Revival of the Modern Wing Sails for the Propulsion of Commercial Ships

Pravesh Chandra Shukla and Kunal Ghosh

***Abstract*—**Over 90% of the world trade is carried by the international shipping industry. As most of the countries are developing, seaborne trade continues to expand to bring benefits for consumers across the world. Studies show that world trade will increase 70-80% through shipping in the next 15-20 years. Present global fleet of 70000 commercial ships consumes approximately 200 million tonnes of diesel fuel a year and it is expected that it will be around 350 million tonnes a year by 2020. It will increase the demand for fuel and also increase the concentration of CO_2 in the atmosphere. So, it's essential to control this massive fuel consumption and CO_2 emission. The idea is to utilize a diesel-wind hybrid system for ship propulsion. Use of wind energy by installing modern wing-sails in ships can drastically reduce the consumption of diesel fuel. A huge amount of wind energy is available in oceans. Whenever wind is available the wing-sails would be deployed and the diesel engine would be throttled down and still the same forward speed would be maintained. Wind direction in a particular shipping route is not same throughout; it changes depending upon the global wind pattern which depends on the latitude. So, the wing-sail orientation should be such that it optimizes the use of wind energy. We have made a computer programme in which by feeding the data regarding wind velocity, wind direction, ship-motion direction; we can find out the best wing-sail position and fuel saving for commercial ships. We have calculated net fuel saving in certain international shipping routes, for instance, from Mumbai in India to Durban in South Africa. Our estimates show that about 8.3% diesel fuel can be saved by utilizing the wind. We are also developing an experimental model of the ship employing airfoils (small scale wing-sail) and going to test it in National Wind Tunnel Facility in IIT Kanpur in order to develop a control mechanism for a system of airfoils.

***Keywords*—**Commercial ships, Wind diesel hybrid system, Wing-sail, Wind direction, Wind velocity.

I. INTRODUCTION

WIND energy is the kinetic energy associated with the movement of atmospheric air. It has been used for hundreds of years for sailing, grinding grain. Wind energy systems convert this kinetic energy to more useful forms of power. Wind energy systems for irrigation and milling have been in use since medieval times and since the beginning of the 20th century it is being used for generating electric power. Windmills for water pumping have been installed in many countries particularly in the rural areas. Wind energy is favoured by many environmentalists as an alternative to fossil fuels, as it is plentiful, renewable, widely distributed, clean, and produces no greenhouse gas. Humans have been using wind power for at least 5,500 years to propel sailboats and sailing ships. "Sail-assist" is a term which is applicable to ships in which most of the power is generated by fossil fuel and a part of the total power required for ship is generated by sails in order to reduce the fuel consumption. The advantage with the wind-assisted ships is that substantial wind energy is available over most of the oceans. Table I shows the relative energy over the different terrains. In 1981, an American Company, named Windship, tested a 278.70 m^2 soft sail, a 8.36 m^2 magnus rotor and a 27.87 m^2 model of wing sail [15]. A cat rig is a soft canvas sail and a wing sail is an airfoil like structure. These types of cat rig and wing sail can be easily retrofitted on existing ships by making some modifications. Many projects have been done in the past on this type of application. The project named INDOSAIL was taken by Indonesion Ministry of Research and Technology. A project to retrofit a 300t ship named 'Na Mataissu' was carried out by the Macalister Elliott and Partners Ltd. [1] in 1984. Since, fuel prices are continuously increasing and India has limited reserves of fossil fuel, it is necessary to find an alternative way to remove the dependence of ship propulsion on fossil fuel.

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II. TYPES OF SAIL-RIGS AND THEIR SELECTION

There are different types of sailing rigs which can be use in propulsion of ship. Some of them are Square Rigs, Princeton Sail wing, Sail Airfoil, Magnus Rotor, Cat Rig and Wing Sail (Fig. 1) [19]. Square rig are not efficient because they mainly operate by drag forces. In Princeton sail wing, a cloth wraps over a rod, the other end of the cloth acts as trailing edge; its maintenance cost is high. Magnus rotor is a cylinder like structure which can rotate vertically on deck space about its rotation axis. A Magnus rotor can provide a better performance than the wing sails and soft sail. Cat sail is a triangular piece of fabric stretched between a vertical unstayed mast and a horizontal boom. In 1981, 278.70m^2 cat rig was installed and tested by the Wind Ship Company on the cargo ship named MINILACE [15]. A wing sail is a structure like airfoil cross-section, like an airplane wing, which can provide a much better lift-to-drag ratio than conventional sails [1]. In our estimation, we assume that the ANNAPURNA ship has been retrofitted with wing sails having airfoil cross section of NACA 0018. Before selecting a sail rig for a ship, several points should be considered follows [1]:

- propulsion performance of the sail rig;
- initial cost of installation of the rig;
- operating cost;
- weight;
- size (volume or area occupied by the system);
- safety while operating the rig;

- cargo handling interference;
- visibility.

TABLE I
TYPES OF TERRAIN AND ROUGHNESS CLASSES [14]

Roughness Class	Terrain	Relative Energy
0	Water areas	10
1	Open country areas with very few bushes, trees and buildings	7
2	Farmland with scattered buildings and hedges with separation in excess of 1000 m	6
3	Built-up areas, forests and farmland with many hedges	3

III. Sailing Mechanism And Different Modes Of Sailing

Sailing mechanism works on the principle of the wing of an aircraft which produces a force called 'Lift' in a direction normal to wind direction. In case of wing sail, lift force is a major contributor in the propulsion of ship. There are different modes of sailing as follows:

Running: When apparent wind is astern with respect to the ship, the ship propels by the Drag force. Fig. 2(a). Drag force can be calculated by the formula:

Drag Force, $D = C_D \times (1/2) \times (\rho A V^2)$ (1)

where C_D is the coefficient of drag, ρ is the density of air, V is the velocity of apparent wind and A is the projected area of the wing sail. There is not so much significance of this mode because drag coefficient is almost same for all the surfaces in this condition.

Reaching: When apparent wind is directly abeam (ship is traveling approximately perpendicular to the wind), ship propels by the Lift force this is called reaching.

Lift force can be calculated by the formula:

Lift Force, $L = C_L \times (1/2) \times (\rho A V^2)$ (2)

where C_L is the coefficient of lift, ρ is the density of air, V is the velocity of apparent wind and A is the projected area of the wing sail. This is a course steered at right angles to the wind. Fig. 2(b).

Close reaching: When the apparent wind is forward abeam, drag reduces the propelling thrust. . This is any upwind angle between Head wind and a Reaching. In this condition, it is desirable to attain the maximum lift coefficient and accept the corresponding drag coefficient. Fig. 2(c). It should note that L/D for a modern airfoil at incidences below stall is around 100; the drag component in the figure has been shown much larger than actual, so that it becomes visible.

Head Winds: When wind comes directly from the front of the ship, known as head winds. In this condition sail should be inoperative and angle of attack should be at 0º (Fig. 2d).

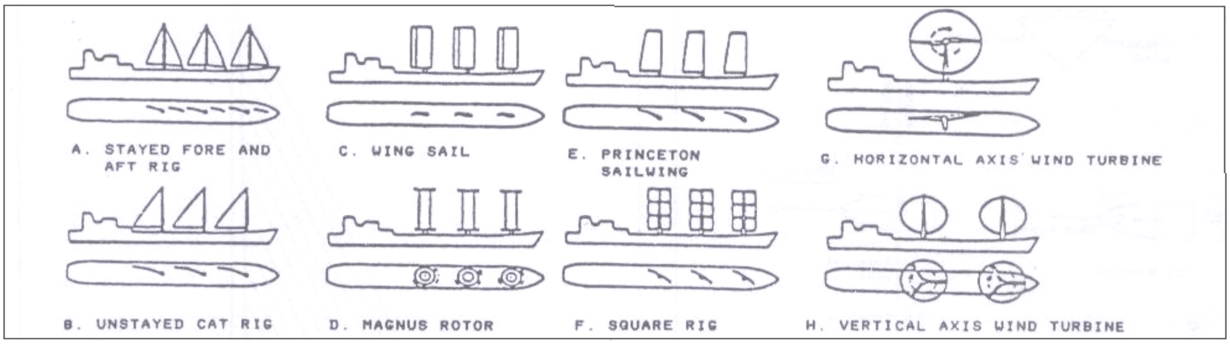

Fig. 1 Various sail rigs [19]

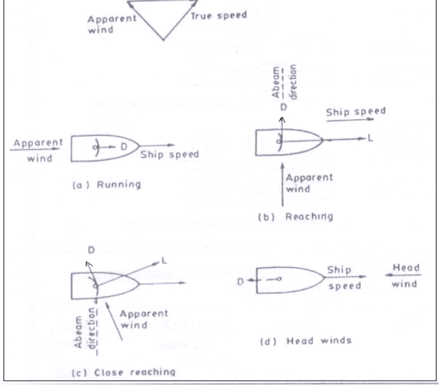

Fig. 2 Different modes of sailing (L and D denote lift and drag forces)

IV. Method

The objective of this paper is to estimate the saving of Diesel fuel consumption by retrofitting of wing-sails in existing ships. Shipping Corporation of India limited has provided us different data of the ship ANNAPURNA related to its dead weight tonnage, engine capacity, length of ship, and approximate average traveling time in an annum in order to complete our calculation. For our estimation we consider that the ship is retrofitted with the wing sail of NACA 0018 cross section [3]. The values of the lift and drag coefficient of NACA 0018 with respect to the angle of attack are given in the Fig. 3 and Fig. 4 respectively. In the first step of our estimation we have estimated the maximum possible sail area and maximum possible number of sails that can be employed on the Annapurna ship. While moving in water the ship experiences a resisting force. We have calculated the resisting force due to water using the data of MINILACE, a vessel chosen by Bergeson, et al [19]. We have chosen Mumbai-Durban route for our estimation because this route is very significant in the context of Indian overseas shipping trade. Finally we have estimated the diesel fuel saving per annum in Mumbai – Durban route. The Geographical coordinates of Mumbai and Durban are (19ºN, 73ºE) and (30ºS, 31ºE), Fig. 5. Mumbai-Durban route is straight, while in estimation, we have divided this route into three segments because the wind direction and velocity change with latitude.

We have studied and used the Global Wind Map for the calculation [11], [12], [24]. The strong winds flowing on either side of equator between 5º and 30º latitude are knows as Trade winds and derive their name from the trade routes charted through them by sailing vessels in earlier times. Trade winds flow from the North-East direction in the northern hemisphere and South-East direction in the southern hemisphere. Substantial wind energy is available in this region.

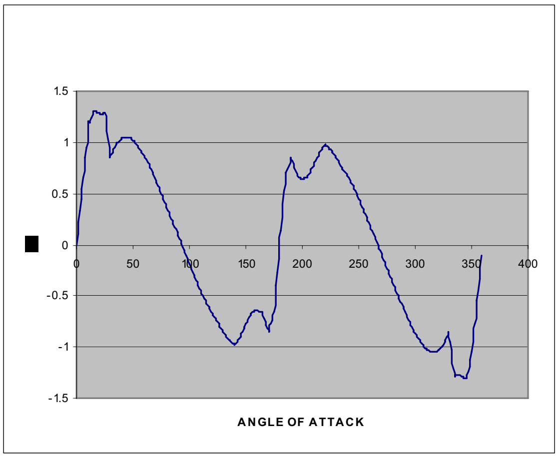

Fig. 3 Graph of the coefficients of lift (NACA 0018) with respect to angle of attack. (Reynolds number =6160000)

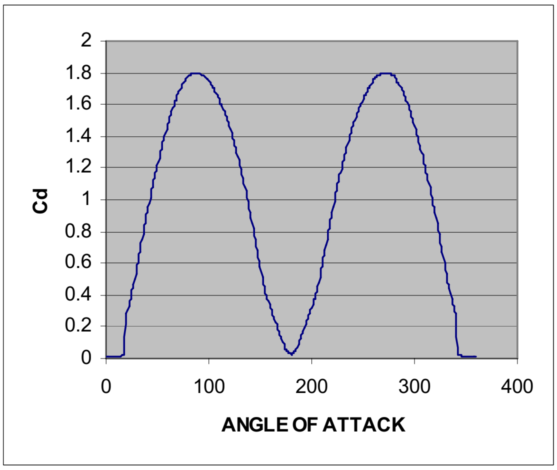

Fig. 4 Graph of the coefficients of drag (NACA 0018) with respect to angle of attack. (Reynolds Number =6160000)

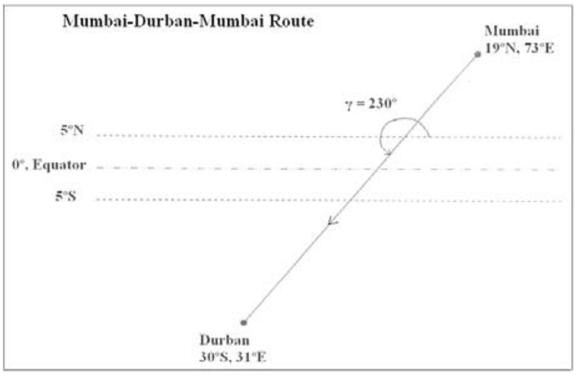

Fig. 5 Route from Mumbai to Durban

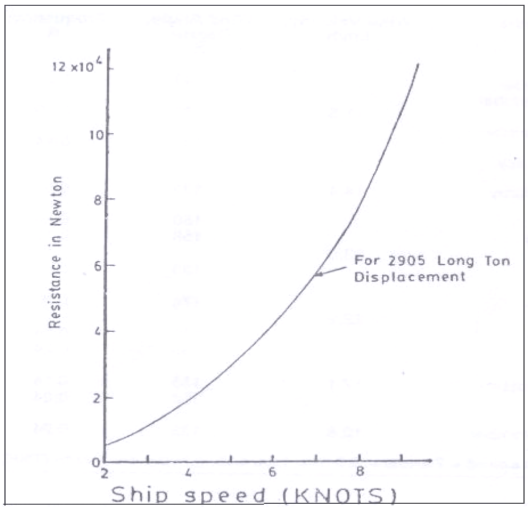

Fig. 6 resistance curve for minilace for 2951.48 t, 1long ton = 1.016 ton

The equatorial belt between 5ºN latitude and 5ºS latitude are known as doldrums [11]. Heated air rising in the doldrums and equatorial low pressure belt makes this area a belt of calm. Much of air movement is in the nature of upward currents with scarcely any horizontal winds. In this condition the ship cannot use wind energy and has to use the diesel engine.

It is considered that ANNAPURNA is sailing from Mumbai to Durban considered. ANNAPURNA, is a ship from the fleet of Shipping Corporation of India Ltd. For the calculation of fuel saving in the route, wind data is taken from the map made by Pacific Northwest Laboratory [24]. Most of the part of travel lies on the trade wind region. The vessel chosen by Bergenson, et al [15] is the 3000 deadweight general purpose cargo ship ‘MINILACE’ having the following characteristics:

Displacement (average)	2951.625 m^3
Service speed	8 knots (4.115 m/s)
Installed power	1000 hp
Specific fuel consumption	2.323×10^{-4} t/hph
Sail size (cat rig)	278.709 m^2
Operating speed	7 knots (3.6 m/s)

It is observed that MINILACE is much like a typical general purpose cargo vessel used in the Indian overseas shipping. MINILACE has a resistance of 26334.49 N when its speed is 7 knots (Fig. 6). The average wind speed is 3.6 m/sec [24] in Mumbai-Durban route. Shipping corporation of India limited has provided us the vessel's particular for ANNAPURNA. It has the following specifications:

Displacement	32992.2 m^3
Installed power	9501 KW at 111 rpm
Service speed	15 knots
Bow length	125.02 m
Beam length	25.9 m

V. Results And Discussions

In the first step of our estimation, we have calculated the maximum possible sail area that can be employed in ANNAPURNA. For a particular ship, the maximum possible sail area is dependent on the displacement volume of that ship[26] according to the following formula [26],

$$K = (SA/ (D)^{2/3}) \quad (3)$$

where, K=constant, for wing sail its value is 3.2, SA=Maximum possible sail area that can be employed in a ship, m^2. D=Displacement volume of ship, m^3.

It is assumed that ANNAPURNA has wing sails of NACA 0018 cross section. It has displacement volume of 32992.2 m^3. According to the above formula, the maximum possible sail area for the ship is 3291.73 m^2. A ship has limited deck area and if we retrofit the wing sails on existing ships, it is not possible to fit the sails with the maximum possible sail area. Again wing sail size should be such that it can be moved within the available deck space without damaging the previous structures on the deck. Wing sail span cannot be too long otherwise this can increase the possibility of instability. We have considered the wing sail span as 15 m with the aspect ratio of 3. Wing sail has chord length of 5 m and the area of the single wing sail employed on ship would be 75 m^2. There should be some space between two consecutive masts of the wing sails to achieve accurate movement and to avoid the wake effect. The distances between two consecutive masts are taken as 1.1 times of the chord length of the wing sail. ANNAPURNA has a length of 153.5m, considering that 120 m length of the ship would be used for the wing sail deployment and 33.5 m length for other constructions. Form the above discussion the maximum possible numbers of wing sails that can be employed on the deck of ANNAPURNA are 22. The total area of the 22 wing sails is 1650 m^2 (<3291.73 m^2) which is well within the limit of the maximum possible sail area.

In the second step of our estimation we have calculated the water resistance for ANNAPURNA. The ship resistance is proportional to the wetted area of the ship. Wetted area of the ship gives the surface area of the hull below the water level. The wetted area can be calculated for a particular ship using displacement volume, length between perpendiculars, beam, draft and height of the ship. According to the calculation, MINILACE and ANNAPURNA has a wetted area of 1226.85 m^2 and 6773.29 m^2 simultaneously. MINILACE has the water resistance of 26334.49 N at a speed of 7 knots (3.6 m/sec). From Fig. 6, the resistance of the ANNAPURNA is estimated to be 145389.5 N for the speed of 7 knots (3.6 m/sec).

TABLE II
WATER RESISTANCE OF THE SHIPS.

Ship name	Wetted area (W.A.)(m^2)	Resistance(N)
MINILACE	1226.85	26334.49
ANNAPURNA	6773.29	145389.5

In the final step, we have estimated the saving of diesel fuel. The global wind pattern is different in northern hemisphere and southern hemisphere. The trade winds flow in the region of 5º-30º latitude from the North-East in northern hemisphere and 5º-30º latitude from the South-East in the southern hemisphere. Velocity of trade winds is constant. Thus a retrofitted ship can use wind energy only in the region of trade winds and it cannot use wind energy in doldrums region for reasons given earlier.

The total distance between Mumbai and Durban is around 4450 km. The distance from Mumbai and Equator is 1750 km and the distance between equator and Durban is 2700 km. Doldrums has no horizontal wind, a ship cannot use wind energy in this region (region between 5ºN-5ºS latitude, approximately 400 km on both side of equator). Therefore, ANNAPURNA can use wind energy only for the 1350 km distance in the northern hemisphere and 2300 km in the southern hemisphere during its travel.

Now, if a ship runs 70% days of a year and rests for another 30% days of a year for repairing and loading, it will spend 27.5% days of a year in between Mumbai and equator and 42.5% days of a year in between equator and Durban on Mumbai-Durban route. It means that ship will spend 13.75% day of a year for onward travel between Mumbai and equator, and 21.25% days of a year for return travel between equator and Durban. Due to the doldrums, effective wind energy gain would be in 10.61% days of a year and 18.1% days of a year respectively.

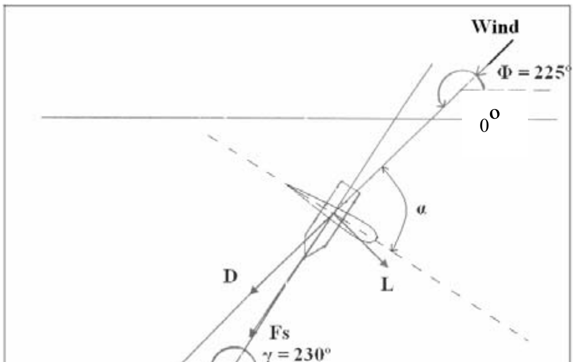

Fig. 7 Mumbai to equator
Φ = angle made by the wind direction to the 0º latitude measured from the east.
γ = angle made by ship motion direction to the 0º latitude measured from the east.
α = angle of attack
S = ship motion direction
D = drag force
L =lift force
Fs = Component of forces in the direction of ship motion.

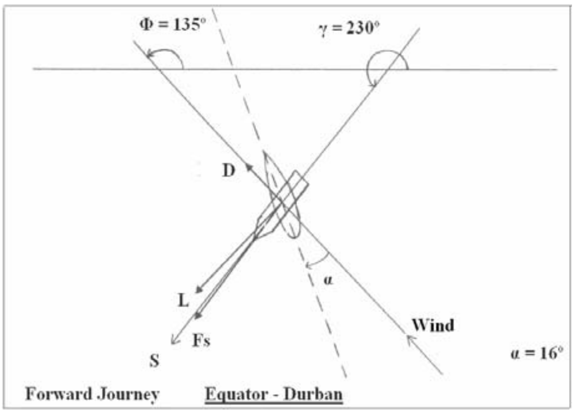

Fig. 8 Equator to Durban

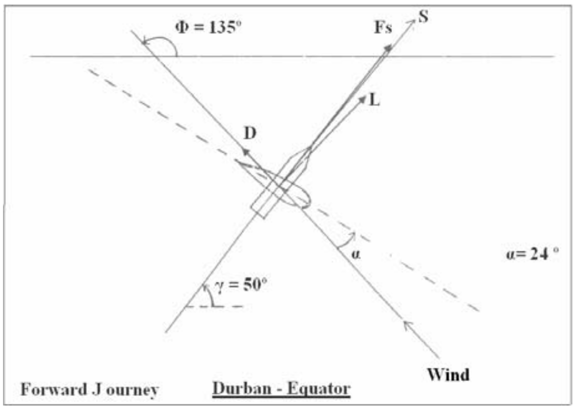

Fig. 9 Durban to equator

A. Calculations Performed

1) Without Sail Assist

If ANNAPURNA does not use the wind energy in Mumbai-Durban route, then the total energy required for the propulsion of ship can be calculated as:

Effective Power of the ship=Resistance × Velocity of the ship. Power required to run the ANNAPURNA at constant speed of 3.6 m/sec = 523402.2 W. Assume the ship has a propulsion efficiency of 35%. Therefore, the power that should be generated by the engine at a speed of 3.6 m/sec = 1495434.857 W = 2004.6 hp. Total hp-hr required per annum in Mumbai-Durban-Mumbai route = 12292207.2 hp-hr/annum. = 33012023.5 MJ/annum.

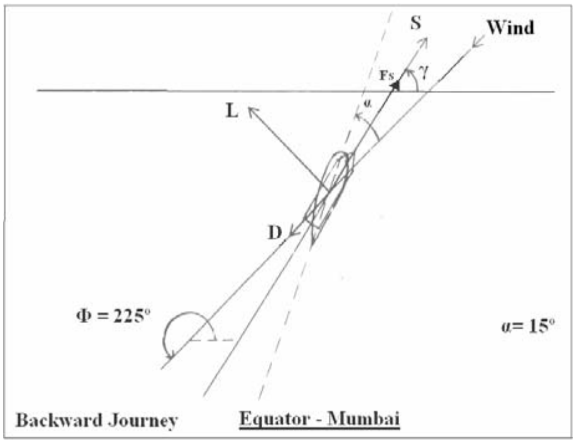

Fig. 10 equator to Mumbai

2) With Sail Assist

If ANNAPURNA uses wind energy, the ship will gain a part of required propulsive force from the component (in the direction of ship motion) of the lift and drag forces developed by the wing sails. This component force depends on the direction and magnitude of the drag and lift generated by wing sail and desired direction of ship motion. Drag and lift forces for the different parts of the travel path can be calculated using equation (1) and (2):

where,

ρ = Density of air = 1.220 kg/ m^3

A = area of a single wing sail = 15 × 5 = 75 m^2

V = average wind velocity = 6 m/sec.[24]

C_D = Coefficient of Drag

C_L = Coefficient of Lift

The value of C_D and C_L for the NACA 0018 wing sail (Reynolds Number =6160000) are taken from the Fig. 3 and Fig. 4. Component values of drag and lift forces in the direction of the ship motion generated by wing sail in different parts of the travel path are different because wind direction is different in different parts of the travel. The calculation of the resultant forces in the different part of the travel path in their corresponding condition is as shown in the Table III. The components of the drag and lift forces are taken in the direction of the ship motion according to the Figs. 7 to 10 respectively.

TABLE III
CALCULATION OF THE COMPONENT FORCE IN THE DIRECTION OF THE SHIP MOTION

S. No.	Part of the travel path	Average Wind Velocity[24] (m/sec.)	Number of wing sails employed in the ship	Wind Angle	Angle of ship motion direction	Angle of attack of wing sail	Component force in the direction of ship motion, Fs (N)
1	Part I	6	22	225 º	230 º	85 º	64892.278
2	Part II	6	22	135 º	230 º	16 º	46523.774
3	Part III	6	22	225 º	50 º	24 º	47016.244
4	Part IV	6	22	135 º	50 º	15 º	3398.6612

TABLE IV
CALCULATION OF THE ENERGY GAIN BY THE WIND IN AN ANNUM

S. No.	Part of the travel path	Component force value, Fs (N)	Average Velocity of ship (m/sec.)	Power gain by wind (watt) =Wind force(Fs) × Velocity of ship	Percentage of days of a year which ship uses wind energy for propulsion (x) (%)	Energy gain in a year (MJ) = Power gain by wind(watt) × 60 × 60 × 24 × (x/100) × 365
1	Part I	64892.278	3.6	233612.201	10.61	781659.323
2	Part II	46523.774	3.6	167485.586	18.1	956010.405
3	Part III	47016.244	3.6	169258.478	18.1	966130.101
4	Part IV	3398.6612	3.6	12235.18	10.61	40938.540

Part I : Ship is going from Mumbai to equator on the way Mumbai- Durban
Part II : Ship is going from equator to Durban on the way Mumbai-Durban
Part III : Ship is going from Durban to equator on the way Durban-Mumbai
Part II : Ship is going from equator to Mumbai on the way Durban-Mumbai

From Table IV, total energy gain from the wind per annum for the route Mumbai-Durban=2744738.3 MJ/annum. The Calorific Value of the diesel fuel = 45 MJ/kg. Therefore Diesel Saving will be = 61 tonnes. The total energy saved by using wind energy in ship propulsion is 2744738.3 MJ/annum for theroute Mumbai- Durban-Mumbai route. This is about 8.3% saving in fuel.

VI. CONCLUSION

It is established that the use of modern wing sail in ship propulsion will reduce diesel fuel consumption considerably. These wing sails can be retrofitted on existing ships. From the above estimation it is clear that the use of wind energy in ship propulsion may save 8.3% of fuel. For the route Mumbai-Durban-Mumbai, the total saving in diesel fuel is 61 tonnes/annum by using sail assist device for the ANNAPURNA ship. India is importing 70% of her oil requirement; therefore the use of wind energy in ship propulsion may partially reduce this dependency. Hence it is recommended that India should invest in the R & D in this area since she has huge international shipping trade.

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