AN OVERVIEW OF MEASURES FOR IMPROVING THE ENERGY PERFORMANCE OF SHIPS

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Abstract

A "green ship" is a term given to ships that contribute to the improvement of the present environmental situation. Maritime industry is one of the greatest contributors of the greenhouse effect and in order to reduce carbon emissions coming from it many actions were taken worldwide. The efforts taken by the International Maritime Organization (IMO) can be particularly pointed out, but there is number of other opportunities that can be applied to improve the energy efficiency of ships. Ship designers and shipbuilders have at their disposal a number of measures that could be used to increase the energy performance of ships. This paper focuses on some of these opportunities, some of which are regulated by mandatory regulations and rules while other are applied on a voluntary basis.

Keywords: *ship; energy performance; improvement measures; overview;*

Sažetak

"Zeleni brod" je pojam koji se dodijeljuje brodovima koji doprinose poboljšanju sadašnjie situacije u okolišu. Pomorska industrija jedan je od najvećih doprinositelja učinku staklenika. Kako bi se smanjile emisije ugljika koje proizlaze iz te industrije, poduzete su mnoge akcije širom svijeta. Posebno se mogu istaknuti napori Međunarodne pomorske organizacije (IMO), ali postoji niz drugih mogućnosti koje se mogu primijeniti za poboljšanje energetske učinkovitosti brodova. Projektantima i brodograditeljima na raspolaganju stoji niz mjera kojima bi se mogla povećati energetske značajke brodova. Ovaj se rad usredotočuje na neke od njih, od kojih su neke regulirane obveznim propisima i pravilima, dok se druge primjenjuju na dobrovoljnoj osnovi.

Ključne riječi: *brod; energetske značajke; pregled mjera za poboljšanje;*

1. Introduction

A comprehensive concept of a "green ship" implies a ship that will not harm the natural environment and that will meet the right criteria from the very beginning to the end, i.e. not only during the ship's service life but also during the building as well as going to the ship-breaking yard. The ships, by their function, spend most of their time sailing the seas so this concept mostly refers to a ship in service. Therefore, to make a ship "greener", one of the most important matters to do is to reduce greenhouse gas emissions (GHG).

The key findings from the Third IMO GHG Study 2014 pointed out that international shipping emitted 796 million tons of CO_2 in 2012, accounting for about 2.2% of the total global anthropogenic CO_2 emissions for that year, [1]. If the world maritime trade continues this trend of growth, those emissions have the potential to grow between 50% and 250% by 2050. Because of that, IMO is increasing its engagement in a global approach of enhancing the ship's energy efficiency and developing measures to reduce GHG emissions from ships.

Initial IMO Strategy on reduction of GHG emissions from ships reviews a reduction in total GHG emissions from international maritime shipping and identifies the following crucial steps [2]:

1) Implementation of further phases of the EEDI (Energy Efficiency Design Index) for new ships that should result in decreasing of the ship's carbon intensity;
2) Reduction of international shipping carbon intensity by at least 40% by 2030, with the target of 70% by 2050, compared to 2008;

3) To peak GHG emissions from international maritime shipping as soon as possible with the target to reduce the total annual GHG emissions by at least 50% by 2050 compared to 2008;

IMO regulations will evolve through the years and the newbuildings will have to comply with even more strict constraints. In addition to the environmental impact caused by a ship in regular service, the problems of the deliberate release of oil into the sea and accidents at sea that result with oil leakages are also being taken more seriously.
One of the prerequisites for "greener" ships would also be the modernization and equipping of coastal infrastructure. Ports and terminals should be equipped with modern transshipment and cargo handling facilities that would enable the fast and efficient loading and unloading of cargo on and off the ship so that ships could only be designed to carry out their basic task, to sail and to carry cargo by sea as efficient as possible.
This paper focuses on measures that could contribute to reducing the carbon footprint of merchant ships. The main aim is to maximize the energy efficiency of the ships in service, i.e. to reduce the GHG emissions to a minimum. To achieve that, it is important to define the main requirements, restrictions and regulations at the initial stage of ship design according to which the ship will be designed and built.

2. Measures for improvements

There are numerous measures that can be implemented to improve the energy performance of ships and Table 1. provides an overview of some of them. Some measures are discussed in more detail hereafter.

Table 1. Measures that could be used to increase the energy performance of ships

Ship design	Propulsion & Machinery	Operation & Maintenance
- Optimization of main dimensions and hull form	- Type of fuel	- Hull coating system and cleaning
- Optimization of hull appendages and openings	- Sulfur-cleaning scrubbers	- Energy saving lighting
- Air lubrication	- Waste heat recovery system	- Voyage performance management
- Optimization of ship structure	- Electric propulsion systems	- Ship speed reduction
- Reduction of main deck equipment	- Renewable energy propulsion: wind power, solar power	- Turnaround time in port
- …	- …	- …

2.1. Ship design

Hull and appendages

In the context of ship design, the most fundamental and everlasting problem is the design of low resistance ship satisfying given requirements of deadweight and speed. All of the essential features of a ship, such as hydrostatics, stability, hydrodynamic characteristics, strength, and seakeeping mostly derive from the underwater ship hull form.
Ship owner's requirements often require a certain ship's deadweight at a given draught, resulting in excessive length, breadth and block coefficient. This results in a higher amount of construction material, higher main engine power, and thus higher fuel consumption, with a lower deadweight coefficient. For the given limited draught, due to the limited depth of ports

or sea passages, reasonable main dimensions and optimal main dimension ratios and form coefficients should be chosen. The values of the main dimension ratios and block coefficient recommended in [3] are:

$5 < L/B < 8$, in accordance with value of Froude number defined as $Fr = V/(g \cdot L)^{1/2}$,

$8 < L/D < 10$, depending on the size of the ship,

$1{,}8 < B/T < 2{,}5$,

$0{,}6 < C_B < 0{,}8$, depending on the value of Fr and the size of the ship,

where L, B, D, T and C_B are ship's length, breadth, depth, draught and block coefficient, respectively.

Ship's length can be described as a function of displacement and speed, [4], and it is known as the most expensive dimension because it significantly influences the steel, accommodation, and outfitting mass. The steel mass increases, [3]:

- with the length on exponent $a \approx 2$,
- with the breadth on exponent $b \approx 2/3$,
- with the depth on exponent $c \approx 1/3$,

so the formula for calculating the mass of steel can be written as:

$$W_S = k \cdot L^a \cdot B^b \cdot D^c, \tag{1}$$

where k is the coefficient that depends on the type of ship. One of the accepted ways to reduce the ship's total resistance and thus fuel consumption is to increase L or to reduce B in order to obtain a satisfactory L/B ratio. To achieve good hydrodynamic characteristics, it is recommended not to have the value of L/B below 6.5. While the increase of the L/B ratio has a beneficial effect on reducing the total resistance, it negatively affects the ship's stability. The increase of L at the expense of other characteristics of the ship usually results with higher construction cost, so this suggests keeping L as short as possible, [4]. On the other hand, some research shows that a lengthening of a ship for 10 to 15% could result in the reduction of power demand by 10%, [5]. Both approaches have their advantages and disadvantages, but it is very likely that in practice the length of the ship will be determined from requirements which are not of a hydrodynamic nature.

A ship with a large draught can be fitted with a larger and higher efficient propeller rotating at the lower number of revolutions. Also, the larger draught allows the fitting of a larger rudder for improved steering and maneuverability. When designing new ship, the limiting of the draught should be avoided as much as possible, especially in cases where the space lost by reducing draught is compensated by an increase in the main dimensions and coefficients. This results in unreasonable ratios between main dimensions, such as L/B>8 or L/B<5, L/D>14, B/T>2.5, or even B/T>3. Some experiments have confirmed that a ratio B/T≈2.5 is the best from both frictional and wave resistance point of view, [4].

The formulas for determining the block coefficient are usually based on the ship's relative speed, i.e. the Froude number Fr, which means that the higher the Fr the lower the C_B. However, C_B is a function of several factors and not only Fr. Ship's size and type determine the selection of C_B, in a way that larger ships usually require higher C_B. Also, a higher L/B ratio, for the same ship size and Fr tolerates slightly higher C_B due to the relatively smaller curvatures and less pronounced shoulders. The economics of shipbuilding generally follows the direction of higher C_B, and there are several reasons for that. Higher C_B makes it possible to get the same deadweight and cargo space with a smaller ship and consequently smaller mass of the lightship.

As for the hull appendages, only bilge keels will be briefly discussed here although there is a whole range of appendages on ships. The normally derived increase in resistance from 1 to 3% at the expense of the bilge keels can be accepted as a minimum that matches a special case when the bilge keels are placed in the water flow direction. Otherwise, in real service conditions, their resistance is even higher. However, there is still no device for reduction of rolling motions that could be an alternative for bilge keels, given their cost of installation, maintenance, and reliability of operation. On some ships, it is possible to reduce the length of the bilge keels, or even to completely leave them out. This could enable savings in both power and fuel consumption.

As for the hull openings, by installing a transverse pipe to place the bow thruster, the ship loses some of the displacement while the integrity of the hull is disrupted and the total mass is increased. The water flow disturbance from openings of the bow thruster tunnels and sea chests can be high, and this certainly increases the resistance. Therefore, it is beneficial to install scallops behind openings. Good design of all openings combined with proper location can give up to 5% lower power demand than one with poor design. For containership, corresponding improvement in total energy consumption could reach almost 5%, [5]. In some cases, the option of a merchant ship without the lateral thrust, which relies on the assistance of a local tugboat, could prove to be an optimal design.

Air lubrication

EEDI as an integral part of energy efficient ship concept has classified air lubrication as "Innovative Energy Efficiency Technologies" that can reduce ship resistance, [6]. Although technology is still between development and testing phase, confident data are available. A total of 18 full scale performance tests between 2002 and 2015 were identified. The net energy savings reported range approximately between 4% to 10%, [6]. These sea trials were not monitored and analyzed as required for EEDI trials so air lubrication system still needs official confirmation of effectiveness.

Reduction of equipment on main deck

Port infrastructure with modern transshipment and cargo handling facilities could enable to free the ships from deck cranes and transshipment facilities that have a permanent impact on the entire ship design. Cranes that are mounted on the ship's main deck take up a lot of space, increase its mass, and have a negative impact on a ship's stability. Besides that, it is necessary to reinforce the ship's structure under the cranes and this also unnecessarily adds mass. The operation of the ship's cranes increases the energy consumption of the whole system, and it is known that the energy produced on board is more expensive than that of the shore. Lastly, there are also maintenance costs that could expel some of the more important costs.

Structure

Optimization of structure requires a significant amount of additional working hours and usage of more expensive materials, but a reduction can have a large effect on fuel consumption i.e. savings. Furthermore, a decrease in structural mass means that there is an increase in available deadweight with which transport efficiency can be improved. Initial ship construction design price will be higher but return on investment (ROI) will follow with the more profitable ship in operation.

There are two main ways of optimizing ship structure. Firstly, it can be implemented in the basic design of a ship. During the design of ship structure, rules and regulations of classification societies must be respected and followed. In the process of meeting rules and regulations there are a lot of doubtful places for which in common practice a designer will always take greater scantlings of structure elements and with that make the structure heavier.

That additional mass can be avoided with usage of finite element method with which doubtful element scantlings can be checked and most effective dimensions of structure element can be chosen. Described procedure can produce lighter ship structure but would require additional working hours and therefore result with more expensive ship at the beginning.

Another option is to use lighter materials with which considerable saving can be achieved. Materials that can be used to create light mass ships are high tensile steel (HTS), aluminum and composites. It was shown that usage of 10% more of HTS can reduce mass by 1.5% to 2%. With the mentioned reduction ships like tankers and bulk carriers can have an increase in deadweight and cargo payload of 0.2 to 0.3%, or fuel consumption per ton of cargo transported can be reduced 0.2% to 0.5%, [7]. While HTS is for now the best option for large cargo ships, aluminum and composite materials can be applied for the structure of ferries and Ro-Ro/Ro-Pax ships. Fiber reinforced plastic (FRP) can be applied to the structure and superstructure of high-speed crafts and can produce 30% to 70% mass savings which would then reflect on the fuel savings, [7]. An example of FRP implementation can be found on the car carrier that had top three of the 13 vehicle decks built from PVC foam-cored glass/polyester sandwich panels, [8]. In this case, these composite decks were 25% lighter than steel decks, which saved 230 tons overall. The lower vertical center of gravity reduced ballast requirement by 575 tons and total mass savings enabled 805 ton increase in payload which resulted with 4.5% reduction in fuel consumption.

2.2. Propulsion & Machinery

Heavy Fuel Oil

The powerful ship main engines burn huge amounts of heavy fuel every day to give thrust to heavily loaded ships. Fuel costs represent as much as 30 to 50% of the ship's total operating cost so these engines usually use low-grade heavy fuel oil to lower these costs.

The propulsion of marine diesel engines with heavy fuel has numerous negative effects on the ship, which are less frequently mentioned. Heavy fuel is stored in large tanks that require additional space on board, thus reducing usable space or increasing ship dimensions. This results in an increase in displacement and thus resistance and fuel consumption, as well as maintenance costs. It may be suggested to phase out the use of heavy fuel on ships and marine objects, by switching to just one type of fuel both for main engine and auxiliary machinery, i.e. marine diesel oil.

This would allow the reduction of the lightship's mass saving the space in the engine room. Heavy fuel supply systems are complicated and require a lot of auxiliary equipment such as additional tanks, pipelines, transfer pumps, heaters, purifiers, and measuring instruments. These systems also require crew members, that takes care of these equipments, which otherwise would not be necessary. All ship systems require permanent maintenance, which is especially important for ship propulsion and power supply systems. A lot of energy is wasted for the transport, heating and preparation of the heavy fuel, and also to power all the associated systems.

It is important to mention that the use of the heavy fuel for ship propulsion significantly shortens the engine life and its lower heating value, high amount of small particles and sulphur content increase the green house gas emissions. Most of the ships still use heavy fuel, which is also of lower quality compared to marine diesel oil and this results in much higher green house gas emissions. Switching to alternative fuels is happening slowly and gradually and such big changes require a lot of time.

Sulfur-cleaning scrubbers

As from January 1, 2020, the limit for sulphur in fuel oil used on ships operating outside designated emission control areas is reduced to 0.5% m/m (mass by mass), [9]. For ships that are in operation and have propulsion system based on oil fuel, sulfur cleaning scrubber is temporary solution between oil fuels and more eco-friendly fuels. Exact benefits of scrubbers are reduction of the SO_X emissions by at least 95% and particulate matter by at least 60%. Scrubbers can also reduce the NO_X emissions, but it is still unknown by how much, [10].

LNG fuel

In desire to gradually reduce usage of oil-based fuels on ships, maritime industry has found potential in liquefied natural gas (LNG) fuel. That is because even though renewable energy (solar, wind) may have some potential to reduce carbon emissions, they cannot meet the needs of commercial maritime shipping on their own. Currently, there are over 175 ships using LNG fuel in operation, [11], and this has shown environmental benefits like elimination of SO_X emissions, significant reduction of NO_X and particulate matter (PM) as well as a small reduction in GHG emissions, [12]. DNV GL forecast is that by the 2050 47% of energy for shipping will come from oil-based fuels, 32% from gas fuels and rest will be provided from biofuels and electricity, [13]. While technology of electric propulsion that run on batteries is in development, LNG has proven itself as good replacement and is certainly contributing to the "green ship" idea.

Waste heat recovery system

The usage of wasted heat can be directed in reduction of need of more energy that is coming from fuels. Appropriate waste heat recovery system should be selected for each ship separately based on engine type, engine power, demand for electricity etc. One of the possible methods to reduce the fuel consumption is to use steam generated in waste heat recovery boilers to meet the demand for heating and to feed turbochargers, [14]. Exhaust reduction can be 36.28% for NO_X and 16.88% for CO_2 while maintain a 5%-10% reduction in EEDI at 400,000 tons of deadweight. Furthermore, a saving of 16.1% was achieved by installing waste heat recovery system, [15].

Electric propulsion systems

Electric propulsion system is offering best alternative to conventional propulsion systems in today's time. Electric propulsion can be based on two different main propulsion systems; diesel driven or turbine (steam) driven propulsion. Main advantage of the electrical propulsion system is its environmental benefits from lower fuel consumption and emissions and the fact that it requires much less space for installation, [16].

It is worth mentioning electric ships powered by lithium-ion batteries which could present a major change in reduction in CO_2 emissions. There are currently several important electric ship projects which test this alternative to traditional fuels for maritime shipping. Implementation of this technology on ships is still in early phase but with the development of technology it can be expected more and more electric ships powered on batteries, [17].

Renewable energy propulsion – wind power

Mechanically propelled ships have pushed out sail ships from commercial maritime shipping, but as the industry is turning to green and renewable energy, former sail technology will probably be more and more present.

Technology of towing kites which are used like sails have already been implemented on commercial ships, Figure 1, even though technology is still in verification and optimization phase, [18, 19]. In the current state of development, large fuel saving are possible on slow-speed ships like tankers and bulk carriers and savings in fuel consumption can be up to 30%. Issues that should be further addressed are safety and complexity of operation, [18].

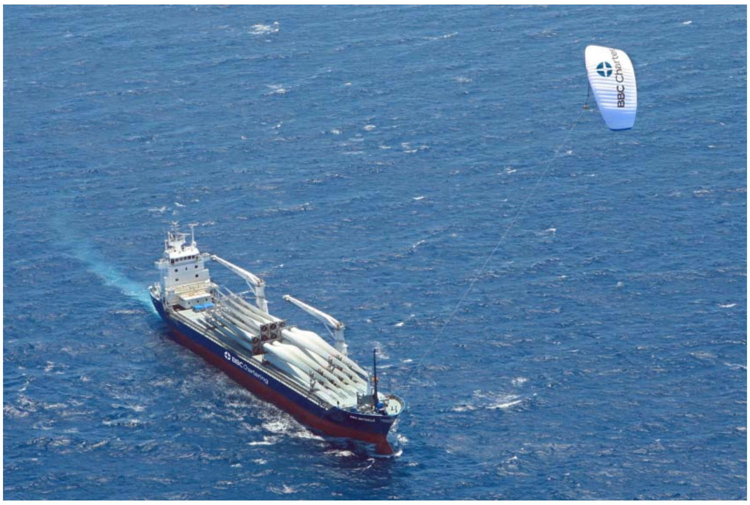

Figure 1. Towing kite system, [20]

Besides towing kites, Flettner rotor places itself as potentially efficient wind propulsion technology. Flettner rotor is vertical cylindrical sail that works on principle of Magnus effect. This device is named after German aviation engineer and inventor Anton Flettner who studied in 1920s the effectiveness of spinning cylinders as a ship's propulsion system. Technology is still in testing phase and its actual impact on performance of commercial ships is still ongoing. There were few cases of open sea trials that were carried on by the companies Norsepower and Maersk on a product tanker "Maersk Pelican", [21], Figure 2. The Flettner rotors were implemented on bulk carrier "Afros", [22]. The reduction potential on fuel consumption of the main engine was estimated to be around 3% to 15%, [23].

Figure 2. Flattner rotors on board Maersk Pelican, [21]

Renewable energy propulsion – solar power

Over the last years solar panels which convert sunlight into electricity have been recognized as potential additional source of auxiliary power. The cost of implementing solar power units on ships on which usually there are no free flat areas is another negative aspect and it is not surprising that there has been no wider application in the maritime shipping industry. As an example of implementation of solar power units on commercial ship, NYK car carrier "Auriga Leader" can be given, [24]. This ship has 328 solar panels on its top deck that provide 40 kilowatts of power, Figure 3. Today solar panels can be used only as additional power source.

Figure 3. NYK car carrier "Auriga Leader" (left), solar panels on the top deck (right), [24]

2.3. Operation & Maintenance

Hull coating system and cleaning

Harsh conditions in which ships operate cause corrosion and abrasion, especially of underwater parts of the hull which result in increased resistance and fuel consumption. Marine coating systems are used to protect materials from corrosion and abrasion. Additional segment of marine coating system other than protective one is to improve the flow of water over the hull in order to reduce resistance. To improve overall performance of the ship, high-performance coating system should be used and some producers claim that up to 10% improvement in speed can be achieved and up to 13% improvement in fuel economy as well, [25]. While the accuracy of information given by coating producers should be taken with caution, it is certain that coating systems have positive impact on overall ship performance.

Reduction in power consumption – lighting

Rapid increase of energy efficient lighting equipment was recorded in almost all industries and marine industry is no exception. It is important to take into consideration energy consumed by lighting because it is estimated that on usual merchant ship 5% of total consumed electrical power goes on lighting while on passenger ships it can be higher than 10%. The emission reduction potential on usual merchant ships is estimated to 3% of the total auxiliary engine consumption, [26].

The low energy halogen lamps, fluorescent tubes and LED (Light Emitting Diode) fall into the energy efficient lighting equipment that can be used on ships. In addition to the use of this type of lighting, it is also necessary to install controlled systems for dimming, automatic shut off, etc.

Some experiments done at bulk carrier proved "that the energy-efficient light sources provide remarkable advantages in comparison with the traditional light sources of ships." It was also stated that lighting system power capacity can be reduced by 65%, marine fuel consumption by 59.4% and lighting cost by 53% The CO_2, NO_X, SO_2, and PM emissions can also be decreased by 53% by more efficient lighting, [26]. All of the above is in line with the claims of companies manufacturing lighting equipment that the total energy for lighting on board ships can be reduced by 50%, [27, 28].

Voyage performance management

Energy saving operational decisions can be managed by crew or vessel management systems. Some of operational factors that have effect on overall energy consumption are "just in time speed", reduction of added resistance (wind, waves and current), weather routing, minimizing rudder movements and optimizing ballast carried and trim for lowest hull resistance.

Voyage speed optimization proves to be effective tool in energy saving management. The largest opportunities for reducing fuel consumption are present on fast ships while on other types of ships this depends on their speeds. According to some rough estimates, it turns out that 10% reduction in speed can result in 20% reduction in propulsion fuel consumption, [7].

Weather routing is another tool in energy saving management which can have significant impact on fuel consumption, but savings of route planning significantly depend on weather and voyage length. Percentage of fuel consumption varies significantly from case to case but saving can go up to around 30% and more, [29].

3. Conclusion

Ship designers and shipbuilders have at their disposal a number of measures that could be used to increase the energy performance of ships. Some of these measures are regulated by mandatory regulations and rules while other measures are applied on a voluntary basis. However, designers and shipyards are only one side in the whole process of ship design and construction, while the other side, most often crucial, is the investor, i.e. the ship owner who is usually not too inclined to some innovative solutions that have not yet been proven in the marine environment. There have been cases in the past where untested technologies, which at one point seemed to be very good solutions that could contribute to the fuel consumption reduction, in practice very quickly proved to be completely unsuitable for the marine environment.

When it is discussed about a “green ship”, it is usually meant a ship that has the lowest carbon footprint. In that sense, a ship which is fuel efficient can be considered as a “green ship”. From this viewpoint, the ship’s engine room is the largest contributor to environmental impact. However, a “green ship” needs to be viewed much more broadly, not only as the ship's hull form with its appendages and an efficient propulsion system with low fuel consumption. As an example, an eco-friendly ship built with recycled materials that uses renewable energy can be mentioned. The above can be further broaden by many other entries, like zero discharge of gray or black water, etc., including the ports that should also become much more environmentally friendly.

Shipbuilding and the maritime industry are facing great challenges today, and these challenges will certainly intensify in the near future. This leads to a large number of questions that the industry will need to adequately answer.

ACKNOWLEDGMENTS

This study was carried out within the project METRO (Maritime Environment-friendly TRanspOrt systems) funded by the 2014-2020 Interreg V-A Italy - Croatia CBC Programme.

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