Wind Assisted Ship PropulsionTechnologies – Can they Help in Emissions Reduction?

Tehnologije propulzije broda s pomoću vjetra – mogu li one pomoći u smanjenju emisija?

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Summary

According to International Maritime Organization, emissions coming from global shipping are expected to increase 50% to 250% by the year 2050. This concern led to the introduction of various regulations that aims to encourage ship owners and builders to explore innovative renewable technologies. The main focus of this article is on wind-assisted ship propulsion technologies, as a complement to ship propulsion, such as rigid sail, soft sail, wing sail, kite, and Flettner rotor. These technologies are not widely accepted because ship owners have doubts due to the lack of real-life results and their implementation and efficiency greatly depends on ship design and purpose. This article shows the progress in the field of wind-assisted ship propulsion in the last 15 years which proved the concept as they have the potential to reduce fuel consumption, thus emissions, by double digits. The conclusion is drawn, from fuel savings percentages, that rotor and soft sails technologies have great potential in the future of the shipping industry.

KEY WORDS
WASP
rigid sail
wing sail
rotor sail
kite
flettner rotor

Sažetak

Prema Međunarodnoj pomorskoj organizaciji, očekuje se da će se emisije koje stvara pomorska industrija na globalnoj razini povećati između 50% i 250% do 2050. Ova svijest dovela je do uvođenja različitih propisa koji imaju cilj ohrabriti brodovlasnike i brodograditelje te istraživati inovativne obnovljive tehnologije. Glavni je fokus ovoga članka na tehnologijama propulzije broda s pomoću vjetra kao dopuna propulziji broda kao što su: kruta jedra, mekana jedra, krilna jedra, kajt i Flettner rotor. Ove tehnologije nisu općenito prihvaćene jer brodovlasnici imaju sumnje zbog nedostatka stvarnih pouzdanih rezultata te njihova implementacija i djelotvornost uvelike ovise o dizajnu namjeni broda. Ovaj članak pokazuje napredak u području propulzije broda s pomoću vjetra u posljednjih 15 godina koji potvrđuje tu zamisao jer ima potencijal smanjiti potrošnju goriva, a time i emisije na dvoznamenkasti broj. Izvodi se zaključak na temelju postotaka uštede da rotorske i tehnologije mekanih jedara imaju velik potencijal u budućnosti brodarske industrije.

KLJUČNE RIJEČI
WASP
kruto jedro
krilno jedro
rotorsko jedro
kajt
Flettner rotor

1. INTRODUCTION / *Uvod*

Global shipping transport demand is increasing around 4% per year, while the world's trade carried by sea reached over 90% [1]. Shipping is the most energy-efficient mode of transport which is probably the reason why the sector has got away with ignoring the carbon dioxide emissions problem. In 2014, a greenhouse gas study presented by International Maritime Organization (IMO) [1], carbon dioxide emissions coming from global shipping are expected to increase 50% to 250% by the year 2050. IMO concluded that this rapid increase of emissions proves the need for energy efficiency regulations, and made them effective by January 2013 [2]. The regulation requires all 5000 GT ships and above to record fuel and oil consumption and report them. As of March 2018, MARPOL Annex VI sets of regulations [3], became mandatory. Also, IMO introduced the Energy Efficiency Design Index (EEDI) which states that all newly built ships, from 2013 and onwards, have to follow EEDI sets of mandatory carbon dioxide emissions reduction targets. Also, to ensure future production of more efficient ships, reduction targets are tightened every five years up until 2030. Reports [4], [5] submitted to the IMO Marine Environment Protection Committee (MEPC) pointed that the EEDI is only encouraging "mainstream" innovation. Proving that there has been no uptake of innovative measures that yield significant savings, which are necessary to keep shipping's CO_2 emissions in line. To decrease carbon dioxide emissions and improve energy efficiency in shipping activities, utilization of renewable energy solutions and technologies is considered a necessary direction. According to [6] EEDI is calculated:

$$EEDI = \frac{\left(\prod_{j=1}^{M} f_j\right)\left(\sum_{i=1}^{nME} P_{ME(i)} \cdot C_{FME(i)} \cdot SFC_{ME(i)}\right) + \left(P_{AE} \cdot C_{FAE} \cdot SFC_{AE^*}\right)}{f_c \cdot f_l \cdot f_i \cdot Capacity \cdot V_{ref} \cdot f_w}$$
$$+ \frac{\left(\left(\prod_{j=1}^{M} f_j \cdot \sum_{i=1}^{nPTI} P_{PTI(i)} - \sum_{i=1}^{neff} f_{eff(i)} \cdot P_{AEeff(i)}\right) \cdot C_{FAE} \cdot SFC_{AE}\right) - \left(\sum_{i=1}^{neff} f_{eff(i)} \cdot P_{eff(i)} \cdot C_{FME} \cdot SFC_{ME}\right)}{f_c \cdot f_l \cdot f_i \cdot Capacity \cdot V_{ref} \cdot f_w} \tag{1}$$

where:

V_{ref} – ship speed at reference conditions

$Capacity$ – deadweight tonnage (DWT) rating for bulk ship and tankers; gross tonnage for passenger ships

$P_{ME(i)}$ – individual power of main engines

P_{AEe} – combined installed power of auxiliary engines

$P_{PTI(i)}$ – power of individual shaft motors divided by the efficiency of shaft generators

$P_{AEeff(i)}$ – auxiliary engine power reduction due to individual technologies for electrical energy efficiency

$P_{eff(i)}$ – main engine power reduction due to individual technologies for mechanical energy efficiency

SFC – fuel use per unit of engine power

C – CO_2 emission factor based on type of fuel used by given engine

f_c – cubic capacity correction factor (for chemical tankers, LNG carriers and RoPax)

f_l – correction factor to compensate deadweight losses through cargo-related equipment like cranes

f_i – capacity adjustment factor for any technical/regulatory limitation on capacity

f_w – coefficient indicating the decrease in ship speed due to weather and environmental conditions

f_j – correction factor for ship-specific design elements

$f_{eff(i)}$ – availability factor of individual energy efficiency technologies.

If we influence $P_{eff(i)}$, the main engine power requirement will be reduced, thus the overall EEDI value will be decreased. Wind energy has great potential and advantage since its availability is continuous at the open sea when comparing to the other renewable solutions [7] and can offer significant savings on existing ships [8]. For example, in [9] seasonal forecasting of winds, waves, and currents in the North Pacific were analyzed, with the conclusion that the western North Pacific is the most predictable region and therefore seasonal forecast data could be used for vessel routing and confirms the potential application of some wind-assisted technology. According to [10] wind assisted ship propulsion (WASP) technologies have the potential to decrease fuel consumption, thus emissions, by double digits. This leads to the conclusion that this renewable technology will play important role in the future of the shipping industry. Fuel savings, that can be achieved, depending on the design of the ship (rig and hull), the operating speed, and the wind speeds and directions experienced [10]. Also, it is noted that of the available wind assist technologies, kites and Flettner rotors have received the most attention concerning to helping reduce the fuel consumption and emissions from larger commercial ships.

2. WIND ASSISTED SHIP TECHNOLOGIES / *Brodske tehnologije s pomoću vjetra*

2.1. Rigid sails / *Kruta jedra*

Rigid sails are a mature technology with low uncertainties on costs and with simple architecture with no huge motor. But, we must keep in mind that the aerodynamic efficiencies on the vessels are limited by the tip speed ratio. Racing sailboats or foiling catamarans, in specific situations, can sail faster than the wind and achieve tip speed ratios above one, allowing their sails to obtain a higher propulsion efficiency [11]. Also, the author noted when the ship is loaded with all the needs for her serving purpose and cargo, the efficiency is reduced by the lack of ability to achieve the same tip speed ratios.

In paper [12] power profile for a rigid sail is proposed which could assist with modeling potential fuel savings and emission reductions. Strengths, weaknesses, opportunities, and threats (SWOT) analysis was conducted for rigid sail technology by [13]. The analysis recognized that strengths are lower fuel consumption, emission reduction, lower operating costs, improved vessel stability, propulsion in emergencies, and less volume for fuel bunkering. Weaknesses are safety for the crew, additional operational cost, initial cost, interference with cargo operations, increased weight of the ship, additional training, and workload for the crew. Opportunities are the implementation of IMO regulations, higher fuel costs which make this approach economically viable, marketing regarding brand presentation, slow steaming. Threats are shipping industry suspicion, lower fuel cost, alternative or new fuels, route changing, thus placing the ship in the conditions that make rigid sail unfavorable and overall complex structure (hardware and software solutions).

2.2. Soft sails / *Mekana jedra*

Soft sails are flexible sails similar to traditional sails characterized by very different innovative features and are automated to a great extent i.e. duplex rigs, freestanding square rigs, rotating masts etc. Some of the innovative technologies are Pinta-Rig, DynaRig, Delta wingsail and Fastrigs. DynaRig became a popular soft sail technology mainly because of its easy to use characteristics and self-sustainability. The main characteristic is the mast, which is lightly guyed and rotatable, making maneuvres of DynaRig safe and secured. When comparing to the wing sail, its lift coefficients are lower, but by utilizing the larger surface areas greater lift forces are achieved [14]. It is noted that when sailing upwind efficiency of this type of sail decreases. In [15] a coastal sailing vessel (3000 DWT) is proposed, aiming to have zero carbon emissions by utilizing the DynaRig soft sail system. By using this technology total required thrust was reduced by 61%. In [16], a sailing Mult-

Figure 1 Cargo Vessel "Eco liner"

Slika 1. Teretni brod „Ecoliner"

Source: (*WASP (Ecoliner) - Dykstra Naval Architects*, 2019) [16]

purpose Cargo Vessel "Eco liner" 8000 DWT was proposed. In [17], the characteristics of the "Eco liner" has been compared with similar-sized motorized ship under given estimated time of arrival by using computational fluid dynamic (CFD) simulations and weather routing programs. At a cruise speed of 12 knots, simulations showed fuel savings up to 35% and approximately 22% fewer costs of operation. When compared to a similar conventional ship, "Eco liner" has a 3% cost benefit after 10 years of operation if we consider capital costs and depreciation.

2.3. Wing sails / *Krilna jedra*

The wing sail profile and the thickness of the airfoil shape can generate a strong lift effect and provide a strong propulsive force while decreasing the induced drag that slows down the ship [14].The operating principle of the wing sail is to maximize the aerodynamic lift force by rotating to the optimum wind angle of attack. By using mast which rotates 360˚, the wing sail works in different wind angles and even upwind. Figure 1 illustrates the geometrical relationship between forces acting on the wing sail due to apparent wind.

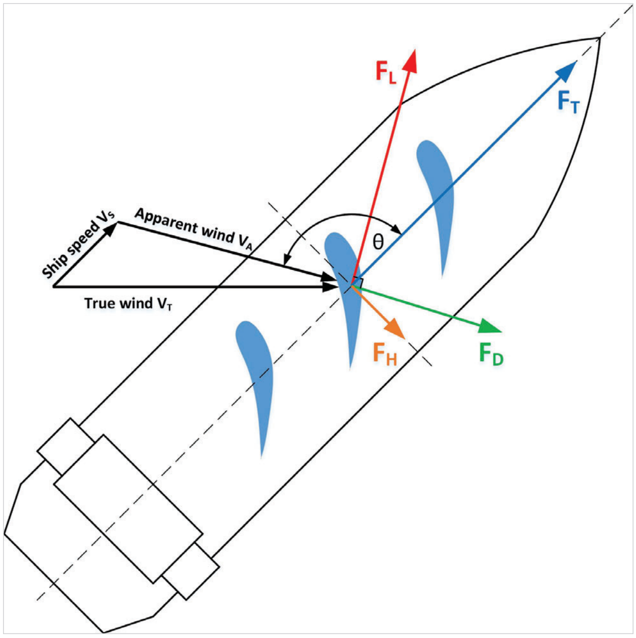

Figure 1 Illustration of forces acting on wing sail; F_T – thrust force, F_H – drift force, F_L – lift force, F_D – drag force, θ – the angle between apparent wind and ship's longitudinal line.

Slika 1. Ilustracija sila koje djeluju na krilno jedro; F_r – porivna sila, F_h – plovna sila, F_l – sila uzgona, F_d – sila povlačenja, θ – kut između prividnog vjetra i longitudinalne linije broda

Source: Authors

According to [18] wing sail should be as small as possible and therefore should apply high lift devices, also sails or their skins should be reefable from the wing structure. In [19], [20] a collapsible wing sail is proposed with double flaps. Also, the best configuration of parameters was investigated and using a numerical simulation method the aerodynamic performance of the new wing sail was analyzed. These papers show that double-flap wing sails provide more thrust force in comparison to arc sail, variable-chamber sail [21], and NACA0021. Another case study [22] states that with wing sail technology, on a route from Ras Tanura (Saudi Arabia) to Yokohama (Japan), 2.6 % fuel savings can be achieved per trip. Four wing sails were considered in this case study. Numerical analysis of aerodynamic performances was conducted by [23] for a two-element wing sail. Also, it is stated that multi-element wing sails are difficult to operate so there is a need to thoroughly investigate the flow around the wing sail. The paper investigates the influence of the construction parameters on the lift and drag coefficients.

The WindShip project [24] proposed a new rigid concept of a wing sail, as a case study ship a Product Carrier 50000 DWT was selected. For the given wind direction and speed, a program was developed to predict the ship's speed, rudder angles, and drift. Within areas with strong winds wing sail technology achieved 10% fuel savings when compared to a similar conventional Product Carrier. But, it is noted that

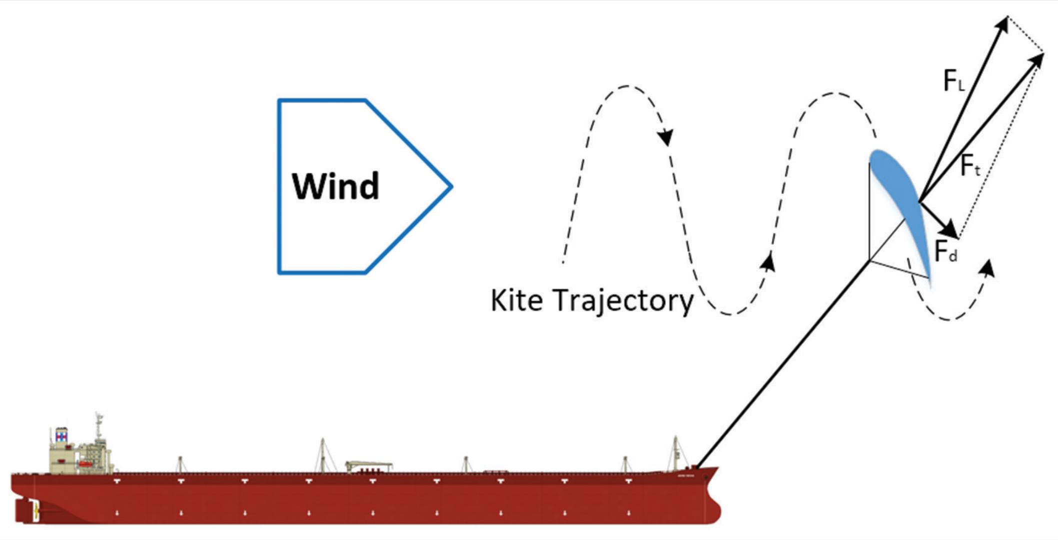

Figure 2 Forces acting on the towing kite; F_L – Lift force, F_t – Total force, F_d – A drag force
Slika 2. Sile koje djeluju na kajt koji tegli; Fl – sila podizanja, Ft – ukupna sila, Fd – sila povlačenja

Source: Authors

during voyages with high average speeds, in a less windy area, fuel savings could be marginal. Another concept of wing sail was studied during the Wind Challenger project [25] on the Bulk Carrier "UT Wind Challenger" 18000 DWT. The result was the development of the energy prediction program which predicts operational performance, also on the route Yokohama - Seattle simulation showed fuel savings up to 22%.

In another project [26], a wing sail concept for the KVLCCM type hull is proposed. Under certain wind and ship speeds computational fluid dynamics (CFD) simulation showed the reduction of thrust, required by the main engine, for approximately 10% with proposed wing sails. The variables investigated in the paper are true wind speed, ship speed, wing sail area, and aspect ratio. Maximum power reduction in this study was achieved for the case were total wing sail area and the height of the sails were kept constant while the variable was the number of the sails. The reduction of 14 % is achieved for 8 wing sails and a true wing angle of 80 °.

2.4. Kites / *Kajtovi*

The operating principle of a kite is to tow the ship when deployed off his bow and Figure 2 illustrates forces acting on the towing kite. They operate at an altitude between 100 – 300 m to tame the power of the higher altitude winds. In paper [27] parameters are used, based on experimental data, to create the point-mass model. A path following strategy was designed so that the kite can follow an eight-shaped trajectory using a simple proportional controller. The result of their simulation showed that a 15 m^2 kite was enough to tow a small fishing boat, also a 30 m^2 kite was enough to tow a zero greenhouse gas emissions vessel 30.5 meters long by 12.80 meters wide.

Skysails is one of the prominent kite technology's and some ships have used or are using it (general Cargo ship "Michael A.", container/cargo ship "M/V Theseus", Bulk carrier "Aghia Marina"). the manufacturer claims that 10 – 15 % fuel saving can be achieved and up to 2 MW of power generation under favorable wind conditions [28]. In paper [29], the power output of a kite on five potential trade routes is estimated. It is calculated that towing kite can provide between 127 and 461 kW of power generation resulting in 1 to 32 % of fuel savings, depending on the ship type. In [30], an analytical model is used to evaluate the performance of a towing kite as an auxiliary power source. On a tanker (50,000 DWT) with 320 m^2 towing kite, themodel showed up to 10% of fuel savings on a 10 m/s wind speed and up to 50% savings at 15.6 m/s. The performance of towing kites proves to be volatile [29], but they are a low emissions solution that should be considered.

2.5. Rotor sails – Flettner rotor / *Rotorska jedra – Flettner rotor*

The rotor sails or Flettner rotor is a rotating cylinder vertically installed on the deck, the rotation of the cylinder is achieved by using an electrical motor. By utilizing the Magnus effect it generates lift force which is perpendicular to the apparent wind vector as shown in Figure 3 b). The direction of the lift force vector depends on the rotational direction of the cylinder. The first rotors were installed on the ship named Backau in 1925. In 1926 it crossed the Atlantic and anchored in the port of New York. The concept was proven technically sound and plausible but was abandoned because of the economical situation regarding low oil prices [31]. In [8] it is claimed that rotor sails could achieve up to 20% fuel savings for commercial cargo ships, assuming three rotors were installed. The lift and drag coefficient study for the 2D case was conducted by [32] and it showed that rotor spin ratio has significant implications for the flow control strategies. The influence of the Thom disc on the lift and drag coefficient was studied by [33] and is illustrated in Figure 3 a).

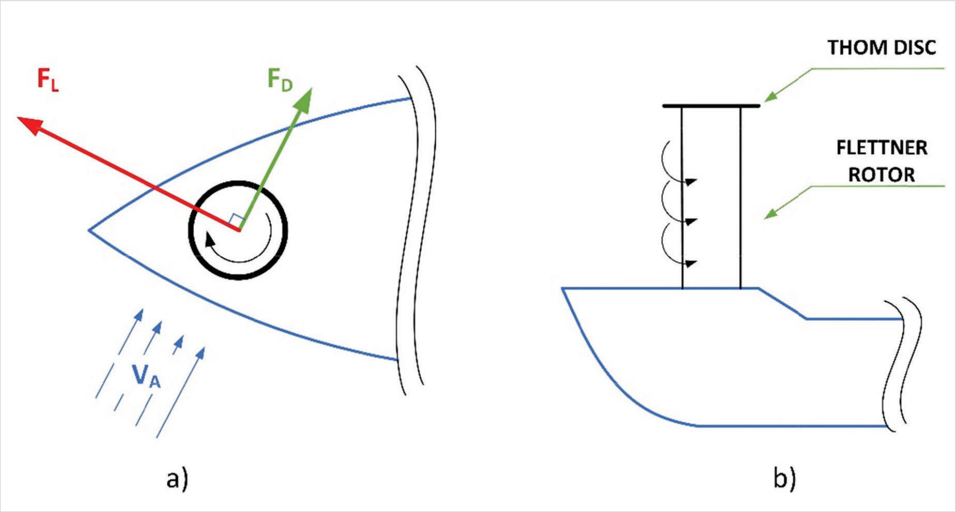

Figure 3 a) Illustration of Magnus effect; F_L –Lift force, F_d –Drag force, b) Illustration of Flettner rotor and Thom disc
Slika 3. a) Ilustracija Magnus efekta; F_L – Sila podizanja, F_d – Sila povlačenja; b) ilustracija Flettner rotora i Thom diska
Source: Authors

Analytical evaluation of net generated power for different values of rotation coefficient was performed by [34], net generated power decreased as the coefficient of rotation increased. Evaluation of the aerodynamic performance of the Flettner rotor was done in [35] by using CFD simulations which showed the importance of 3D simulations over 2D simulations. While evaluating CFD simulation results, in [29] a performance model for power saving simulation of Flettner rotors is proposed. A cargo ship (5500 DWT) was used as a case study, with three Flettner rotors (27m in height and 4m in diameter) installed. The simulation showed a 50% power reduction used by the main engine. In another study [36], the authors followed the performance and handling tests of the Panamax Bulk Carrier with installed Integrated Greenwave MK1 Rotor. A scaled model of a 182 m Bulk carrier with Flettner rotor installed, was used. The results of the experimental tests were that Flettner rotor provided 50% of nominal thrust during light wind conditions and 100% during moderate winds.

In 2010 the Cargo ship "Enercon E-ship" (10500 DWT) came into operation with four rotors, 25m high and 4 m in diameter, installed onboard [37]. On the voyage between Germany and Portugal, fuel consumption was decreased by 23 %.

In 2015 Ro-Ro Carrier "Estraden" (9700 DWT) was retrofitted with rotors, 18 m in height and 3 m in diameter, made by Norsepower [38]. Sea trials conducted on a route between the Netherlands and the United Kingdom showed a 2.6% fuel saving with only one rotor, after installing second rotor trials showed 6.1% fuel savings.

Currently, there are six ships with installed rotor technology. All six are stated in the Table 1.

3. ANALYSIS OF WASP TECHNOLOGY RESULTS / *Analiza rezultata WASP tehnologija*

Summary of results from WASP technology's literature, discussed in this paper, is presented in Table 2.

Based on the literature, this paper presents that wing sail technology can achieve fuel saving in the range of 2.6 – 22 %, depending on the route, ship type, sail angle, number of sails. Soft sail, even though having a lower lift coefficient, can achieve fuel saving up to 35 %. For DynaRig soft sail system,it is reported that 61 % reduction of main engine power is possible. Towing kite can provide 1- 32 % fuel savings. Simulations results show that for Flettner rotor technology fuel savings up 50 % can be expected. From the results, it can be seen that Flettner rotor and soft sail technologies have the most potential.

Table 1 Ships in operation with installed Flettner rotor
Tablica 1. Brodovi koji djeluju s ugrađenim Flettner rotorom

Ship	Type	Year of Built	No. of rotors	Rotor dimensions (H x d) [m]
Fehn Pollux [39]	General Cargo	1996	1	18 x 3
Estraden [38]	Ro-Ro Cargo	1999	2	18 x 3
Maersk Pelican [40]	Crude Oil Tanker	2008	2	30 x 5
E-Ship 1 [37]	General Cargo	2010	4	25 x 4
Viking Grace [41]	Ro-Ro/Passenger	2013	1	24 x 4
Afros [42]	Bulk Carrier	2018	4	/

Source: Authors

Table 2 Summary of wind-assisted ship propulsion technology

Tablica 2. Sažetak tehnologija propulzije broda s pomoću vjetra

WASP tech.	Ref.	Methodology	Results	Real ship / Simulation	Fuel savings
Rigid sails	[12]	Methodology (power profile) is developed by which key performance values can be calculated and displayed in a standardized format by using a virtual wind tunnel.	Power profile will outline key performance characteristics and allow comparisons to be made between different types of rigid sails.	Simulation	
	[13]	SWOT analysis	Strengths, weaknesses, and opportunities are emphasized for rigid sail technology	Simulation	
Soft sails	[14]	Developed software to calculate fuel-saving performance of three wind-assisted ship propulsion technologies – the Flettner rotor, the Soft sails - DynaRig, and a wing sail	Comparison of DynaRig soft sail with Wing sail showed lower lift coefficients of DynaRig, but greater lift force can be achieved.	Simulation	
	[15]	Performance of zero carbon emission coastal sailing vessel is simulated	Simulation showed 61% reduction of required thrust	Simulation	
	[17]	Using CFD simulations and weather routing programs "Eco liner" has been compared with similar-sized motorized ship	The simulation showed up to 35% fuel savings and approximately 22% fewer costs of operation	Simulation	35%
Wing sails	[19] [20]	Using numerical simulations methods aerodynamic performance of collapsible wing sail was studied	Double flap wing sails provide more thrust force in comparison to other wing sail technologies	Simulation	
	[22]	ANSYS is used to perform simulation-based study	On a route from Ras Tanura to Yokohama, 2.6% fuel savings can be achieved per trip	Simulation	2.6%
	[23]	Numerical analysis of aerodynamic performance for two-element wing sail	Influence of the construction parameters on the lift and drag coefficients	Simulation	
	[24]	A new rigid concept of wing sail with realistic simulations based on measured and simulated performance	Rigid wing sail mounted on a case study ship of a Product Carrier achieved 10% fuel savings when compared to similar conventional Product Carrier	Real ship	10%
	[25]	Development of energy prediction program for Wind Challenger project on the case study ship	The simulation showed fuel savings of up to 22% on the route from Yokohama to Seattle	Simulation	22%
	[26]	CFD simulation of a wing sail concept for KVLCCM type hull	Under certain wind and ship speeds simulation showed a reduction of required thrust, by the main engine, for approximately 10%. Also, the reduction of 14% is achieved for 8 wing sails and a true wing angle of 80 degrees.	Simulation	
Kites	[27]	Based on experimental data parameters are used to create a point mass model	The simulation showed that 30 m^2 kite was enough to tow zero carbon emission vessel 30.5 m long and 12.8 m wide	Real ship	
	[28]	Performance test of Skysails kite is conducted on a general Cargo ship	10 - 15 % fuel savings and up to 2 MW of power generation can be achieved under favorable wind conditions	Real ship	10 – 15%
	[29]	The numerical model of a kite on five potential trade routes	Towing kite can provide between 127 and 461 kW of power generation resulting 1 to 32% of fuel savings	Real ship	1 – 32%
	[30]	Analytical model for towing kite performance evaluation	Tanker with 320 m^2 towing kite, the model showed 10% of fuel savings on a 10 m/s wind speed and up to 50% savings at 15.6 m/s	Simulation	10 – 50%
Rotor sails	[8]	Techno-economic and environmental analysis study	Authors claim that rotor sails could achieve up to 20% fuel savings	Simulation	20%
	[32]	Using the finite element method the flow past a rotating cylinder in 2D is calculated	Rotor spin ratio has significant implication for the flow control strategies	Simulation	
	[33]	CFD simulation of spinning cylindrical rotors for maritime propulsion	Influence of the Thom disc on the lift and drag coefficient	Simulation	
	[34]	Analytical evaluation of net generated power	Net generated power decreases as the rotation coefficient increases	Simulation	
	[35]	Aerodynamic performance of Flettner rotor by using CFD simulations	Importance of 3D simulations over 2D simulations	Simulation	
	[29]	A performance model for power saving simulation of Flettner rotors	On a case study, Cargo ship simulation showed 50% power reduction used by the main engine	Simulation	50%
	[36]	Authors followed tests on a scaled model of a 182 m Bulk carrier with installed Flettner rotor	Experimental tests showed that Flettner rotor provided 50% of nominal thrust during light wind conditions and 100% during moderate winds	Simulation	50 – 100%
	[37]	Experimental tests on the Cargo ship "Enercon E-ship"	On the voyage between Germany and Portugal, fuel consumption was decreased by 23%	Real ship	23%
	[38]	Sea trials on Ro-Ro Carrier "Estraden" retrofitted with rotor sails	Sea trials showed 2.6% fuel savings with only one rotor, after installing second rotor trials showed 6.1% fuel savings	Real ship	2.6 – 6.1%

All WASP technologies can be analytically described with lift and drag force. These forces are mathematically expressed by the following equations [43]:

$$F_L = \frac{1}{2}\rho v_A^2 A c_L \tag{2}$$

$$F_D = \frac{1}{2}\rho v_A^2 A c_D \tag{3}$$

Where:
F_L – lift force [N]
F_D – drag force [N]
ρ – air density [kg/m^3]
A – projected area of the rotor [m^2]
v_A – apparent wind speed [m/s]
c_L – lift coefficient
c_D – drag coefficient

The efficiency of these technologies is defined by their lift and drag force ratio. Paper [44] reports that for towing kite technology value of lift and drag ratio is from 3 to 8, depending on relative power setting. Paper [43] reports that Skysail towing kite has a lift to drag ratio of 5. For Flettner rotor lift to drag ratio is a function of a spin ratio. In [45] author reported that a lift to drag ratio depends on the ratio of the diameters of Thom disc and spinning rotor. Lift to drag ratio is a non linear function, for spin ratio interval from 0 to 2, its value increases achieving maximum when the spin ratio is around 2. When the value of spin ratio is from 2 to 8, a lift to drag ratio decreases. The maximum values of lift to drag ratio ranges from 2.5 to 6.5. In the study [46] authors reported nine lift to drag ratio curves where each curve differs one from another in terms of shape and maximum value. For example, one curve has a maximum value of 2.5, where another curve has a maximum value of 13.5. This shows the discrepancy in research data and proves the need for thorough research in this field.

4. CONCLUSION / *Zaključak*

Wind technologies that directly contribute to ship's propulsion, were presented in this paper. This segment of renewable energy sources is potentially of great meaning to a shipping industry when considering the requirements from IMO for emissions reduction. This conclusion is drawn from the percentages of fuel savings achieved, thus reduction of CO_2, NO_x, SO , and PM emissions. Due to different construction designs, different WASP technologies contribute more or less to ship propulsion. The utilization of these technologies depends on the ship deck construction, speed, and ship routing (weather situation along the route). WASP technologies are not widely accepted because ship owners have doubts due to the lack of real-life results regarding fuel savings, for example, from 1999 till 2020 there were only six commercial ships in the world fitted with Flettner rotors. The fact that simulations provide high fuel saving is the motivation for the shipbuilders and owners to consider these technologies as a measure for compliance with IMO emissions regulations. Also, the implementation of fuel cells, solar energy, and other energy-efficient technologies should be considered for emissions reduction for IMO regulations compliance and these technologies will be scope in our future work.

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