IOP Conference Series: Materials Science and Engineering

PAPER • OPEN ACCESS

Wingsail technology as a sustainable alternative to fossil fuel

To cite this article: N I B Ariffin and M A Hannan 2020 *IOP Conf. Ser.: Mater. Sci. Eng.* **788** 012062

Wingsail technology as a sustainable alternative to fossil fuel

N I B Ariffin[1] and M A Hannan[1]

[1] Newcastle University, UK (Singapore Campus)

*Corresponding author: abdul.hannan@ncl.ac.uk

Abstract. Since 3000 BC, wind sailing has been a means of travelling for the humankind. However, the objective of wind propulsion technology research these days is to ensure efficient, sustainable energy source for propulsion which will help to reduce the harmful impact of fossil fuel to the environment. Wingsail is one of such wind propulsion technologies widely studied these days. Although wingsail is mostly used in yacht, surfing and racing boats; this paper reports the findings of a feasibility study on using such technology in commercial vessels. ANSYS Fluent is used to perform this simulation-based study. A particular oil tanker of length 228 m is chosen, and it is found that wingsail can help to save around 2.6% of fuel per voyage for this particular ship on a particular route.

Keywords. Wind propulsion, wingsail, sustainable shipping, wind ship, CFD.

1. Introduction

Harnessing the wind energy to propel ships started many years ago as the form of sails. A sail is usually a tensile rectangular or triangular shaped structure made of fabric or other membrane materials that utilize wind power to propel ships. Since its inception, the technology evolved from the conventional soft sails to the current technologically advanced retractable hard sails. Figure 1 shows the combination of both sails in a single racing boat. However, with the advancement of technology people started to limit the use of sails only on small boats as high-power engines are now available to propel the bigger commercial vessels at a significantly higher speed compared to the vessels running on sails. Such aggressive use of engines running on fossil fuels is severely affecting the environment.

IMO reports that the marine sector is releasing about 3% of the total global CO_2 emission [1]. Shipping industry is also one of the biggest pollutant emitters in the world as well. In 2005, about 1.7 million tons of Sulphur Oxides (SOx), 2.8 million tons of Nitrogen Oxides (NOx) and 195,000 tons of Particulate Matter (PM) was released into the atmosphere near Europe only. The shipping via water is expected to be increased by 70% in the next 20 years [2], which will worsen the situation. This has resulted in the release of international standards for marine vessels to meet – The MARPOL 73/78 which consist of six annexes released by the International Maritime Organisation (IMO) [1]. The aim of this standard is to reduce marine pollution by ships. This stringent regulation has affected the demand and supply of shipping which could ultimately result in high cost of services to the shipping industry. As such, many shipping lines are looking for alternative to fossil fuels to reduce the cost of services in order to maximise profit.

IOP Conf. Series: Materials Science and Engineering **788** (2020) 012062 doi:10.1088/1757-899X/788/1/012062

Figure 1. USA-17A racing boat with a rigid mainsail wingsail, and a conventional jib at the fore (source: Oracle team USA).

Use of renewable energy is one of the best alternatives so far and many renewable energy technologies are being researched and developed to improve the shipping industry. Studies over the years was done to consistently investigate alternatives to improve the shipping environment. Since wind is the most commonly available source of renewable energy at offshore, many researchers are now revisiting the possibility of using wind propulsion technologies to minimise environmental effect of commercial shipping.

A review of various wind propulsion technologies available in the market can be found here [3]. Most of these technologies use the same principle as sailing to produce thrust. As reported by [4], it is believed that the first type of sail invented was the square soft sail. Soft sail refers to sail made of woven materials including canvas, polyester cloth. Wingsail is a variation of conventional soft sail with was inspired by airplane wings design. Wingsails are of two basic types soft shaped wingsail (fabric shaped) and hard wingsail (rigid surface mostly made of carbon fibres). The advantage of wingsail over traditional sails is that its variable camber aerodynamic shape (aerofoil shape) provides more lift and a better lift to drag ratio than traditional sails.

Lift and drag are the forces that plays a very important role for an airplane's take off, cruising and landing. Similarly, on a vessel, by installing wingsails, the objective is to improve the aerodynamic performance of the vessel by reducing drag and creating lift forces in order to reduce resistance against the air. The asymmetrical design (aerofoil) of the wingails causes a difference in air velocity around it, resulting in a combination of higher and lower pressure which causes the lift. Figure 2 provides a better understanding of forces acting on a wingsail. Here, *drag* is the force that acts opposite the direction of motion. *Lift* is the force that acts at a right angle to the direction of drag. *Thrust* is the force required to overcome the drag and to generate the lift force.

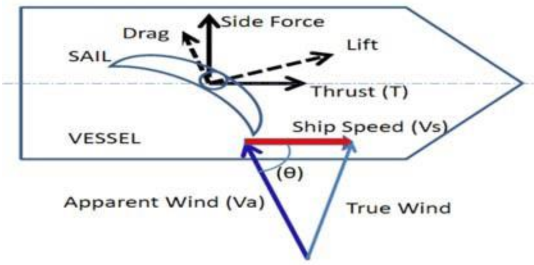

Figure 2. Forces acting on a wingsail [5].

One of the main objectives of wingsail researches, therefore, is to design more efficient wing profiles to maximize lift to drag ratio. Application of wingsails can be traced back to 1970s. A ship named Shin-

Aitoku Maru (figure 3) was fitted with two Japan Machinery Development Association (JAMDA) rigid wingsails on it. The vessel reduced fuel consumption by approximately 10% to 30% during its lifetime while using the JAMDA rigid sails [5]. However, the problem is that these sails can only be fitted on smaller type of vessels. With the advancement of technology, vessels became too large to have such sails fitted on them. As such, these sails are no longer in the interest of the ship designers.

Figure 3. Shin-Aitoku Maru fitted with wingsails [6].

However, recently a new design was studied [5], a ship with large, retractable rigid wingsails. These smart wingsails are about 50m high and 20m wide, fairly larger compared to the sails fitted on Shin-Aitoku Maru and able to propel larger cargo vessel (figure 4). Installing these sails, (while taking into consideration the length of vessel as well as the number of wing sails installed) could reduce fuel consumption of the ship by up to 20%.

Another new types of wingsails, Aquarius MRE, which harnesses both the wind and solar energy is proposed by [6]. This technology will bring together two of the most common renewable resources available at sea - hybridising wind and solar for energy (figure 5). It is still in the developmental stage; hence, the result of this technology is not yet known. However, it is expected to be able to reduce fuel consumption by about 10%.

Figure 4. Artist impression of the UT challenger vessel with the installation of rigid, retractable wing sails [5].

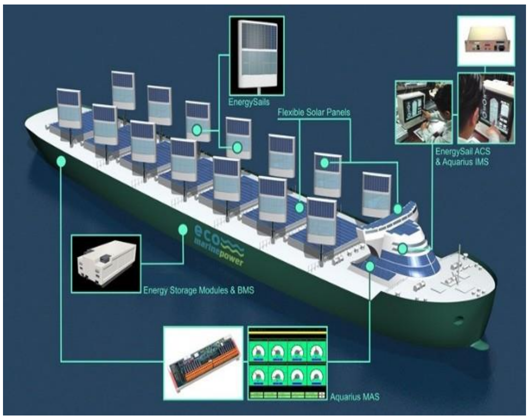

Figure 5. Artist impression of the new wingsail technology by Eco Marine Power which hybridising solar and wind energy [6].

Several experimental and numerical studies were also conducted worldwide to understand this wingsail technology. An experimental study was performed [7] to understand the effects of certain factors such as ship speed, wind speed and sail area on sails. A new design of wingsails was studied where a flap was attached with the wingsails [8]. FEM modelling of the wingsails was done [6] to calculate the stress acting on the sails. The same paper [6], reports a three-dimensional CFD simulation performed to understand the aerodynamic efficiency of the wingsails. In this research, the apparent wind angle (AWA) was varied. The three-dimensional modelling and the result of the simulation with the varied AWA is shown in figure 6. The forward thrust, *T*, here is calculated as follows:

$$T = \frac{1}{2} \times \rho \times v^2 \times A \times C_T \quad (1)$$

Where,

ρ: Density of air ($\frac{\text{kg}}{m^3}$)

v: Apparent wind speed (m/s)

A: Area of wing sail (m^2)

C_T: Thrust Coefficient

As can be seen, wind propulsion technology requires a set of requirements for it to be able to work efficiently. Factors such as wind speed, ship speed and ship type must be taken into consideration. Many research and successful application of this technology was done mostly on yacht and sailing boats. The feasibility of installing it on cargo ship still requires a lot of studies to further improve this technology such as looking into better options for profile design that is aerodynamically more effective. It is suggested by some researchers [8] that more studies should be done on wing/chord ratio of wingsails. It is predicted that wing sails technology could be in demand as we enter a new era of low-carbon emission in the future.

This paper, therefore, focuses on the commercial aspects of applying wingsails on larger vessels. It presents a feasibility study on installing wingsails on an oil tanker and reports the results obtained from this simulation-based work. The next section describes the modelling and simulation details of the proposed wingsails design, followed by the results and discussion.

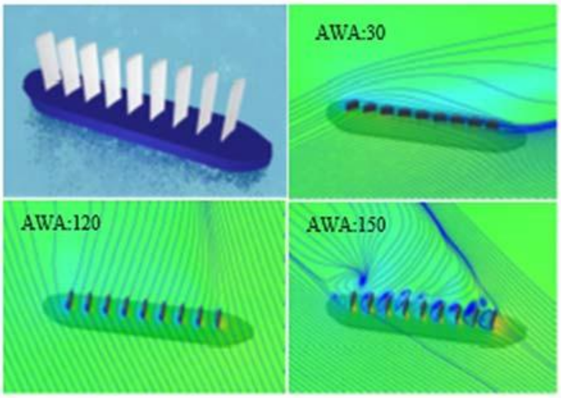

Figure 6. CFD simulations of modelled ship with wingsails at varying AWA [6].

2. Numerical modelling and validation

The first step of this study was to select the appropriate aerofoil shape for the simulation. It is well-known that standard aerofoil shapes were developed by the National Advisory Committee for Aeronautics (NACA) which were designed from past experiences of known shapes and experimental modifications of those shapes. NACA aerofoil series which comprises of the basic 4-digit and 5-digit series were generated using analytical equations which describes the camber of the mean-line of the aerofoil section as well as the section's thickness distribution along the length of the aerofoil. The newer types of aerofoils are the 6-digit series which are more complicated in shapes and was derived from using theoretical reasoning rather than geometrical reasoning.

Two of the most popular series in the NACA aerofoil 4-digit database - NACA 4412 and NACA 6412 were being widely used for the design of wingsails. Table 1 below shows the lift to drag (L/D) ratios obtained for these two aerofoils at various Reynolds number. At a lower Reynold number, NACA 4412 seems to be generating a higher L/D ratio. When Reynolds number increased to about 200,000, the L/D generated for NACA 6412 is higher. It is seen that at different Reynold number, maximum coefficient of L/D was obtained at different attacking angle, a. This shows that Reynolds number plays an important role in determining the generated maximum L/D while varying the different angles. As such, considering the present application scenario, NACA 6412 is chosen as the primary aerofoil design for the wingsail.

Table 1. Comparison of NACA 4412 and NACA 6412.

NACA 4412		NACA 6412	
Reynolds Number	Max CL/CD	Reynolds Number	Max CL/CD
50,000	33.4 at a=9.75°	50,000	9.8 at a=3.75°
100,000	56.1 at a=8.5°	100,000	53.1 at a=10.25°
200,000	78.1 at a=7°m	200,000	80 at a=8.25°
500,000	107.5 at a=6°	500,000	114.2 at a=6.25°
1,000,000	129.4 at a=5.25°	1,000,000	142.7 at a=5.75°

ANSYS Fluent CFD solver is used to perform this study. At first a simple aerofoil shape is modelled and the L/D ratio for various Angle of Attack (AoA) for this simple model is compared with published results [9] for a particular Reynolds number. The simulation parameters are shown in table 2 and the comparison of the results are depicted in figure 7. As noticed, both the results matches quite well. The slight discrepencies in results can be attributed to the differences in modelling and meshing.

Table 2. Simulation parameters for the validation model.

Ansys Fluent Simulations	
Aerofoil	NACA 4412
Solver	Density - Based
Model	Spalart-Allmaras
Material	Ideal gas
Boundary Inlet Velocity	0.53682 m/s
Reynolds Number	30 000

3. Developing the wingsail design

The validated model is then used to simulate the NACA 6412 at various angles of attack. The aerofoil is first modelled in Solidworks and later imported to ANSYS. Table 3 shows the necessary inputs for this simulation. The cross section of the aerofoil modelled and the corresponding domain mesh around it is shown in figure 8.

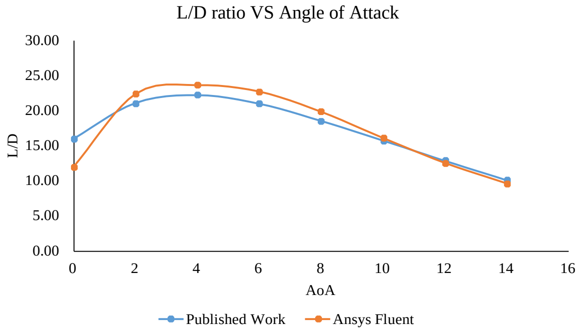

Figure 7. Comparison of present simulation results with published work.

Table 3. Simulation parameters for the validation model.

ANSYS Fluent Simulations	
Aerofoil Type	NACA 6412
Design model	2D
Chord length (NACA 6412)	20 m
Number of wing sail simulated	1
Solver	Density - Based
Model	Spalart-Allmaras
Material	Ideal gas
Boundary Inlet Velocity	15 m/s

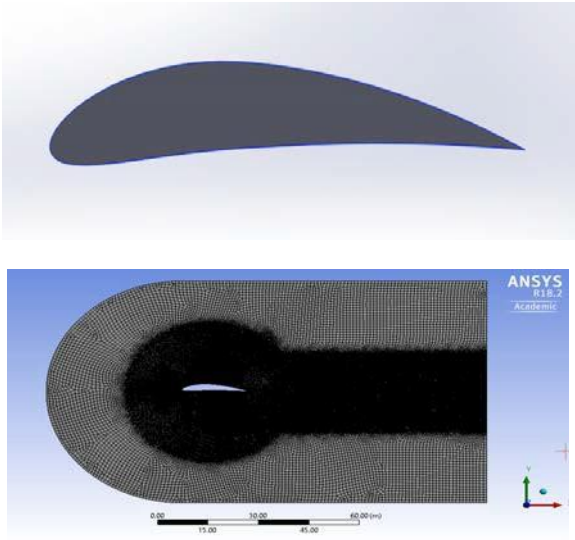

Figure 8. NACA 6412 modelled for simulation (top), Meshing in ANSYS Fluent for the aerofoil NACA 6412 (bottom).

However, it should be mentioned here that the simulation performed here do not consider the superstructure above the vessel's waterline. No structures other than the aerofoil shaped wingsails is considered. For wind, an average speed of 15m/s is used based on the study reported in [5]. The objective of this first set of two-dimensional simulation is to find the L/D ratios at various angle of attack. The results obtained are presented in table 4.

Table 4. Simulation results for NACA 6412.

a (°)	CL	CD	L/D
-2	8.20210	0.20300	40.40443
0	12.58700	0.21203	59.36424
2	16.30331	0.250882	64.98397
4	19.82500	0.35126	56.43967
6	22.02528	0.434998	50.63305
8	24.85200	0.62392	39.83203
10	27.14862	0.86950	31.2232

As can be seen, the coefficient of drag and lift increases as the attacking angle increases which is expected; and the masimum L/D ratio is generated at an angle of attack of 2 degree. The findings are futher elaborated in figure 9 for a better understanding.

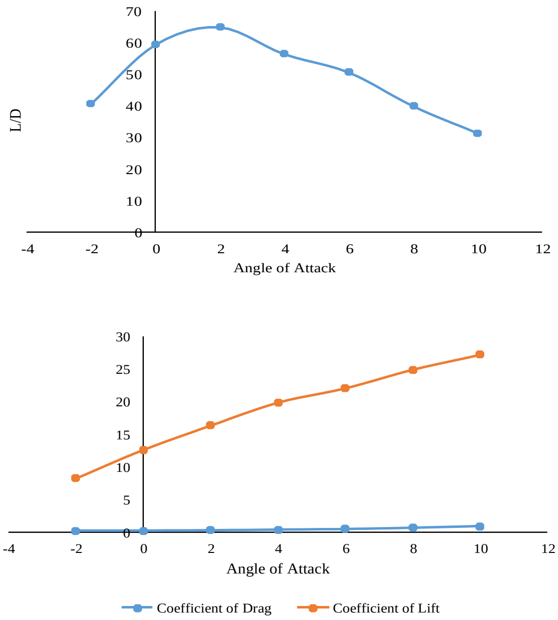

Figure 9. L/D vs angle of attack (top), Coefficient of lift and drag vs angle of attack (bottom).

Figure 10 shows the pressure contour around the aerofoil at an angle of attack 2 degree. As noticed, the leading edge of the aerofoil faces a significant pressure as compared to the other parts of the aerofoil. This is due to the pressure generated at the inlet boundary which is facing 15 m/s wind, during the simulation. A higher pressure is also generated at the lower part of the aerofoil then the upper part which produces that high lift force as shown in table 4 for this particular angle of attack.

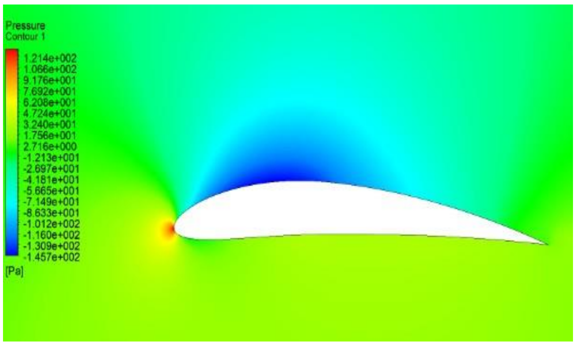

Figure 10. Pressure contour on NACA 6412 at maximum L/D at an angle of attack of 2°.

4. Results and discussion

Keeping in mind the viability of wingsails on commercial ships, it appears that wingsail technology is mainly relevant to tankers or bulk carrier due to the massive space availability on the main deck. According to current market statistics (2018), about 45% of the total merchant ships comprises of bulk carriers as well chemical or oil tankers. Therefore, the potential successful application of wingsails even on a small portion of this large fleet can significantly contribute to lower the adverse environmental impact of shipping.

An oil tanker having the particulars shown in table 5 is therefore, chosen to perform this feasibility study. Considering the total length of the ship, the number of wingsail to be installed will vary. It will

IOP Conf. Series: Materials Science and Engineering **788** (2020) 012062 doi:10.1088/1757-899X/788/1/012062

also depend on the load the vessel carries as well as the availability of space on deck. Other factors such as the material of the wing sails must be chosen perfectly as to keep the loading on the vessel on acceptable limits to prevent stress related problems. It should be noted here that the focus of this study is to calculate the effectiveness of the wingsails on larger vessel. Hence, other technical aspects for example, materials, stress calculations are not considered.

The wingsails designed for this particular installation has a dimension of 20m by 40m (chord length by height). This is chosen based on the dimension of the selected model ship.

Table 5. Particulars of the Oil Tanker selected for this study.

Chosen Ship Characteristics	
Ship type : Oil tanker	Engine
Displacement : 81400 ton	MAN 6S60MC-C71-TII
	Power : 13560 kW
DWT : 74999 ton	N : 105RPM
LOA : 228.5 m	SFOC :174 g/kWh
Breadth : 32.34 m	Propeller
Draft : 14.7 m	Type : Conventional CPP
Depth : 20.45 m	
Speed : 15.1 knots	Diameter : 6.5m

The three-dimensional model of the proposed wingsail is shown in figure 11 while the two-dimensional sketch of the model ship profile with 5 wingsails installed on the deck is shown in figure12.

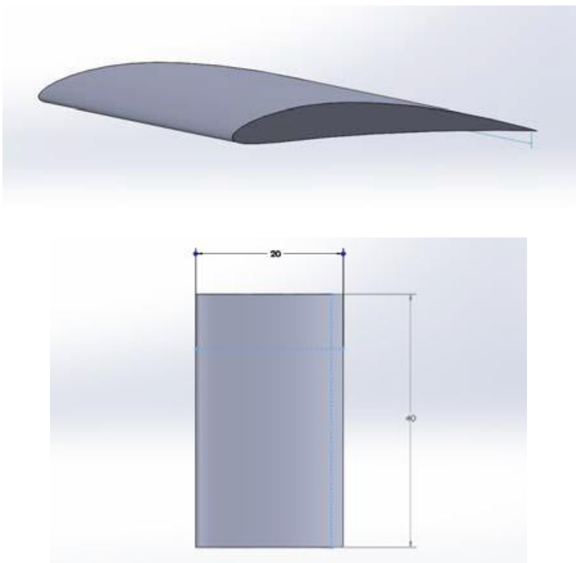

Figure 11. NACA 6412 with extrusion for the wing sail design (top), Wingsail design with dimensions (bottom).

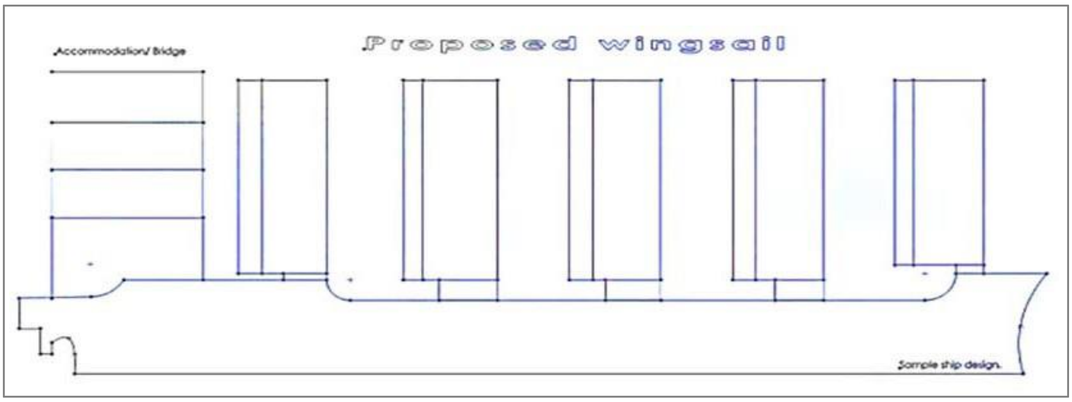

Figure 12. An artist's impression of the selected Oil Tanker with installation of 5 proposed wingsails.

The area of the wingsail plays an important role in the generation of thrust by the wingsail. A higher surface area usually will produce more thrust. However, the maximum sail area to be designed is dependent on the displacement volume of a particular ship.

The following formula is used to estimate the maximum sail area to be installed on the ship [10]:

$$K = \frac{A_S}{(\Delta)^{\frac{2}{3}}} \qquad (2)$$

where, K = Wing sail constant, fixed at 3.2; A_s = Sail area (m^2) and Δ = Displacement (m^3)

Upon calculation using the above formula, the maximum possible sail area for the Oil Tanker under consideration is found to be 3370.8 m^2. Each of the proposed wingsail has a sail area of 800 m^2. Therefore, by installing 4 wingsails on the proposed model ship, a maximum area of 3200 m^2 could be covered which would be within the allowable value of 3370.8m^2 as well.

After finalizing the design, a particular ship route from the port of Ras Tanura, Saudi Arabia to the port of Yokohama, Japan is chosen (figure 13). This route is one of the popular for an oil tanker of similar size as proposed in this study. According to the sea route calculator, the distance between the two port is 6593 Nm and it would require a total of 437 hrs travelling time between the two port, following the shortest possible route.

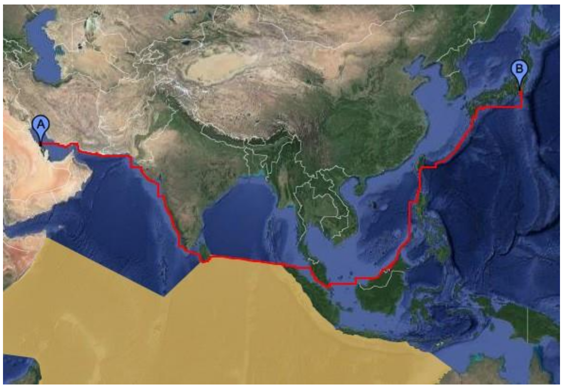

Figure 13. Proposed Ship routes from Ras Tanura to Yokohama.

The total fuel needed for this journey can be calculated using the following equation:

$$Total\ fuel\ needed = p_b \times sfoc \times time \quad (3)$$

where, p_b = Brake Power (kW); *sfoc* = Specific fuel consumption (g/kWh); *time* = Journey time taken (hr)

Hence, the total fuel required by the ship (with no wing sail) will be 1044.2 tons per voyage.

Now, after installing the wingsails, the amount of thrust generated by wingsails can be calculated using equation (1) as mentioned in section 1. Considering the standard thrust coefficient of 1.5, the thrust generated by the 4 wingsails is found to be 146471.04 N. Applying the method presented by [10] to estimate the power gained by the wind as a result of the installation of wingsails, the power gained for the proposed ship model of this study is shown in table 6.

Table 6. Force and energy gained by wingsails for the model ship.

Average wind speed (m/s)	Force generated by wing sail (N)	Average speed of ship (m/s)	Power gain by wind (kW)
7	146471.04	7.7681	1137801.69

A wind speed of only 7m/s is considered to make a very conservative estimation of the fuel saving. Now, assuming the calorie value of diesel fuel is 42700 kJ/kg, the fuel saving for this particular voyage will be about 27 tons. This will result in about 2.6% of fuel savings per voyage.

5. Conclusion

A wingsail design based on NACA 6412 aerofoil is proposed for installation on an existing oil tanker. It is found that a significant amount of fuel can be saved using this sustainable energy source. The benefit of using this technology is twofold: it will minimize the atmospheric pollution and it is using green energy.

However, further studies should be done to investigate the commercial viability between the cost of fuel saved and the cost of wingsail installation. Also, studies can be done to improve the design of wingsails, hybridising wingsails with solar energy and possible other new innovations. The ultimate objective of developing such technology is to reduce the amount of pollutant being released into the atmosphere by reducing the fuel consumption of the vessel.

References

[1]Smith, T. W. P., Jalkanen, J. P., Anderson, B. A., Corbett, J. J., Faber, J., Hanayama, S., and Raucci, C. (2015). Third imo ghg study.

[2]Shukla, P. and Ghosh, K. (2009). Revival of the Modern Wing Sails for the Propulsion of Commercial Ships. International Journal of Physical and Mathematical Sciences, 3(3).

[3]Rutkowski, G. (2016). Study of Green Shipping Technologies – Harnessing Wind, Waves and Solar Power in New Generation Marine Propulsion Systems. International Journal on Marine Navigation and Safety of Sea Transportation, 10(4).

[4]Casson, L. (1964). *Illustrated history of ships & boats*. Doubleday.

[5]Ouchi, K. and Uzawa, K. (2011). Huge Hard Wing Sail for the Propulsor of Next Generation Sailing Vessel. The University of Tokyo, Japan.

[6]Atkinson, G. (2017). Aquarius Eco Ship Concept. 2017.

[7]Jackson, P. (1999). Modelling the aerodynamics of upwind sails. Journal of Wind Engineering and Industrial Aerodynamics, 6, pp. 17-34.
[8]Haack, N. (2011). C-class catamaran wing performance optimisation (Doctoral dissertation, The University of Manchester (United Kingdom)).
[9]Miller, P., Judge, C., Sewell, D. and Williamson, S. (2018). An Alternative Wing Sail Concept for Small Autonomous Sailing Craft. In: Øvergård K. (eds) Robotic Sailing 2017. Springer, Cham.
[10]Chapin., Vincent, G., Nicolas, V., Nicolas, F., Alessandro, S. and Julien. (2015). Aerodynamic study of a two-elements wingsail for high performance multihull yachts. In: High Performance Yacht Design, 10 March 2015 - 12 March 2015 (Auckland, New Zealand).
[11]Chen, J., Ye, Z., Yang, R., Cai, G., Li, J. and Li, H. (2018). Design and Control of Multiple Wing-sail Land Yacht Robot. IEEE International Conference on Mechatronics and Automation (ICMA), Changchun, 2018, pp. 1800-1805.
[12]David, S. (2016). Curve and tilt passive cambering keel and steering fin mastless wingsail. USA Patent no: US9937993B1.
[13]Robert, D., Ninan, M.and Ian, M. (2016). Curve and tilt passive cambering keel and steering fin mastless wingsail. USA Patent no: US9937987B2.
[14]Ahmed Yassin, A. and Ahmed Elbashir, A. (2011). Simulation around aerofoil NACA 4412. University of Khartoum.
[15]Shukla, P. and Ghosh, K. (2009). Revival of the Modern Wing Sails for the Propulsion of Commercial Ships. International Journal of Physical and Mathematical Sciences, 3(3).