literature. For example, methanol has a lower volumetric energy content (Shamsul vd., 2014) and has a low energy density compared to (Joghee vd., 2015) gasoline. El Nakschabandi et al. (Said vd., 2021) mentioned smaller volumetric and gravimetric energy density of methanol leads to the need for larger tank to obtain identical ranges and also leads to the need for higher mass flow. Moreover, low volumetrical energy content of alternative fuels such as hydrogen (Arutyunov, 2022) and ammonia (Chiong vd., 2021) is known as major drawback for fuels. These properties usually referred to as “disadvantage”, “drawback” etc. However, the precise impact of this disadvantage was not specified in the literature. In this study, these changes and their numerical results will be revealed by dynamic ship resistance analysis. Ship range, ship resistance, fuel, power and energy consumption have been analyzed. By this way, dynamic responses of different alternative fuels have been demonstrated. This study is structured as follows: In Section 2, the main particulars of the ship used in the study are presented. Then, the fuel properties, scenarios and solution strategy are explained in detail. The results of the developed code in MATLAB are provided in Section 3 and in the last section (Section 4) the conclusions and potential future works are discussed.

2. MATERIALS AND METHODS

In this section, detailed descriptions of the fuels employed in this study and their specific properties are provided. Additionally, the developed scenarios are outlined, accompanied by a comprehensive flowchart illustrating the structure and process of the proposed model. The methodologies utilized in the study are elaborated upon, along with the underlying assumptions and inherent limitations.

2.1. Vessel Specifications and Fuel Characteristics

In this study, a container ship, which is one of the conventional ship types, is selected for the analysis thanks to its compatibility with the Holtrop-Mennen method. The container ship belongs to a Turkish company. Properties of the ship are listed in Table 1.

Table 1. *Some of the main parameters of the analysed ship.*

Properties	**Value**
Displacement (Ts)	45569
GRT	26195
Length Overall (m)	210
Breadth (m)	29.8
Revolution (Rev/min)	108
Main fuel	HFO

HFO is the reference fuel since it is the current used fuel in the ship. There are different options, considering alternative fuels. Analyzed fuels in this study can be sorted as conventional fuels (HFO and MGO), low carbon fuels (Methanol, ethanol, LNG, LPG), and zero carbon fuels (Ammonium hydroxide (NH_4OH), ammonia (NH_3), compressed H_2 (C H_2), liquid H_2 (L H_2), cryo-compressed H_2 (CC H_2)). The density and lower heating values of analyzed fuels (Pulkrabek, 2016) (Suner, 2024) (Frost vd., 2021) (*Ammonia solution - Merck*, 2025) (*Online density calculation according to ASTM D1250*, 2024) (*Methanol Safety Data Sheet - Sigma Aldrich*, 2020) (Abd vd., 2019) (Negro vd., 2023)(*Ethyl Alcohol Safety Data Sheet- Sigma Aldrich*, 2020) (Usman, 2022) ("LNG Fundamentals", 2014) (Lee vd., 2009) (Grannell vd., 2008) (Al-Dawody vd., 2023) have been demonstrated in Figure 2.

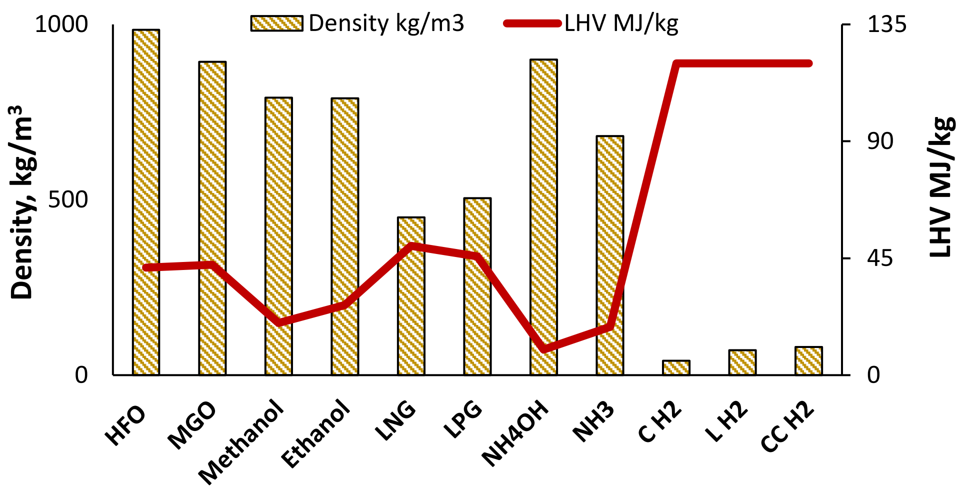

Figure 2. *Density and lower heating values (LHVs) of analyzed fuels in this study.*

2.2. Created Scenarios

In this study, two scenarios have been created. The first one is “same volume” scenario and the second one is “equivalent energy” scenario. Created scenarios have been illustrated in Fig. 3. Each scenario has been explained in this section.

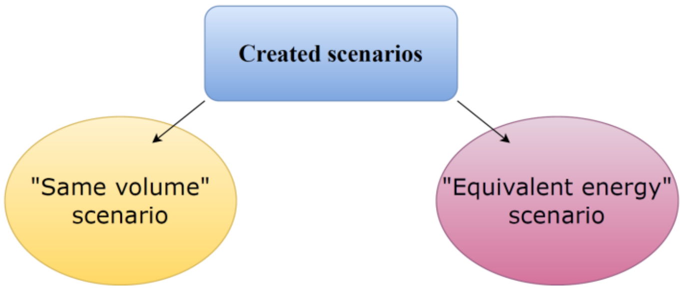

Figure 3. *Created scenarios in this study.*

In each scenario, for each different fuel, consumed energy per time of ship main engine has been taken as constant. Actually, the present situation of the ship in the real life is that; the ship is propelled by a diesel engine and it consumes HFO. The consumed energy per time by engine has been assumed as constant for other analyzed fuels.

2.2.1. Same Volume Scenario

The first scenario created in this study is "same volume" scenario. On this assumption, the existing HFO capacity (m^3) was kept constant. The same volume was considered for other fuels. This means existing tanks were not changed. Same volume fuels have been stored before the sailing. However, this situation creates some differences. First of all, due to density differences the initial weight of the fuel in the tanks varies. This means, the initial displacements before sailings are different. This is important especially for low-density fuels, such as for hydrogen. Since the initial displacement of the ship that uses hydrogen is significantly lower, ship resistance at the initial time interval is low. For this reason, power requirement and fuel consumption per unit mass are low. However, due to low density and low stored energy capacity, maximum sailing range is declined. Moreover, heating value of fuels is different. For this reason, weight loss in time is changing. This affects ship resistance and fuel consumption as well. The advantages and disadvantages of high density and high energy capacities (lower heating values) of fuels have been demonstrated in Table 2 and Figure 4.

Table 2. *Formed trade-off due to fuel property differences.*

Property	Advantages	Disadvantages
High density	More energy at the beginning » More sailing range	Increased initial weight increases displacement » Increased ship resistance can reduce sailing range
High LHV	More energy at the beginning » More sailing range	Causes low weight reduction with time; reduction of ship resistance is declined » Reduced sailing range

Above description of advantages and disadvantages is illustrated in Fig. 4.

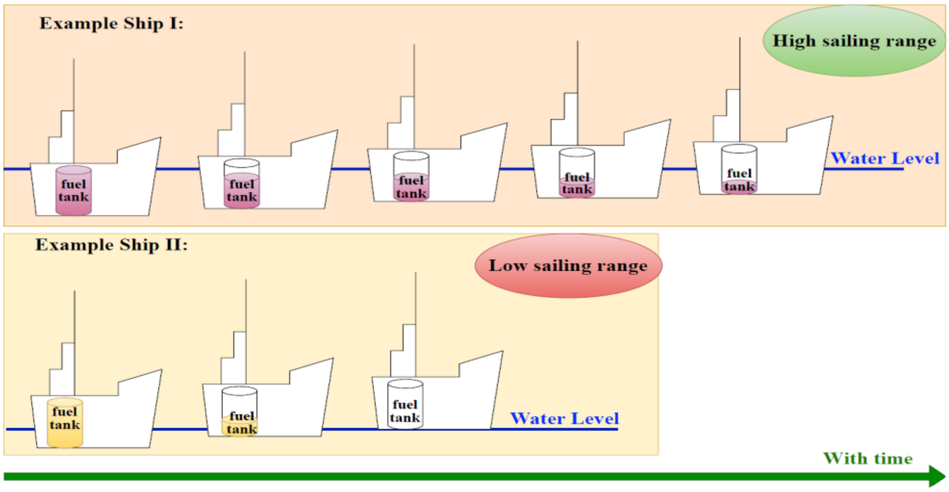

Figure 4. *Description of "same volume" scenario for different fuel use.*

2.2.2. "Equivalent Energy" Scenario

The second created scenario is "equivalent energy". In this scenario, the initial stored calorific energies of fuel tanks have been assumed to be the same for different fuels. In this scenario, the lower heating value (LHV) becomes more important. Fuels that have more LHV increase initial displacement that creates a disadvantage by increasing ship resistance at the beginning of the sailing. This situation is demonstrated in Fig. 5.

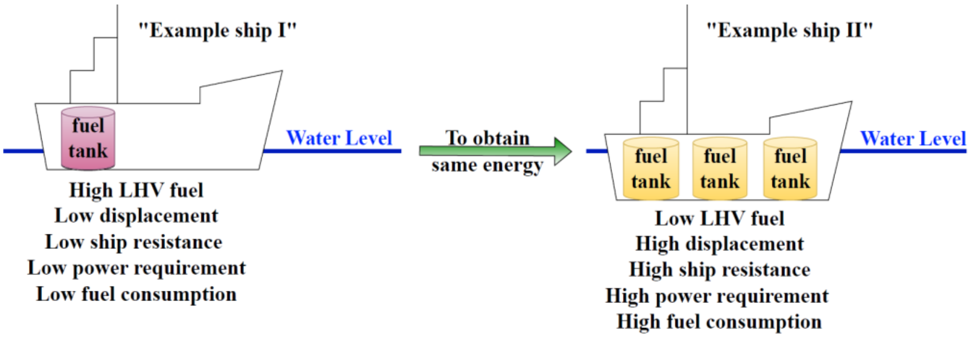

Figure 5. *Demonstration of different LHV effect on initial displacement at "equivalent energy" scenario.*

However, a high LHV creates a disadvantage for the dynamic response of ship at the same time. In a high LHV situation, the weight reduction with time is less. Hence, resistance decline with time is limited.

2.3. Flow Chart, Methods and Softwares

For each scenario, same iterative model was used. At the initial stage, initial displacements differ for each fuel. This situation results in different ship resistances. According to evaluations if the displacement is lower than displacement without fuel tank weight at the end of the iteration, the process stops and the results are printed out. If not, another sailing hour evaluation is started. The created model is demonstrated in Fig. 6.

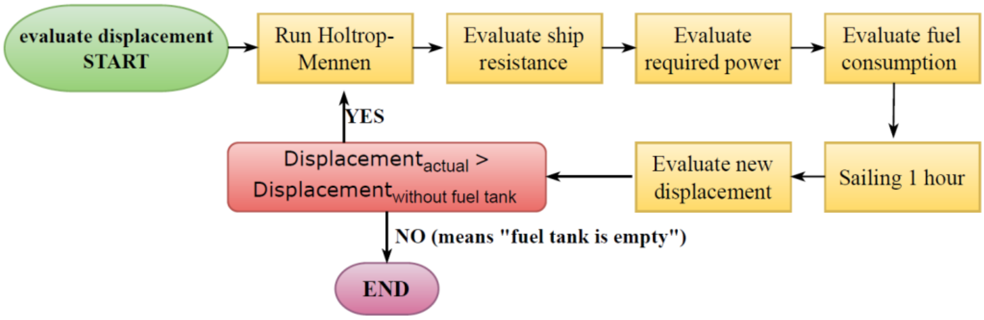

Figure 6. *Flow chart of created iterative model in MATLAB.*

In the present study, ship resistance depends on two main factors: ship speed and displacement tonnage. Throughout this study, 369 power data have been obtained from MAXSURF software using Holtrop-Mennen method with varying speeds and loads. Holtrop-Mennen method (Holtrop & Mennen, 1982)(Holtrop & Mennen, 1978) is a widely used model that gives total ship resistance value:

$$R_{total} = R_F\ (1+k1) + R_{APP} + R_W + R_B + R_{TR} + R_A \qquad (1)$$

In the formula, R_{total}, R_F, (1+k1), R_{APP}, R_W, R_B, R_{TR}, R_A define total ship resistance, frictional resistance, form factor, appendage resistance, wave resistance, bulbous resistance, transom stern resistance and model-ship correlation resistance, respectively. Created and used 3D model according to ship particulars in Holtrop-Mennen method have been demonstrated in Fig. 7.

Figure 7. 3D model of analyzed ship in MAXSURF software.

Among the obtained data, related to ship speed used in this study have been extracted and used in regression model. Obtained regression formulation with 98% accuracy, for 10 m/s ship speed was given below:

$$y=1.089x2+19.87x+18430 \quad (2)$$

This formulation was used in iterative evaluations in MATLAB. In this formula, y defines power and x defines ship displacement. For “same volume” scenario, initial displacement has been obtained with the formulation given below.

$$\Delta_{initial} = \Delta_{without\ fuel} + V_{HFO} * \rho_{fuel} \quad (3)$$

In this formula, $\Delta_{initial}$, $\Delta_{without\ fuel}$, V_{HFO}, ρ_{fuel} define initial displacement, displacement without fuel weight, HFO volume and fuel density, respectively. For the “equivalent energy” scenario, equivalent energy has been calculated as:

$$E_{eq}= V_{HFO} * \rho_{fuel} * LHV \quad (4)$$

Required mass for this energy for each fuel was calculated as:

$$W_{fuel}= E_{eq}/LHV_{fuel} \quad (5)$$

Initial displacement for “equivalent energy” scenario was calculated as:

$$\Delta_{initial} = W_{fuel} + \Delta_{without\ fuel} \quad (6)$$

Required power for each simulation was obtained from regression model, that was created from the obtained data via Holtrop-Mennen method. Power formulation was mentioned below:

For each scenario, consumed fuel in 1 hour was calculated as:

$$\dot{m}_{fuel} = \frac{P*SFOC*LHV_{HFO}}{LHV_{fuel}} \quad (7)$$

In this formula, consumed energy to overcome required power was assumed as constant, same with HFO. However, power and LHV_{fuel} are changing according to displacement of each situation and LHV of each fuel.

More displacement causes more fuel consumption per distance. This situation can cause more CO_2 emission for a specified range. Low carbon fuel use can be resulted as more CO_2 emissions and this probability should be investigated. CO_2 is a greenhouse gas and mitigating its release is one of the main aims of the authorities. To evaluate released CO_2 gases, stoichiometric equations have been used for each fuel. For carbon including fuels, like HFO, MGO, methanol, ethanol, LNG and LPG, released amount of CO_2 has been evaluated with below equations, respectively:

$$C_{14.6}H_{24.8} + 20{,}8\ (O_2 + 3.76\ N_2) = 14.6\ CO_2 + 12.4\ H_2O + 78{,}208\ N_2 \qquad (8)$$

$$C_{12.3}\ H_{22.2} + 17{,}85\ (O_2 + 3.76\ N_2) = 12.3\ CO_2 + 11.1\ H_2O + 67{,}116\ N_2 \qquad (9)$$

$$CH_4O + 1.5\ (O_2 + 3.76\ N_2) = CO_2 + 2\ H_2O + 5{,}64\ N_2 \qquad (10)$$

$$C_2H_6O + 3(O_2 + 3.76\ N_2) = 2\ CO_2 + 3\ H_2O + 11{,}28\ N_2 \qquad (11)$$

$$CH_4 + 2\ (O_2 + 3.76\ N_2) = CO_2 + 2\ H_2O + 7{,}52\ N_2 \qquad (12)$$

$$C_{3.5}H_9 + 5{,}75\ (O_2 + 3.76\ N_2) = 3.5CO_2 + 4.5\ H_2O + 21{,}62\ N_2 \qquad (13)$$

2.4. Assumptions and Limitations

The methodology used in the present study has some assumptions as well as some limitations listed below:

- System density including fuel, tank, pumps, pipes, filters, cables, sensors and etc. is important since it gives final results for the comparison of alternatives. Fuel based density comparison is important as well, it gives an idea and it is the basis of the system density comparison.

- Internal combustion engines can be operated using different alternative fuels. Literature studies usually carry out alternative fuel experiments on existing combustion engines with minor modifications. Some fuels lead to reduced fuel consumption while others result in increased consumption. Specific fuel consumption (SFOC) can change depending on combustion (Lion vd., 2020). In this study, SFOC was accepted as constant. In addition to this, it should be remembered that each fuel should be considered according to developed and optimized engine for that fuel itself. For example, an engine developed for hydrogen fuel, can demonstrate better performance and emission results. Nevertheless, in this study, “same energy consumption” for the “same power requirement” was considered with different fuels used in an internal combustion engine. Moreover, instead of dual fuel operation of internal combustion engine, combustion engine was considered as working in mono-fuel mode.

- To overcome required power to sail ship at the intended speed, a specific amount of energy should be consumed. For each calculation, consumed energy per required power of the internal combustion engine is assumed to be constant.

- Different hydrogen storage methods can be analyzed as well. For instance, solid-state storage methods, liquid organic hydrogen carriers and others can be used. In this study, compressed, liquid and cryo-compressed H_2 were considered.

- Normally, different fuels cause different equipment requirements. For example, internal combustion engines fueled by hydrogen may need fewer after treatment systems. Moreover, although HFO-fueled engines need special equipment (such as filtration system, booster unit, pumps, pipes etc.) for liquid hydrocarbon fuels, gas engines don’t require any of them, or require other specialized equipments. In this study, only fuel weight was considered, ignoring equipments. Besides, ship displacement can be changed with ballast operation, loading-discharge operations and also can be changed continuously by sewage operation, heeling operation and etc. In this study, to see the effect of alternative fuels, only storage capacities of these fuels have been considered.

- To obtain the same energy, the mass of the fuel can need to be increased. However, this could require more volume in on the ship. For example, hydrogen fuel suffers with low volume density values. Obtaining the desired volume can be difficult for ship, but this issue is ignored in this study.

- For different fuel storage options, trim or heel change may occur and therefore, ship resistance may be affected. However, these possibilities have been ignored.

3. RESULTS

3.1. "Same Volume" Scenario Results

In this section, results of "same volume" scenario have been presented. Fig. 8 represents instantaneous displacement and operating time, from beginning of the sailing to the end. First of all, all fuels result as different initial displacement before the sailing since the densities of the fuels vary. Higher initial displacement will create a disadvantage for ship resistance, leading to increased fuel consumption. The results indicate that, heavy fuel oil causes the heaviest initial displacement in the options. The other initial displacements can be ranked as NH_4OH, MGO, methanol, ethanol, ammonia, LPG, LNG, cryo-compressed H_2, liquid H_2 and compressed H_2. Initial displacement of MGO is almost same with HFO with 0.5% difference. However, hydrogen options have lowest initial displacements. Initial displacements of compressed H_2, liquid H_2 and cryo-compressed H_2 are 5.8%, 5.6% and 5.6% lower than HFO.

The second subheading is the displacement reduction rate. Despite the higher initial displacement, some fuels are consumed quickly and this causes a reduction of displacement with sailing. Ammonium hydroxide, ammonia, methanol and ethanol draw attention for this reason. Range result of the ammonium hydroxide is close to the hydrogen results. The last subheading at the results is the maximum sailing duration. This will indicate the maximum range since the velocity of the ship is held constant across all scenarios. According to the results, HFO and MGO are most successful fuels in terms of accessible maximum range. Other fuels are ranked as LPG, LNG, ethanol, methanol, ammonia, cryo-compressed H_2, ammonium hydroxide, liquid H_2 and compressed H_2. Hydrogen options place at the lower side of the results. However, an interesting result can be seen with the ammonia-water solution, since its range falls between cryo-compressed and liquid H_2. Results show that range reductions are 6% for MGO, 43% for LPG, 44% for LNG, 49% for ethanol, 61% for methanol, 68% for NH_3, 76% for cryo-compressed H_2, 78% for NH_4OH, 78% for liquid H_2, 87% for compressed H_2.

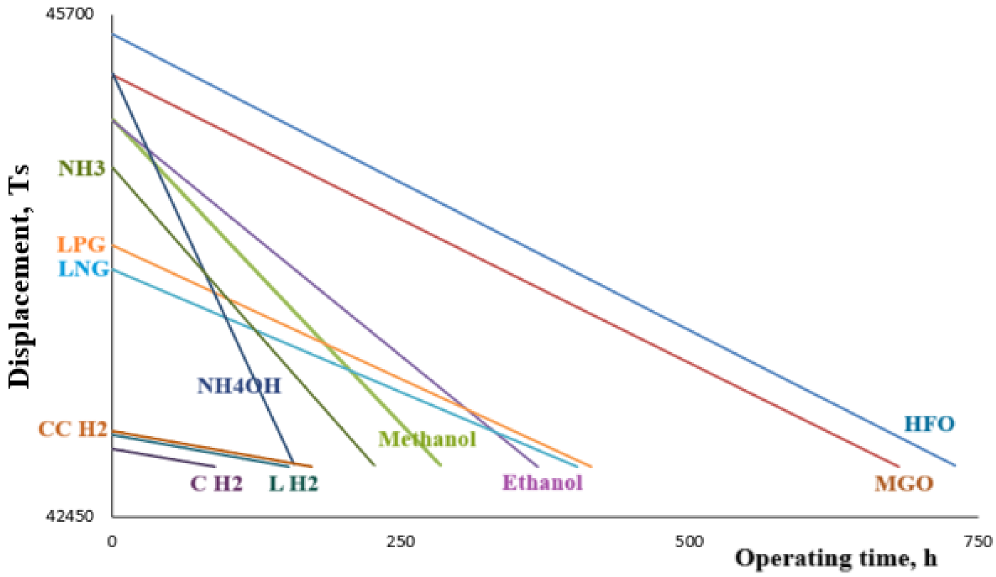

Figure 8. *Ship displacement vs. operating time at constant volume scenario.*

Dynamic fuel consumption results have been presented in Fig. 9. First of all, fuel consumption results are decreasing with time. This result shows that the reduced displacement with time during the sailing causes reduced ship resistance and consequently lower fuel consumption. NH_4OH has the highest consumption rate among the fuels. NH_4OH has high density value which increases initial displacement and fuel consumption. However, its very low LHV is the dominant factor contributing to its high fuel consumption. Other fuels can be sorted from highest to lowest consumption as ammonia, methanol, ethanol, HFO, MGO, LPG, LNG, cryo-compressed, liquid and compressed H_2.

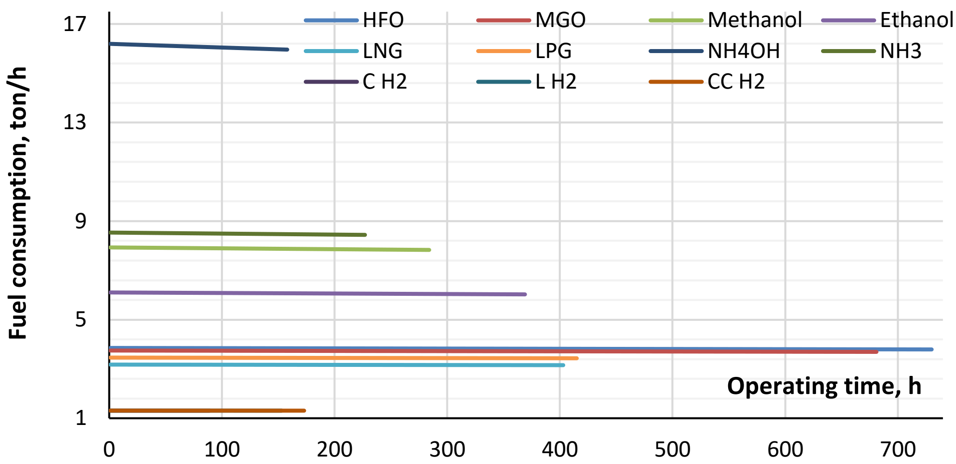

Figure 9. *Fuel consumption vs. operating time at consant volume scenario.*

At the end of the sail, total energy consumption and CO_2 emissions per unit distance are important criteria and have been presented in Fig. 10. According to the results, conventional fuels such as HFO and MGO have higher values, making them disadvantageous in this respect. It should be noted that these results are in line with Fig. 8. In the same volume scenario, the high density of fuels increases displacement and ship resistance, leading to higher energy consumption. However, higher ranges can be obtained as well. Hydrogen options stand out with low energy consumption per range, despite having a shorter range. Among all fuels, MGO shows the smallest reduction in energy consumption, with a value of 0.08%. All fuels have reductions but hydrogen options have higher reductions as 1.16% for cryo-compressed, 1.25% for liquid H_2 and 1.73% for compressed H_2. Nevertheless, this comparison can be more meaningful in the "equivalent energy" scenario.

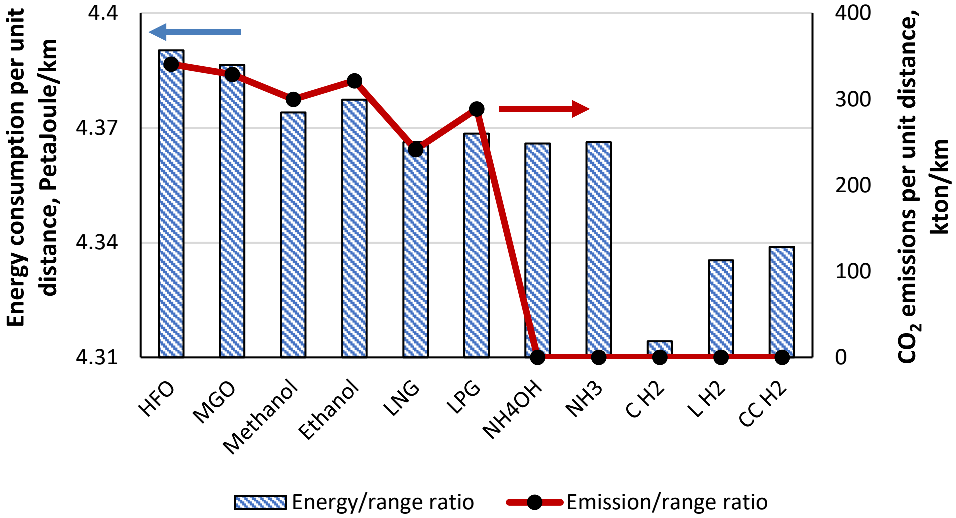

Figure 10. *Energy consumption and CO_2 emissions per unit distance, at constant volume scenario.*

Results show that emission values are in line with energy consumption in general. Zero carbon fuels such as NH_4OH, NH_3, compressed H_2, liquid H_2 and cryo-compressed H_2 resulted zero CO_2 emissions. Among the carbon including fuels, LNG options have the lowest value, it reduces CO_2 emissions by 29%.

3.2. "Equivalent Energy" Scenario Results

In this scenario, stored energy was assumed as to be the same before sailing. As explained before, the differences between LHV values create bigger differences in displacement tonnages compared to the same volume scenario. Displacement vs. operating time hour has been demonstrated in Fig. 11. Here, NH_4OH, NH_3, methanol and ethanol draw attention with low LHV and high displacement. NH_4OH has the biggest displacement tonnage, causes 19.6% tonnage difference while starting to sail. 3%, 6%, 7% and 19% increase in the initial displacement is seen as a result of the use of ethanol, methanol, NH_3 and NH_4OH fuels.

Moreover, 0.1%, 0.5%, 1%, 4% reduction in initial displacement is seen as a result of the use of MGO, LPG, LNG and hydrogen fuels, respectively. Moreover, fuel consumption takes place during the sailing according to different LHVs and at the end of the sail, displacement is equal to displacement tonnage without fuel tank. More displacement during the sailing was observed with NH_4OH, NH_3, methanol, ethanol. On the other hand, lower displacements were observed with MGO, LPG, LNG and hydrogen options. Sailing hours have been observed to be nearly the same across the different fuels in this scenario. These results show that alternative options such as NH_4OH, NH_3, methanol and ethanol have a disadvantage due to the fact that their use create extra tonnage, increases ship resistance, and leads to higher fuel consumption.

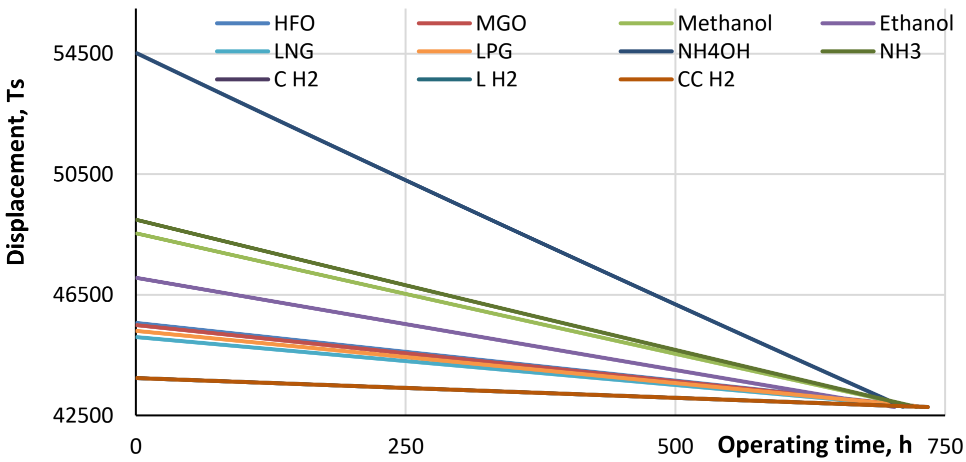

Figure 11. *Displacement vs. operating time at equivalent energy scenario.*

As discussed earlier, dynamic displacement significantly affects ship resistance and fuel consumption. However, another crucial determinant is the lower heating value of fuel, which directly influences the fuel consumption. Fuel consumption results have been demonstrated in Fig. 12. Sailing hours are nearly same accepted initial energy storage and same energy consumption concept. Fuel consumptions reduce with time, it means dynamic analysis is working correctly.

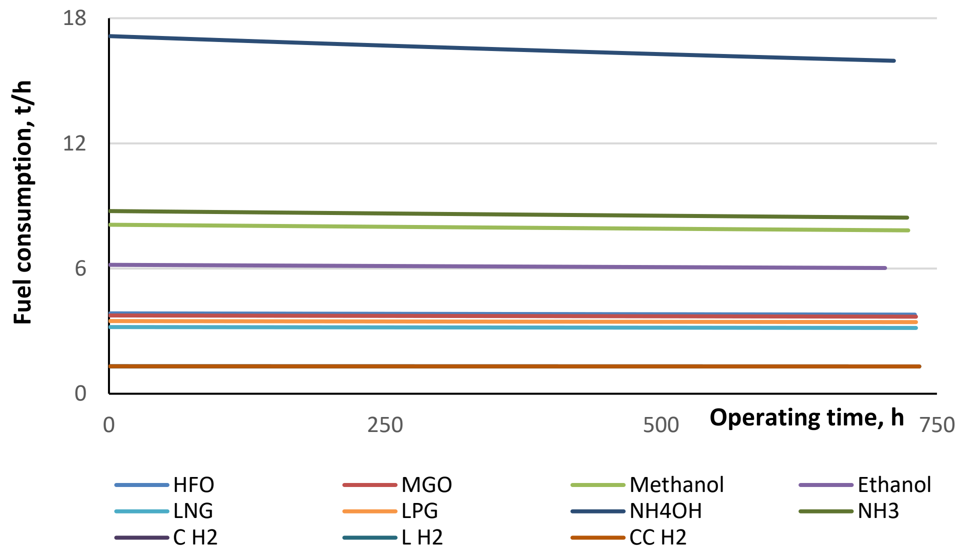

Figure 12. *Fuel consumption vs. operating time at equivalent energy scenario.*

Nearly same ranges are obtained at equivalent energy scenario. In this scenario, consumed energy per range results are more meaningful. Lower values are more preferable. Consumed energy per distance has been summarized in left side of Fig. 13 (yellow color). According to results, NH_4OH, NH_3, methanol, ethanol has higher values. NH_4OH increases energy consumption as 2.7% compared to HFO. Among the popular fuels, NH_3 and methanol increase energy consumption by 1% and 0.8% respectively. Compared to the “same volume” scenario, hydrogen options have advantages in this scenario again. These results are important for ship energy efficiency evaluations. Consumed energy per distance can be thought as critical indicator and can be used to compare different fuels and systems. Obtained results show us that clean attributed fuels may increase energy consumption. This effect should be considered in energy efficiency evaluations. Moreover, it should be remembered that heavy batteries may have the same results with these alternative fuels.

Energy consumption per distance is an important parameter, but released emission during sailing is important as well. Despite lower energy consumption, HFO and MGO options result as worse emissions. As expected, zero carbon fuels have zero tailpipe CO_2 emissions. Among the carbon including fuels, LNG takes attention with 28% reduction in CO_2 emissions. Other reductions can be sorted as 14% for LPG, 10% for methanol, 4.9% for ethanol, 3% for MGO.

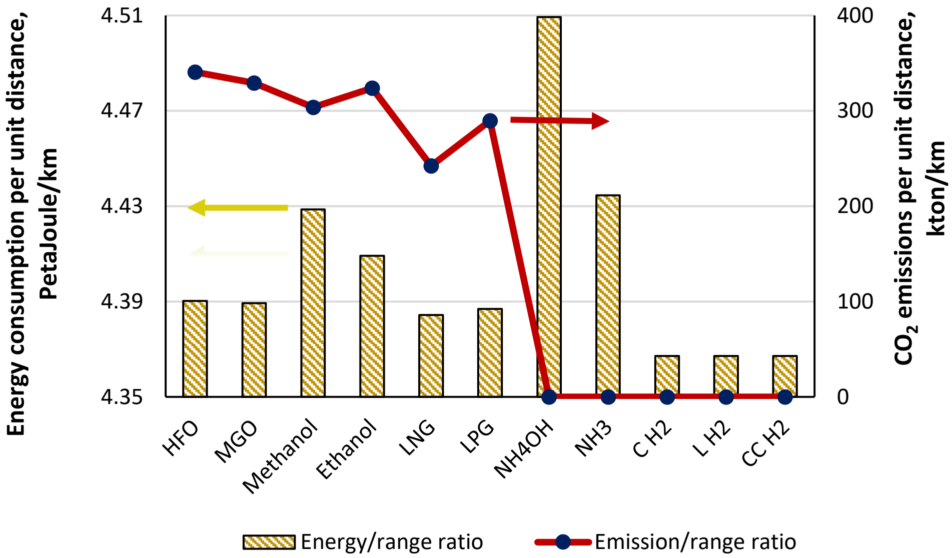

Figure 13. *Energy consumption and CO_2 emissions per unit distance in equivalent energy scenario.*

4. CONCLUSION

In this study, a dynamic fuel-based energy analysis of fuel storage options has been carried out. The results have been summarized below:

- Considering fuel transition, "same fuel tank volume" can be preferred to store new alternative fuels in the ship. In this "same volume" scenario, conventional fuels such as HFO and MGO present longest allowable ship ranges compared to alternative fuels since they have more stored energy at the initial stage of the sail. However, their use creates more energy consumption and more emission per distance. NH_4OH and NH_3 cause higher initial ship displacement, but they are consumed rapidly. Hydrogen options draw attention with low energy consumption per distance, but range of the ships using hydrogen is around 1/8 of range of the ships using HFO.

- Instead of low ship sailing range (mentioned above), same sailing range can be more desirable. Same energy can be stored in fuel storage tanks and nearly same ranges can be obtained. However, in this situation, low LHV fuels such as NH_4OH, NH_3, methanol and ethanol increase ship displacement, causes more energy consumption per distance. As similar to "same fuel tank volume", hydrogen options have advantages again with lower energy consumption per range.

- Common opinion for fuel transition is that NH_3 is clean considering emissions and will be the main propulsion fuel in ships in the future. However, it causes 68% less range compared to HFO considering same fuel tank volume is used. Instead of same fuel tank (same volume) use, same energy can be stored to increase range. Some cargo space can be occupied by fuel, for this reason. In this situation, NH_3 causes a 1% increase of consumed energy per distance.

- Among carbon including fuels, LNG takes attention with low energy consumption, low emission profile (29% CO_2 reduction) and moderate (compared to hydrogen and ammonia) ship range reduction (%44 range reduction compared to HFO).

- Considered "clean" fuels may cause an increase in energy consumption due to increased ship displacement and ship resistance. This effect should not be underestimated. Moreover, alternative fuels may reduce sailing range of ships. In this situation, it should be remembered that this reduction will be compensated with more voyage or vessel.

- This study considers fuel weight and does not consider required equipment weight. In future studies, ship displacement analysis will be carried out including all system weights such as individual pumps, compressors, fuel treatment systems, propulsion equipment etc.

ACKNOWLEDGEMENT

The author(s) declare(s) no conflict of interest.

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